Biphasic attentional orienting triggered by invisible social signals

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Abstract

Biological motion (BM) is one of the most important social cues for detecting conspecifics, prey, and predators. We show that unconscious BM processing can reflexively direct spatial attention, and that this effect has a biphasic temporal profile. Participants responded to probes that were preceded by intact or scrambled BM cues rendered invisible through continuous flash suppression. With a short inter-stimulus interval (ISI, 100 ms) between the invisible BM cues and the probe, responses to probes at the same location as the invisible, nonpredictive BM cue were faster than to probes at the location of the scrambled BM cue. With a longer ISI (800 ms) this effect reversed, with slower responses to probes at the location of the invisible, nonpredictive BM. These effects were absent when BM and its scrambled control were made visible with both short and long cue durations across variable length of ISIs, indicating that the saliency of BM itself cannot account for the dynamic orienting effects from invisible social cues. Moreover, this dynamic attentional shifts were specific to upright BM cues and not obtained for inverted stimuli. Thus, this reflexive and dynamic attentional modulation triggered by invisible BM, with initial facilitation followed by inhibition, demonstrates that in the complete absence of conscious awareness, cue predictiveness, and saliency differences, attentional systems promote exploration of our visual environment for social signals.

1. Introduction

Biological motion (BM), which broadly refers to the movements of animate entities (Johansson, 1973; Troje, 2013), is a social signal that carries information critical for survival and interpersonal interactions. BM can be detected quickly and automatically by the visual system. Many studies have demonstrated that human observers are highly adept at detecting and interpreting BM signals, even when they are portrayed via a simple set of tiny light points (e.g., 12 points) placed at distinct joints of a moving agent (Johansson, 1973). Although highly impoverished (e.g., without texture and form cues), once in motion, these point-light displays (PLDs) are rapidly recognized as coherent, meaningful movements. Moreover, multiple aspects of social information, such as walking direction, gender, interactions, and emotion, can be readily perceived, even if the PLDs are presented within dynamic noise (for reviews, see Blakemore, 2008, 2012; Puce & Perrett, 2003; Steel, Ellem, & Baxter, 2015; Troje, 2013). Such findings have led to the notion that BM can be processed automatically, requiring little attentional resources (see Thompson & Parasuraman, 2012, for a review; Thornton & Vuong, 2004). One intriguing possibility is that the processing of BM does not even require conscious awareness. Indeed, recent evidence suggests that even when rendered invisible, some low-level aspects of BM continue to be accessed at relatively early stage of visual processing (Fairivre & Koch, 2014).

One challenge for studying unconscious BM processing consists in rendering BM stimuli invisible. Standard psychophysical techniques such as backward masking require stimuli to be presented very briefly, and therefore do not allow for sufficient presentation time for a temporal sequence necessary for BM. This issue can be circumvented by using continuous flash suppression (CFS), a particularly potent interocular suppression technique in which a stimulus presented to one eye can be rendered fully invisible for several seconds by dynamic, high-contrast masks flashed onto the other eye (Tsuchiya & Koch, 2005). With this CFS technique it is possible to study unconscious processing of stimuli that require longer presentation durations, such as motion and BM (Fairivre & Koch, 2014;
Maruya, Watanabe, & Watanabe, 2008). CFS has been used to demonstrate that, in addition to low-level stimulus properties (e.g., Hong & Blake, 2009; Maehara, Huang, & Hess, 2009; Tsuchiya & Koch, 2005), also some high-level biological and social information can be processed without awareness. For example, upright faces break through CFS faster than do inverted faces (Jiang, Costello, & He, 2007). Although this breaking CFS paradigm (b-CFS; Jiang et al., 2007; Stein, Hebart, & Sterzer, 2011) may not provide unequivocal evidence for unconscious visual processing (Stein & Sterzer, 2014), the advantage of upright faces in gaining access to awareness suggests that the upright facial configuration is extracted before awareness of the face. Recently, Stein, Sterzer, and Peelen (2012) extended these findings by showing that upright human bodies break CFS faster than inverted bodies, indicating that perceptual processing under CFS is tuned to visual signals diagnostic of other human beings.

What could be the functional significance of such preferential unconscious processing of biologically and socially relevant visual signals? One possibility is that unconscious processing guides visual attention to those stimuli in the environment that are particularly important for survival and social interaction, without involving capacity-limited, metabolically costly conscious awareness (Dehaene & Changeux, 2011). Indeed, Jiang, Costello, Fang, Huang, and He (2006) provided initial evidence for this idea, using sexually arousing stimuli. This study used an unconscious variant of the Posner cuing paradigm, in which attention is attracted exogenously by a physically salient cue flashed in a peripheral probe location (Posner & Cohen, 1984) to investigate whether unconscious, nonpredictive (cue validity: 50%) stimuli can attract attention. The results from Jiang et al. (2006) demonstrated that fully invisible erotic images reflexively attracted spatial attention, in contrast to predictive (cue validity: around 70% or higher), exogenous cues defined by physical salience, such as abrupt onsets. However, it is possible that such unconscious attentional cuing is restricted to sexually arousing stimuli, and it is thus unknown whether similar effects exist for sexually neutral stimuli of outstanding biological and social significance, such as BM. While there is some evidence for the extraction of gender information from invisible BM (Fairen & Koch, 2014), to the best of our knowledge, it has not been tested whether invisible BM can induce reflexive attentional shift.

Recent work shows that visible BM walkers can reflexively and robustly direct spatial attention in their walking direction. This attentional orienting effect from visible BM was first shown by Shi, Weng, He, and Jiang (2010). In their study, following a brief display (i.e., 500 ms) of BM (as a central cue) walking either to the left or to the right, observers’ performance in a subsequent probe discrimination task was better when the probe was presented in the walking direction than in the opposite direction even when observers were explicitly aware that walking direction was not predictive of probe location (Shi et al., 2010). This attentional orienting effect from BM is similar to classic results from the literature on attentional orienting from gaze directions (Friesen & Kingstone, 1998; Langton, Watt, & Bruce, 2000). Thus, like gaze direction, BM represents an important social cue that can induce reflexive shifts of attention.

In the present study, we used an unconscious variant of the Posner cuing paradigm, similar to Jiang et al., 2006, to investigate whether invisible BM can reflexively attract spatial attention. A meaningful, intact BM cue and its scrambled control were presented in different spatial locations to the non-dominant eye and were rendered invisible by novel, custom-built CFS masks (Fig. 1, see also Tsuchiya & Koch, 2005) to the dominant eye. To assess whether unconscious social signals can modulate spatial attention and whether this influence has a specific temporal profile, probes followed the cues with varying inter-stimulus intervals (ISIs). With visible, exogenous cues, the Posner cuing paradigm yields a classic biphasic pattern of facilitation and inhibition: For short ISIs (e.g., 100 ms) reaction times (RTs) are faster to probes at the cued location than at the non-cued location (facilitation), but slower for longer ISIs (e.g., 800 ms, inhibition of return IOR). IOR is often described as a ‘foraging facilitator’, because it facilitates visual search by preventing attention from returning to previously attended locations before exploring other parts of the visual field (Klein, 2000). There is some evidence that IOR can be observed with subliminal, predictive (i.e., cue validity around 70% or above) spatial cues (Mulckhuyse & Theeuwes, 2010), but there has been no investigation on biphasic attentional effects from invisible, nonpredictive (i.e., cue validity: 50%) social stimuli such as biological motion.

2. General method

2.1. Participants

Twenty observers (16 female, age range: 19–30 years, mean age: 21 years) participated in Experiment 1a, and a new group of twenty observers (13 female, age range: 19–30 years, mean age: 21 years) participated in Experiment 1b. Another new group of twenty observers (17 female, age range: 19–30 years, mean age: 21 years) participated in Experiment 2a, and an additional group of twenty observers (16 female, age range: 19–22 years, mean age: 20 years) participated in Experiment 2b. Participants were recruited from Shandong Normal University, and all had normal or corrected-to-normal vision. Participants were naive to the purpose of the study and provided written consent prior to the participation. The study was approved by the Research Ethics Board of Shandong Normal University.

Twenty students from Zhejiang University (9 female, age range: 18–22 years, mean age: 19 years) were paid to participate in the Experiment 3 and signed consent forms. The study was approved by the Research Ethics Board of Zhejiang University.

To ensure adequate power, the sample size was determined by a power analysis based on predicted effect size using G-power 3 (Faul, Erdfelder, Buchner, & Lang, 2009). Based on the results of previous studies (Jiang et al., 2006; Xu, Zhang, & Geng, 2011), we predicted a large effect size (d = 0.65, according to Cohen, 1988) for our experimental design. With 80% power at the 0.05 significance level, the suggested sample size was approximately 20 individuals. The sample sizes for all experiments reported here were determined by the same rule.

2.2. Apparatus and stimuli

Visual stimuli were generated on a PC computer using Psychopy (Peirce, 2007), and presented on a linearized CRT monitor (21” Sony G520; resolution: 1024 x 768 pixels; refresh rate: 100 Hz). Participants viewed the screen from a distance of 70 cm in a dark room. Binocular fusion frames (10.9° x 5.45° for Experiments 1a, 1b, 2a, and 2b) surrounding the stimuli were always presented to promote stable binocular eye alignment. Stimuli were viewed through a mirror stereoscope and presented against a uniform gray background at mean luminance (17.5 cd/m²).

Five BM stimuli (crawl, jump, row, walk, and wave) were selected from the Vanrie and Verfaillie (2004) database. Each original BM sequence comprised 13 dots depicting the movement of the head and the major joints (shoulders, elbows, wrists, hips, knees, and ankles). Pair-wise shuffled motion (PSM) variants of these BM stimuli (for Experiments 1a, 2a, 2b, and 3) and inverted BM stimuli (for Experiment 1b) were used as foils. PSM stimuli are improved scrambled controls in which relations among local
Fig. 1. Illustration of the experimental methodology. (a) Schematics of the stimuli presented to the dominant and non-dominant eye and illustration of participants’ perception. In the invisible condition, awareness of the biological motion (BM) and pair-wise shuffled motion (PSM) cues presented to the non-dominant eye was suppressed by the dynamic, colorful continuous flash suppression (CFS) masks presented to the dominant eye. In addition, one hundred randomly moving dots were overlaid on the CFS masks. Thus, participants perceived only CFS masks and moving dots. In the visible condition, participants could perceive both BM and PSM cues, which were identical to the invisible condition, but were presented to both eyes, and no CFS masks were displayed. (b) Schematic illustration of the experimental paradigm for the invisible condition. Each trial began with a black fixation cross (500 ms). For the next 900 ms, a BM and a PSM cue were presented to the non-dominant eye, while dynamic CFS masks were presented to the dominant eye. After this cue display, there was either a 100-ms or a 800-ms inter-stimulus interval (ISI) in which only the fixation cross was displayed, followed by a Gabor patch, which was presented until response or for a maximum duration of 1500 ms. At the end of each trial, observers pressed one of two buttons to indicate the perceived orientation (clockwise or counterclockwise) of a Gabor patch briefly presented on either side of fixation as quickly as possible while minimizing errors.

Segments are destructed but pair-wise relations within those segments are preserved. Pairs are formed between head and hip, right and left shoulder, left elbow and wrist, right elbow and wrist, left knee and ankle, and right knee and ankle. Pairs of dots are randomly repositioned within the first frame, then all dots execute the trajectories in the original sequence in subsequent frames (see Kim, Jung, Lee, & Blake, 2015 for more details). For both BM and PSM stimuli, two hip points were combined as the waist point. Specifically, the coordinates of the waist were computed by taking the average of the two hip coordinates. Thus, both BM and PSM stimuli used in the present experiments consisted of only 12 dots (each dot 0.18° × 0.18°, totally subtended approximately 2.15° × 1.74°; Michelson contrast: 0.1). When presenting the stimuli to participants, we clipped 23 frames out of each PLD (i.e., 900 ms) with a randomized initial frame to reduce predictability.

We developed novel CFS masks that were optimized for suppressing motion stimuli (i.e., moving dots, see also Maruya et al., 2008; Moors, Wagemans, & de-Wit, 2014, 2017). These CFS masks (4.85° × 4.85°) consisted of a dynamic series of 16 × 16 squares of equal size (0.31° × 0.31°) and randomly selected colors that updated every 100 ms (see Fig. 1a). Considering the feature-selective suppression of CFS masks (i.e., suppression is deeper and more robust when properties of the masks are similar to those of the to-be-suppressed stimulus, Yang & Blake, 2012), one hundred randomly moving dots (each dot 0.18° × 0.18°; Michelson contrast: 0.1) were overlaid on top of traditional CFS masks to enhance the masking effect and to induce deeper interocular suppression. For all three experiments, two Gabor patches (1.5° × 1.5°, 3° clockwise or counter-clockwise rotation, and 4.0 cycles per degree) were used as probes.

2.3. Procedure

2.3.1. Experiment 1a: intact vs. shuffled biological motion

A 2 (cue visibility) × 2 (cue type) within-subject design was used in Experiment 1. CFS masks were presented on a randomly selected subset of 50% of all trials (invisible cue trials), and no CFS masks were presented on the remaining 50% of the trials (visible cue trials). For half of the invisible cue trials, probes were presented on the same side as the BM stimuli (valid cues). For the other half of cue visible trials, probes were presented on the same side as the BM stimuli (invalid cues). In visible cue trials, the cues were identical to invisible cue trials. Participants completed 160 trials.

Before the experiment began, a variant of the Porta test was used to identify the dominant eye (Porta, 1593; Roth, Lora, & Heliman, 2002). The participant extended one arm, and aligned the index finger with the corner of the room while keeping both eyes open. Next, the participant closed each eye and reported which eye closure caused the largest alignment change. The closed eye causing more change was recorded as the dominant eye. In the actual experiment, as illustrated in Fig. 1b, each trial began with a black fixation cross (500 ms). Next, a BM and a PSM cue were presented to the non-dominant eye for 900 ms. In the invisible condition, dynamic CFS masks were presented to the dominant eye during these 900 ms. In the visible condition,
the BM and PSM cues were also presented to the dominant eye. The contrast of the BM and PSM stimuli was ramped up (i.e., the points gradually appeared) during the initial 500 ms to avoid abrupt transients and then kept the peak level during the remaining 400 ms. The horizontal distance between the center of the BM (or PSM) cue and the fixation cross was 3.64°. After the offset of the cue display, there was a 100 ms inter-stimulus interval (ISI) in which only the fixation cross was displayed, followed by a Gabor patch that was presented on the left (or right) side of the fixation until the observer’s response or for a maximum of 1500 ms. Observers were required to press one of two buttons to indicate the orientation of the Gabor patch as quickly as possible while minimizing errors, and to press another button to abort the trial whenever any part of the BM (or PSM) stimulus became visible. At the beginning of each experiment, observers were explicitly told that both BM and PSM cues were not predictive of probe location.

2.3.2. Experiment 1b: upright vs. inverted biological motion

The procedure of Experiment 1b was identical to the procedure of the invisible cue condition in Experiment 1a, except that in Experiment 1b the control stimuli were inverted intact BM stimuli (i.e., rotated by 180 degrees) instead of PSM stimuli.

2.3.3. Experiment 2a: short vs. long cue-target interval

A 2 (ISI) × 2 (cue type) within-subject design was used in Experiment 2. As the visible cue was not included any longer, CFS masks were always presented. On a randomly selected subset of 50% of all trials the ISI between the cues and the Gabor probe was 100 ms (100-ms ISI trials). On the remaining 50% of the trials the ISI was set to 800 ms (800-ms ISI trials). For half of the 100-ms ISI trials, the probe was presented on the same side as the BM stimulus (valid cues). For the other half of 100-ms ISI trials, the probe was presented on the same side as the PSM stimulus (invalid cues). For 800-ms ISI trials, cue randomization followed the same procedure as 100-ms ISI trials. Each participant completed 160 trials. The procedure of Experiment 2a was identical to the procedure of the invisible cue condition in Experiment 1a, except that in Experiment 2a the ISI between cue and probe randomly changed between 100 ms and 800 ms.

2.3.4. Experiment 2b: inversion control

The procedure of Experiment 2b was identical to the procedure of Experiment 2a, with the following exceptions: In Experiment 2b inverted BM and PSM cues instead of upright BM and PSM cues were presented to the non-dominant eye.

2.3.5. Control experiments: objective tests of suppression effectiveness

Following the main experiments all participants took part in separate control experiments to assess suppression effectiveness objectively. Except for the response stage, visual stimulation in these control experiments was identical (for control experiments of Experiments 1a, 2a and 2b, and the first control experiments of Experiment 1b and 2b) or similar (control stimuli were removed for the second control experiment of Experiments 1b) to the respective main experiment. However, at the response stage participants did not respond to the Gabor patch anymore, but instead indicated as accurately as possible, without speed pressure, on which side of fixation the intact BM cue was presented. Thus, this forced-choice experiment assessed participants’ ability to localize the BM cues in a criterion-free way, yielding an objective measure of cue visibility. In the control experiments of Experiments 1a and 1b, there was a total of 80 invisible trials, respectively. There were 160 trials in the control experiments of Experiments 2a, 2b, and a binocular presentation experiment (see Appendix A), respectively.

2.3.6. Experiment 3: visible biological motion

To further examine the potential saliency differences between BM cue and its scrambled control in the visible condition across different temporal durations, we conducted Experiment 3. In this experiment, we added cue duration of BM stimuli (500 vs. 900 ms) as a new variable. Then, a 2 (encoding time) × 2 (ISI) × 2 (cue type) within-subject design was used. In the long cue duration block (900 ms), the experimental details were identical to the visible condition of Experiment 1 with an addition of a long ISI (i.e., 800 ms) condition. Moreover, the short cue duration block (500 ms) was the same as the long cue duration block except that the cue duration of BM was 500 ms (Shi et al., 2010). The order of different cue duration blocks was counterbalanced across participants. Each participant completed 320 trials.

2.4. Data analysis

Incorrect responses were excluded from the analyses (<5% in all experimental conditions). Mean RTs were calculated for correct responses, removing trials with RTs shorter than 300 ms and beyond three standard deviations below and above the mean (<2% of correct trials). Trials on which participants saw part of the moving stimulus were aborted (participants pressed a key and data of the trials were not recorded) and were redone subsequently.

3. Results and discussion

3.1. Experiment 1: invisible BM can reflexively attract attention

This experiment tested whether visible and invisible BM can reflexively attract spatial attention. If BM cues attracted spatial attention, responses to Gabor probes appearing at the same spatial location as the BM cue (valid condition) would be expected to be faster than responses to Gabor probes at the location of the PSM cue (invalid condition).

Reaction times (RTs). A repeated measures ANOVA with the factors cue visibility (visible vs. invisible) and cue type (valid vs. invalid) revealed no significant main effects [cue visibility (visible vs. invisible): 748 vs. 759 ms, F (1, 19) = 1.83, p = 0.192, ηp² = 0.088; cue type (valid vs. invalid): 752 vs. 754 ms, F (1, 19) = 0.22, p = 0.643, ηp² = 0.012; Fig. 2a], but a significant interaction between cue visibility and cue type [F (1, 19) = 7.61, p = 0.013, ηp² = 0.286]. A cueing effect was present only in the invisible condition: when the Gabor probe was presented on the same side as the BM stimulus RTs were significantly faster than when the probe was presented at the same side as the PSM stimulus [valid vs. invalid: 740 vs. 755 ms, t (19) = −3.13, p = 0.006, d = 0.70]. In the visible condition, there was no significant difference between valid and invalid cues [valid vs. invalid: 764 vs. 753 ms, t (19) = 1.33, p = 0.199, d = 0.297]. These results show that invisible BM stimuli reflexively attracted observers’ attention, leading to faster responses in the orientation discrimination task.

Accuracy. In the invisible condition, response accuracy was 94% for valid cues, and 95% for invalid cues; while in the visible condition, accuracy was 95% for valid cues, and 94% for invalid cues. A 2 (cue visibility: visible vs. invisible) × 2 (cue type: valid vs. invalid) repeated measures ANOVA revealed that neither main effects nor the interaction effect were significant (p ≥ 0.239), thus ruling out speed–accuracy trade-offs.

Objective measure of suppression effectiveness. One important challenge for research on such unconscious processing mechanisms consists in ruling out that effects could have reflected residual conscious processing. For example, if BM had not been
fully suppressed by the CFS mask, some participants might have consciously seen the BM stimuli sometimes and might have oriented their attention accordingly. To exclude this possibility, we used optimized CFS masks and adopted a very conservative, objective criterion to assess visibility. In the control experiment that measured participants’ accuracy in localizing the intact BM cue in the invisible condition, none of the participants performed significantly different from chance, as determined by binomial tests all \( p > 0.21 \) (range: 0.219–1.000). Performance of the whole group of participants did not differ significantly from chance performance [mean \( \pm \) SEM: 0.5019 \( \pm \) 0.0074, \( t \) (19) = 0.25, \( p = 0.804 \); Fig. 2b]. These results demonstrate that the suppressed BM cues were truly invisible.

### 3.1.2. Experiment 1b: upright vs. inverted biological motion

In Experiment 1a, we found that invisible BM stimuli can attract spatial attention, as reflected in faster responses in the valid condition. One concern is that this effect might have been specific to the particular comparison between intact and shuffled BM cues used in Experiment 1a. In Experiment 1b, we therefore replaced the PSM control stimuli with inverted (i.e., rotated by 180 degrees) intact BM stimuli. Upright and inverted BM stimuli are identical regarding low-level stimulus properties and motion coherence but differ in social meaningfulness. If the effect found in Experiment 1a reflected unconscious processing of the genuine social signal inherent in upright BM stimuli, we would expect a similar effect in Experiment 1b. For Experiment 1b, the visible condition was removed, and we included two control experiments to check suppression effectiveness. The first control experiment assessed whether participants could discriminate on which side of fixation the upright BM cue was presented when both upright and inverted BM cues were presented simultaneously (as in the main experiment). The second control experiment assessed whether participants could discriminate on which side of fixation the upright BM cue was presented when only the upright BM cue was presented (more akin to a simple detection task).

#### RTs

When the Gabor probe was presented at the same side as the upright BM stimulus, RTs were significantly faster than when the probe was presented at the same side as the inverted BM stimulus [valid vs. invalid: 642 vs. 651 ms, \( t \) (19) = −2.69, \( p = 0.014 \), \( d = 0.60 \); Fig. 3a]. These results replicate the findings from Experiment 1a, again showing that invisible upright BM stimuli attract spatial attention.

#### Accuracy

Response accuracy was 96% for both valid and invalid cues [\( t \) (19) = −0.72, \( p = 0.48 \), \( d = −0.16 \)], thus ruling out speed-accuracy trade-offs.

### Objective measure of suppression effectiveness

All participants in Experiments 1b took part in both the first control experiment and the second control experiment to check suppression effectiveness. For the first control experiment, none of the participants performed significantly different from chance in localizing upright vs. inverted BM cues, as determined by binomial tests all \( p > 0.14 \) (range: 0.146–1.000). Performance of the whole group of participants did not differ significantly from chance performance [mean \( \pm \) SEM: 0.4913 \( \pm \) 0.0107, \( t \) (19) = −0.82, \( p = 0.425 \); Fig. 3b]. Also for the second control experiment, none of the participants performed significantly different from chance in localizing upright BM cues (in the absence of inverted BM cues), as determined by binomial tests all \( p > 0.43 \) (range: 0.434–1.000). Performance of the whole group of participants did not differ significantly from chance performance [mean \( \pm \) SEM: 0.5094 \( \pm \) 0.0063, \( t \) (19) = 1.49, \( p = 0.152 \); Fig. 3b]. These results demonstrate that the suppressed BM cues were truly invisible.

### 3.2. Experiment 2: invisible BM can both attract and inhibit attention— evidence for a biphasic, reflexive attentional effect from invisible BM

#### 3.2.1. Experiment 2a: short vs. long cue-target interval

In Experiments 1a and 1b, we found that, with a short ISI of 100 ms, invisible BM stimuli can reflexively attract spatial attention, as reflected in faster responses in the valid condition. This effect was found when comparing upright, intact BM cues with PSM cues as well as with inverted, intact BM cues. Experiment 2a was designed to test the temporal profile of this reflexive orienting effect. One possibility is that unconsciously attracted attention would dwell on invisible BM for longer time periods. In that case, we would expect facilitation in valid trials both for short and longer cue-probe intervals. Alternatively, if attention reflexively attracted by invisible BM would show a biphasic profile, with initial facilitation at short cue-probe intervals and later inhibition, as in IOR, we would expect faster RTs in valid trials only for the short ISI of 100 ms but slower RTs in valid trials for the newly included longer ISI of 800 ms. Such a biphasic profile would
indicate that even in the absence of awareness and cue predictiveness, attentional systems sensitive to BM serve to actively and efficiently explore the visual field.

**RTs.** A repeated-measures ANOVA with the factors ISI (100 vs. 800 ms) and cue type (valid vs. invalid) revealed a significant effect of ISI [100-ms vs. 800-ms ISI: 723 vs. 674 ms, F (1, 19) = 14.43, p < 0.01, \( \eta^2_p = 0.43; \) Fig. 4a], but no significant effect of cue type [valid vs. invalid: 700 vs. 697 ms, F (1, 19) = 0.44, p = 0.517, \( \eta^2_p = 0.022 \)]. Overall faster responses in the longer ISI condition are consistent with the common observation of generally faster RTs for longer temporal intervals between a cue and a probe, perhaps reflecting greater temporal predictability of the probe. Most importantly, there was a significant interaction between ISI and cue type [F (1, 19) = 18.44, p < 0.01, \( \eta^2_p = 0.493 \)]. For the 100-ms ISI trials, RTs were significantly faster in trials in which the probe was presented on the same side as the invisible BM stimulus (valid condition) compared to trials in which the probe was presented on the same side as the invisible PSM stimulus [valid condition: 716 vs. 731 ms, t (19) = 2.23, p = 0.038, d = 0.499]. For the 800-ms ISI trials, this pattern reversed: Here, observers’ RTs were significantly slower in the valid condition than in the invalid condition [valid vs. invalid: 685 vs. 663 ms, t (19) = 3.68, p = 0.002, d = 0.823]. Thus, we indeed observed a biphasic pattern of initial facilitation and later inhibition by invisible, nonpredictive BM.

**Accuracy.** In the 100 ms-ISI condition, accuracy was 96% both in the valid and in the invalid condition; in the 800 ms-ISI condition, accuracy was 97% for both valid and invalid cues. A 2 (ISI: 100 vs. 800 ms) × 2 (cue type: valid vs. invalid) repeated measures ANOVA showed that neither the main effects nor the interaction effect were significant (ps > 0.289), again ruling out speed-accuracy trade-offs.

**Objective measure of suppression effectiveness.** All participants in Experiments 2a took part in a control experiment to check suppression effectiveness. Except for one participant (p = 0.03), none of the rest performed significantly different from chance in localizing the intact BM cue in the invisible condition, as determined by binomial tests on correct ratio against 50% (all other ps > 0.09, range: 0.097–1.000). Performance of the whole group of participants did not differ significantly from chance performance [mean ± SEM: 0.4906 ± 0.0091, t (19) = –1.03, p = 0.317; Fig. 4b]. These results again demonstrate that the suppressed BM cues were truly invisible.

**3.2.2. Experiment 2b: Inversion control**

Does the biphasic effect found in Experiment 2a indeed reflect attentional orienting to and away from a social signal or rather a difference in motion coherence between intact BM and PSM cues? To address this question, in Experiment 2b, both the intact BM and the PSM cues were inverted, rendering the extraction of social meaningfulness more difficult. If the biphasic effect found in Experiment 2a truly reflected unconscious dynamic processing of the social signal inherent in upright BM stimuli, we would expect the effects to disappear for inverted BM stimuli in Experiment 2b (based on the results of Experiment 1b, in which upright BM stimuli were more effective in attracting attention than inverted BM stimuli). All other aspects of Experiment 2b were identical to Experiment 2a.

**RTs.** A repeated-measures ANOVA with the factors ISI (100 vs. 800 ms) and cue type (valid vs. invalid) revealed a significant effect of ISI [100-ms vs. 800-ms ISI: 696 vs. 638 ms, F (1, 19) = 144.37, p < 0.01, \( \eta^2_p = 0.884 \); Fig. 5a], but no significant effect of cue type [valid vs. invalid: 666 vs. 668 ms, F (1, 19) = 0.05, p = 0.835, \( \eta^2_p = 0.002 \)] and no significant interaction effect of ISI and cue type [F (1, 19) = 0.10, p = 0.759, \( \eta^2_p = 0.005 \)]. These results show that intact BM cues do not attract or repel attention after inversion, suggesting that it is the social nature of upright BM that drives the unconscious orienting effects obtained in Experiment 2a.

**Accuracy.** In the 100 ms-ISI condition, accuracy was 95% in both the valid and the invalid condition; in the 800 ms-ISI condition, accuracy was 96% for both valid and invalid cues. A 2 (ISI: 100 vs. 800 ms) × 2 (cue type: valid vs. invalid) repeated measures ANOVA showed that neither the main effects nor the interaction effect were significant (ps > 0.092), again ruling out speed-accuracy trade-offs.

**Objective measure of suppression effectiveness.** All participants in Experiments 2b took part in a control experiment to check suppression effectiveness. None of the participants performed significantly different from chance in localizing the intact BM cue in the invisible condition, as determined by binomial tests all ps > 0.09 (range: 0.097–1.000). Performance of the whole group of participants did not differ significantly from chance performance [mean ± SEM: 0.5029 ± 0.0093, t (19) = 0.31, p = 0.762; Fig. 5b]. These results again demonstrate that the suppressed BM cues were truly invisible.

**3.3. Experiment 3: visible biological motion**

In Experiments 1a and 1b, we found that invisible BM reflexively attracts attention, but no comparable effect for visible BM. Moreover, in Experiment 2a invisible BM caused a biphasic attentional effect, with initial attraction followed by inhibition. This
intriguing effect of invisible, nonpredictive BM on the distribution of spatial attention left us wondering why no comparable effects were obtained for visible BM. One plausible explanation is that visible BM did indeed initially attract attention, but that this effect decayed due to the relatively long cue duration (900 ms), with strategic attentional disengagement from the non-predictive cue overshadowing any potential effect. Thus, saliency of BM itself should lead to a subsequent attentional bias with shorter cue duration (i.e., 500 ms as in Shi et al., 2010). This explanation was tested in Experiment 3 by manipulating the length of cue duration.

RTs. As shown in Fig. 6, a similar pattern of data as the visible condition in Experiment 1 was obtained. Confirming the observation, in the long cue duration block, a two-way ANOVA with cue ISI (100 vs. 800 ms) and cue type (valid vs. invalid) as within-subjects factors only revealed a significant main effect of cue ISI \( F(1, 19) = 45.53, p < 0.001, \eta^2_p = 0.71 \). Neither the main effect of cue type \( F(1, 19) = 0.02, p = 0.88, \eta^2_p = 0.001 \) nor the cue ISI \( \times \) cue type interaction \( F(1, 19) = 0.27, p = 0.61, \eta^2_p = 0.01 \) was significant. In the short cue duration block, a two-way ANOVA with cue ISI (100-ms vs. 800-ms) and cue type (valid vs. invalid) as within-subjects factors also revealed a significant main effect of cue ISI \( F(1, 19) = 13.62, p = 0.002, \eta^2_p = 0.42 \). Neither the main effect of cue type \( F(1, 19) = 0.66, p = 0.43, \eta^2_p = 0.03 \) nor the cue ISI \( \times \) cue type interaction \( F(1, 19) = 0.08, p = 0.78, \eta^2_p = 0.004 \) was significant. These results replicate and extend the findings from Experiment 1, demonstrating that both 500- and 900-ms visible BM do not cause either a facilitation effect in the 100-ms ISI condition or an inhibition effect in the 800-ms ISI condition.
**Accuracy.** In the long cue duration block, response accuracy was 94% for valid and invalid cues when the ISI was 100 ms; while in the 800-ms ISI condition, accuracy was 100% for both valid and invalid cues. In the short cue duration block, response accuracy was 97% for valid cue, and 96% for invalid cues when the ISI was 100 ms; while in the 800-ms ISI condition, accuracy was 97% for valid cue, and 96% for invalid cue. In either long encoding time block or short encoding time block, a 2 (cue visibility: visible vs. invisible) × 2 (cue type: valid vs. invalid) repeated measures ANOVA revealed that neither main effects nor the interaction effect were significant (ps > 0.12), thus ruling out speed-accuracy trade-offs.

**4. Discussion**

The current study measured the influence of invisible social signals on spatial attention, and tested whether unconscious reflexive orienting of attention to BM would show a biphasic profile of initial facilitation and later inhibition. Results from two experiments demonstrate that invisible BM can influence the distribution of spatial attention. This reflexive orienting effect indeed had a specific temporal profile: In Experiment 1, with a short ISI of 100 ms between the BM cue and the Gabor probe, invisible intact, nonpredictive BM enhanced performance for probes appearing at the same spatial location as the BM cue. Experiment 2 replicated this facilitation effect for the short cue-probe ISI. However, for the longer cue-probe ISI of 800 ms, the effect reversed, with performance for probes appearing at the same spatial location as invisible intact, nonpredictive BM being impaired. This effect is reminiscent of IOR, indicating that invisible socially meaningful stimuli can induce reflexive attentional inhibition after an initial period of facilitation. By contrast, this reflexive and dynamic orienting effects disappeared when BM and its scrambled control were made visible across visible variable length of cue durations, suggesting saliency of BM itself cannot account for an attentional bias for invisible BM. Finally, the effect was specific to upright BM cues and disappeared when their social meaningfulness was reduced by inverting the stimuli. These findings not only demonstrate that unconsciously operating mechanisms of attention are highly sensitive to the social signal conveyed by BM, but that these attentional mechanisms can support the dynamic exploration of visual scenes in the complete absence of conscious awareness, cue predictiveness, and saliency differences.

Previous studies on the extent of unconscious processing under interocular suppression yielded mixed results (reviewed by Sterzer, Stein, Ludwig, Rothkirch, & Hesselmann, 2014; Yang, Brascamp, Kang, & Blake, 2014). For example, recent evidence indicates that unconscious processing under CFS is limited to low- or mid-level shapes, and that extraction of higher-level stimulus properties such as semantic category membership requires conscious awareness (Hesselmann, Darcy, Ludwig, & Sterzer, 2016). However, other findings from experiments using stimuli of particular social and biological relevance, including emotional or sexually arousing stimuli, eye gaze, or BM, challenge this view. For example, Jiang et al. (2006) demonstrated that visible erotic pictures can both attract and repel attention, depending on observer’s gender and sexual orientation. For heterosexual participants, attention was attracted to invisible erotic pictures of the opposite gender; by contrast, for homosexual participants, attention was repelled from invisible erotic pictures of the opposite gender and attracted to that of the same gender. Similarly, eye gaze rendered invisible through CFS can reflexively orient attention (Xu et al., 2011). The present results greatly extend these findings, supporting the idea that complex visual stimuli can escape strong interocular suppression when they are of particular social and biological relevance.

For invisible BM to be effective in attracting attention, information needs to be integrated over time, either at the level of individual dots or over the global BM configuration (Giese & Poggio, 2003; Lange & Lappe, 2006). Such unconscious spatiotemporal integration is consistent with the unconscious binding hypothesis, which posits that visual information can be integrated into more complex structures even when presented outside of conscious awareness (Lin & He, 2009). Indeed, the fact that radial motion breaks CFS faster than random motion is evidence in support of the unconscious binding hypothesis, showing that the visual system can integrate spatiotemporally distributed information before conscious access (Kaunitz, Fracasso, Lingnau, & Melcher, 2013). Such unconscious integration is not restricted to simple motion patterns, but can also occur for BM, as first demonstrated by Faiivre and Koch (2014). In their study, invisible BM stimuli whose motion trajectories were either male or female led to gender adaptation aftereffects. The present findings now demonstrate that such unconscious integration of life-motion signals has direct functional consequences by reflexively guiding spatial attention without conscious awareness.

However, these findings appear inconsistent with a recent study that failed to find an advantage of intact over scrambled biological motion in breaking through CFS (Kaunitz et al., 2013). Three possible explanations for the discrepancy with the current results should be considered. First, Kaunitz and colleagues adopted the b-CFS (Jiang et al., 2007; Stein et al., 2011) paradigm to study access to awareness, while we used an unconscious variant of the Posner cuing paradigm in which biological motion was rendered fully invisible. It is possible that the two paradigms tap into distinct underlying processes (cf. Stein & Sterzer, 2014). Second, these two studies used different scrambled control stimuli. While Kaunitz et al. generated scrambled controls by rotating the trajectories of 12 numbers of point-light markers by 90° or 270°, in the present study we used an improved scrambling technique in which relations among local segments were destructed but pair-wise relations within those segments were preserved. In addition, we used inverted BM control stimuli which preserve all low-level stimulus properties and thereby rule out differences in motion coherence as the potential cause of the effect. Third, other research has provided evidence for biological motion being more potent in breaking CFS than scrambled controls (Miller, Carmel, & Saygin, 2014). Relating such faster access to awareness for BM to unconscious orienting effects from BM represents an interesting avenue for future research.

For efficient exploration, attention should not return to previously visited locations. The results from Experiment 2, in which initial attentional facilitation was followed by inhibition, demonstrate that such inhibition of return (IOR; Klein, 2000) occurs even for fully invisible, nonpredictive social stimuli. While the initial attentional attraction by invisible BM can be accounted by simple unconscious reflexive orienting to life-motion signals, the inhibitory effect found for longer cue-probe intervals provides evidence for more sophisticated unconscious processes. The present findings indicate that unconscious processes are not only capable of prioritizing life-motion signals, but also that they promote active exploration of the visual world, preventing attention from revisiting previously inspected locations, even when this visit occurred without awareness.

Interestingly, this attentional orienting effect was restricted to those objectively invisible trials, and not found when BM was visible. This absence of an effect for visible cues is similar to the results of Jiang et al. (2006)’s study, where attentional orienting was restricted to invisible erotic images but absent for visible erotic cues. Many reasons could account for the null effect in the visible condition, one being the relatively long cue duration (i.e., 900 ms). Such a long duration could be optimal and necessary for eliciting an unconscious orienting effect. In visible trials, by contrast, having been explicitly told that the cues were not predictive
of probe location, observers may have intentionally disengaged their attention from the consciously accessible visible BM cues. One might argue that if the cues would have been shorter, like 500 ms (i.e., the duration of one cycle of a whole movement), this may have not been possible, and attention may have been attracted by the visible BM cues automatically, leading to a cuing effect. The concerns above were tested in Experiment 3, which demonstrated that neither long nor short cue duration could elicit an orienting effect across variable length of ISIs (Fig. 6), suggesting at least in the present case, saliency differences between BM cue and its scrambled control at the conscious level do not necessarily lead to an attentional bias. While 500 ms may be too long for visible BM cues to have an effect, reducing their duration would have created other issues: Durations shorter than 500 ms are not optimal for BM cues to be recognized or discriminated from corresponding PSM cues, because one complete cycle of movement of our BM stimuli lasted 500 ms (see also Shi et al., 2010). Thus, the reflexive and dynamic orienting effect after invisible social cues cannot be explained by potential saliency of BM configurations.

Which neural networks could be involved in such unconscious attentional modulation by BM? Even under strong interocular suppression some aspects of complex visual information can are processed in the extrastriate visual cortex beyond V1 (Lin & He, 2009; Sterzer et al., 2014). For example, emotional faces rendered invisible through CFS can still elicit responses in superior temporal sulcus (STS; Jiang & He, 2006). The STS is the cortical site that has most consistently been implicated in the processing of BM (see Yovel & O’Toole, 2016, for a review). The STS is reciprocally connected with parietal cortex, which is known to play a key role in overt and covert orienting of attention (Harries & Perrett, 1991; Rafal, 1996). Although speculative, it remains plausible that unconscious attentional facilitation and inhibition by BM involves a neural circuit encompassing STS and parietal cortex that is sensitive to life-motion signals and guides attentional exploration in a temporally biphasic fashion.

To conclude, the present study provides novel evidence for a functional link between attentional orienting and unconscious social perception. BM configurations rendered invisible reflexively attracted attention with a short cue-probe interval, and this effect was specific to upright BM stimuli, indicating that attentional systems are intrinsically sensitive to social signals. However, this effect reversed for longer cue-probe intervals, demonstrating IOR (Klein, 2000) for fully invisible, nonpredictive, socially and biologically meaningful stimuli. These findings reveal that attentional orienting to such unconscious socially and biologically relevant signals has a specific, biphasic temporal profile, with initial facilitation followed by inhibition. This effect suggests that even without conscious awareness, cue predictiveness, and saliency differences, attentional systems promote exploration of our visual environment for social signals.

Author contributions

Y. Sun, T. Stein, X. Ding, and Q.-Y. Nie conceived and designed the experiments. Y. Sun, W. Liu, and X. Ding performed the experiments under the supervision of Q.-Y. Nie and T. Stein. Y. Sun and Q.-Y. Nie analyzed the data. Q.-Y. Nie, T. Stein, X. Ding, and Y. Sun wrote the manuscript. Y. Sun and T. Stein contributed equally to this work.

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Appendix A. Binocular presentation control experiment

A.1. Theoretical background

Most awareness check control experiments reported in the main text measured suppression effectiveness or cue visibility using a cue discrimination task: Participants were required to discriminate the location of the intact, upright BM cue vs. the PSM cue (or intact, inverted BM cue). This approach follows the classic dissociation logic for measuring unconscious visual processing (Erdelyi, 1986). Here, the measure of conscious awareness needs to reflect the same stimulus information that gives rise to the effect obtained in the main (cuing) experiment. Given that spatial positioning of intact, upright BM cues vs. PSM cues (or intact, inverted BM cues) is the critical stimulus information underlying the effect in our main experiments, null sensitivity in discriminating their locations demonstrates unconscious processing. Thus, following the classic dissociation logic these awareness check control experiments reported in the main text show that the cues were invisible and provide clear evidence for unconscious processing.

However, one may move beyond this classic dissociation logic and test cue visibility using additional measures such as simple stimulus detection (e.g., see the second control experiment for Experiment 1b, demonstrating null sensitivity using a simple detection task). For example, null sensitivity in the cue discrimination task might have reflected participant’s inability to distinguish upright BM vs. PSM/inverted BM cues against the random moving dots overlaid on the CFS masks even after the cues had broken suppression. If true, cuing effects might be unrelated to the utilization of CFS and similar cuing effects would be expected in a non-CFS condition mimicking this post-breakthrough scenario. To test this hypothesis, we conducted a binocular control experiment in which all stimuli were presented to both eyes with twenty new observers (14 female, age range: 18–30 years, mean age: 22 years). The binocular control experiment was designed after Experiment 2a reported in the main text: Intact BM and PSM cues embedded in the random moving dots on top of the CFS masks were presented to both eyes simultaneously to mimic the post-breakthrough scenario. We then tested cuing effects using short and long ISIs, and cue visibility with two control experiments. In the first control experiment, except for the response stage, visual stimulation was identical to the main experiment, and participants were asked to indicate on which side of fixation the intact BM cue was presented at the response stage, following the dissociation logic. The second control experiment was identical to the first control experiment, except that the PSM cues was removed, such that the task was more akin to a simple detection experiment (as the second control experiment for Experiment 1b reported in the main text).

A.2. Results and discussion

RTs. A repeated-measures ANOVA with the factors ISI (100 vs. 800 ms) and cue type (valid vs. invalid) revealed a significant effect of ISI [100-ms vs. 800-ms ISI: 623 vs. 583 ms, F (1, 19) = 42.93, p < 0.01, ηp² = 0.693; Fig. A1a], but no significant effect of cue type [valid vs. invalid: 603 vs. 604 ms, F (1, 19) = 0.03, p = 0.874, ηp² = 0.001] and no significant interaction effect of ISI and cue type [F (1, 19) = 0.13, p = 0.724, ηp² = 0.007]. This shows that the intact BM cue did not modulate attention when it was embedded in the random moving dots and presented to both eyes. These findings therefore indicate that the effects obtained in Experiment 2a reported in the main text were indeed specific to cues being presented to the non-dominant eye, without concurrent masks and overlaid random moving dots. Thus, unconscious attentional
orienteering by BM seems to be specific to stimuli under interocular suppression.

**Accuracy.** In the 100 ms-ISI condition, accuracy was 96% in the valid and 97% in the invalid condition; in the 800 ms-ISI condition, accuracy was 96% for both valid and invalid cues. A 2 (ISI: 100 vs. 800 ms) × 2 (cue type: valid vs. invalid) repeated measures ANOVA showed that neither the main effects nor the interaction effect were significant (ps > 0.153), again ruling out speed-accuracy trade-offs.

**Control experiments.** All participants in this binocular presentation experiment took part in both control experiments to check whether binocularly presented intact BM and the PSM cues could be discriminated (first control experiment), and, if not, if a single intact BM cue could be detected against the concurrently presented moving dots and masks (second control experiment). For the first control experiment, none of the participants performed significantly different from chance, as determined by binomial tests all ps > 0.09 (0.097–1.000). Performance of the whole group of participants did not differ significantly from chance performance [mean ± SEM: 0.5159 ± 0.0091, t (19) = 1.752, p = 0.096; Fig. A1b]. For the second control experiment, all of the participants performed significantly different from chance, as determined by binomial tests all ps < 0.001. Performance of the whole group of participants was close to ceiling and differed significantly from chance performance [mean ± SEM: 0.9650 ± 0.0038, t (19) = 121.37, p < 0.001]. These results demonstrate that participants can detect the presence of one intact BM cue but cannot discriminate the intact BM cue from corresponding PSM cue.

Thus, these results suggest that the discrimination tasks used to measure cue visibility would have shown null sensitivity even when cues would have broken suppression, i.e., when they would have been detectable as a single stimulus. However, the second control experiment for the CFS Experiment 1b showed null sensitivity even with a simple detection task. More importantly, just rendering the cues non-discriminable without employing CFS did not result in cuing effects. Taken together, these results indicate that the findings reported in the main text reflect unconscious processing under CFS, and cannot be attributed to mere post-breakthrough processing of cues that are simply difficult to discriminate.

**Appendix B. Supplementary material**

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.cognition.2017.06.020.

**Fig. A1.** Results of the binocular control experiment: reaction times for discriminating the orientation of the Gabor probe as a function of cue-probe ISI separately for valid and invalid trials (a), and participants’ accuracy of localizing the intact BM cue in the visible condition (b, the left bar denotes accuracy in localizing intact BM vs. PSM cues, while the right bar denotes accuracy in localizing intact BM cues when no PSM cue was displayed). The dashed line indicates chance level, and error bars represent within-subjects 95% confidence intervals for the respective comparison between valid and invalid cues.

**References**


