

## Dynamic Information Processing of Self and Other Perspectives

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### Abstract

To achieve fluent social interaction, individuals must simultaneously process information from both self- and other-perspectives while effectively distinguishing between them. However, given that individuals exhibit shared neural representations for information from self- and other-perspectives, how does the brain accomplish simultaneous processing of these perspectives without confusion? Through an innovative implicit visual perspective-taking task with high temporal resolution, this study reveals that information processing from self- and other-perspectives exhibits a behavioral oscillation phenomenon at a frequency of approximately 1 Hz, with the two showing a phase difference of approximately 180°. This result demonstrates that in social contexts with others present, the processing of information from self- and other-perspectives is a process of periodic alternating dominance.

### Full Text

## Dynamic Information Processing from Self and Other Perspectives: A Behavioral Oscillation Study

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### Abstract

To achieve fluid social interaction, individuals must simultaneously process information from both self and other perspectives while effectively distinguishing between them. However, self and other perspective information share neural representations. How does the brain simultaneously process self and other perspective information without confusing them? Through an innovative, high temporal resolution implicit visual perspective-taking task, this study found

that information processing under self and other perspectives exhibits a behavioral oscillation phenomenon at approximately 1 Hz, with a phase difference of about 180° between them. This result suggests that in social situations where others are present, information processing from self and other perspectives is a cyclical alternating dominance process.

**Keywords:** implicit social cognition, visual perspective taking, self-perspective, other perspective, behavioral oscillation

## 1 Introduction

As highly social animals, social interaction plays a crucial role in human life. To achieve more fluid and effective social interaction, individuals must maintain their own viewpoints and beliefs while simultaneously adopting others' perspectives, understanding others' beliefs, and recognizing differences between self and other perspectives (Kampis & Southgate, 2020; Ereira et al., 2020). For example, when you notice a grain of rice on the left corner of a friend's mouth, you would naturally remind them to clean their left corner (even though from your perspective it appears on the right). Completing this interaction requires understanding that your friend cannot see what you can see, and that your right corresponds to your friend's left. In fact, in any social scene where others are present, individuals constantly engage in this perspective-taking process and self-other comparison, often spontaneously (Zhao et al., 2015; Surtees et al., 2016; Ward et al., 2019). While processing self-related information, we automatically and implicitly adopt others' perspectives. This may be an implicit tendency formed through long-term explicit social interaction, representing an adaptive outcome of social development that also lays the foundation or provides guidance for explicit interactions that occur at any time (Seyfarth & Cheney, 2013; Bargh & Williams, 2006).

Researchers have proposed that perspective-taking of others' viewpoints, emotions, and beliefs may be achieved through embodied means (Gallese, 2014), where individuals imagine experiencing others' visual experiences and mental states from within others' bodies. Studies have found that when participants adopt others' perspectives, they employ a mental body-transference strategy, imagining transferring their own body to the position of the target (Kessler & Thomson, 2010), thereby obtaining an "immersive" visual experience (Ward et al., 2019). When observing others' pain or experiencing others' emotions, participants also produce similar pain responses and emotional experiences (Dimberg, 1987). When watching others' actions, one's own motor system also shows a certain degree of activation (Naish et al., 2014). Overall, embodied processing enables individuals to more rapidly and accurately obtain others' viewpoints and beliefs by directly simulating others' states (Meltzoff & Decety, 2003). Researchers have pointed out that the key to this processing mechanism lies in the widespread existence of mirror neurons in the brain (Rizzolatti & Fogassi, 2014).

There is a class of neurons in the brain that produce similar activation patterns whether an individual is observing a specific behavior in others or performing the same behavior themselves. These neurons are called mirror neurons (Rizzolatti & Craighero, 2004). Current research has found that such mirror neurons are distributed across multiple brain regions, including the premotor cortex, hippocampus, insula, and cingulate gyrus (Rizzolatti & Fogassi, 2014; Rizzolatti et al., 1996; Mukamel et al., 2010; Molenberghs et al., 2012). Because of mirror neurons, individuals can use the neural mechanisms of self-processing to infer others' mental states, producing embodied experiences. In other words, processing others' mental states and processing corresponding self mental states share neural representations (Decety & Sommerville, 2003; Jackson et al., 2006). This shared neural representation exists at various levels of cognitive processing. For example, research has found that the ventral premotor area simultaneously encodes both one's own peripersonal space and others' peripersonal space (Brozzoli et al., 2013). The insula shows the same activation pattern when viewing others' disgusted expressions and when experiencing disgust oneself (Wicker et al., 2003). Processing self-perspective and adopting others' perspective also show high overlap in activation of brain regions such as the ventromedial prefrontal cortex, posterior cingulate cortex, and temporoparietal junction (TPJ) (Lombardo et al., 2010). In some situations, this shared representation even leads to interesting self-other confusion phenomena, such as the rubber hand illusion (Botvinick & Cohen, 1998). Therefore, to effectively distinguish whether mirror neuron activation reflects self-related or other-related information during social interaction and avoid confusion caused by this shared mechanism, the brain must possess a mechanism for distinguishing self from others.

Researchers have conducted extensive explorations of this processing mechanism. Numerous studies indicate that prefrontal cortex function is closely related to self-other distinction (Decety & Sommerville, 2003). On one hand, the executive control function of the prefrontal cortex may play an important role in self-other distinction (Seymour et al., 2018). On the other hand, some cells in the dorsomedial prefrontal cortex specifically encode self or other in social interaction (Báez-Mendoza et al., 2021), while the ventromedial prefrontal cortex may be involved in shaping self-other distinction (Ereira et al., 2020). The TPJ is also considered a key brain region for self-other distinction in many studies, possibly having the function of distinguishing different representations, thereby suppressing the influence of irrelevant representations or sending conflict signals when two representations are consistent (Quesque & Brass, 2019). In addition to the prefrontal cortex and temporoparietal junction, regions such as the precuneus, inferior parietal lobe, and posterior cingulate may also participate in self-other distinction (Bukowski, 2018; David et al., 2006; Vogeley et al., 2004). Overall, current neurobiological research on self-other distinction has yielded many findings that partially answer how the brain distinguishes whether current neural representations reflect self or other information when self and other information share neural representations. However, in the process of implicit social cognition, the brain needs to simultaneously process self and other infor-

mation, and these studies cannot answer how the brain avoids conflicts caused by shared neural resources when it needs to simultaneously process self and other information.

One possible hypothesis is that the brain uses a rhythmic processing method that can simultaneously complete self and other information processing without confusing them. Increasing research has found that rhythmic neural activity in the brain has important functional significance, helping individuals process complex, dynamic external world information (Klimesch, 1999; Ward, 2003; Buzsáki, 2006). This rhythmic activity is called neural oscillation. Based on this, researchers have also discovered some behavioral rhythm phenomena. For example, when participants need to attend to target stimuli that may appear in two visual fields, they show rapid switching of attention between the two visual field regions at a frequency of about 4 Hz (Landau & Fries, 2012). This rhythmic behavioral phenomenon is called behavioral oscillation. With accumulating experimental evidence, researchers have found that behavioral oscillation phenomena exist in various cognitive processes, such as visual perception (Erlkhman & Caplovitz, 2017), object attention (Fiebelkorn et al., 2013), feature attention (Mo et al., 2019), and perceptual priming (Huang et al., 2015; Wang & Luo, 2017). The widespread existence of this oscillation phenomenon suggests that the brain tends to concentrate resources on processing a single piece of information at one time and achieves parallel processing of multiple information through periodic switching between different information. Returning to our question, if the brain wants to simultaneously process self and other information, will it also use this periodic switching processing method?

We investigated this question using visual perspective taking as an example. Visual perspective taking refers to the process of imagining and inferring others' visual experiences. This is an early-developing, relatively basic perspective-taking ability (Michelon & Zacks, 2006; Farrant et al., 2006). In social interaction, individuals first generate a visual representation of the current scene (self-perspective information). At the same time, individuals spontaneously imagine others' visual experiences of the current scene (other-perspective information). If individuals adopt a rhythmic processing method—that is, rapidly switching between processing others' perspectives and processing self-perspectives—it may be possible to achieve simultaneous processing of both types of information without confusion. However, traditional behavioral paradigms for visual perspective taking cannot detect this rapid switching process. Therefore, this study hopes to use experimental paradigms that explore behavioral oscillation to design a method for examining the processing of information obtained from self and other perspectives in implicit visual perspective taking.

This study includes three experiments. Since we designed a novel implicit visual perspective taking experimental paradigm using face stimuli, we first verified the effectiveness of this experimental paradigm in Experiment 1—that is, we examined whether face processing would be affected by spontaneous visual perspective taking. Based on positive results, in Experiment 2 we set multiple

interval conditions from the appearance of the perspective-taking target to the appearance of the face to explore whether behavioral oscillation phenomena of alternating self-perspective and other-perspective exist during face processing. In Experiment 3, we extended the time range of the interval to further verify the authenticity and replicability of this oscillation phenomenon.

## 2 Experiment 1

If individuals do indeed rhythmically switch between processing self-perspective and other-perspective information, we need to design an experimental task that can not only sensitively detect participants' efficiency in processing visual information from a particular perspective but also have high temporal resolution to track the dynamic changes in participants' information processing efficiency. Based on this, we designed a high temporal resolution face recognition task. On one hand, individuals' ability to recognize faces is affected by face orientation, with better performance when recognizing upright faces (Farah et al., 1995). On the other hand, research suggests that participants may obtain an immersive visual experience when engaging in visual perspective taking, which can facilitate responses to visual stimuli that are easier to process from others' perspectives (Ward et al., 2019). Therefore, we can speculate that when a face is upright from another's perspective, perspective taking can help us recognize the face more accurately. By detecting how participants' face recognition efficiency changes over time, we can explore the dynamic information processing process from others' perspectives.

However, it has not been experimentally confirmed whether spontaneous perspective taking occurs in social scenes where others are present, thereby facilitating the processing of upright faces from others' perspectives. Therefore, in Experiment 1, we first investigated this question.

### 2.1.1 Participants

Using G\*Power, we calculated that a medium effect size of 0.25 and power of 0.9 required 24 participants. We ultimately recruited 23 university students to participate in Experiment 1, with a mean age of 23.26 years ( $SD = 3.10$ ), including 5 males. All participants had normal or corrected-to-normal vision and no known neurological or visual disorders. Participants signed informed consent before the experiment and received compensation upon completion. The experimental protocol was approved by the Peking University Ethics Committee and Committee for the Protection of Humans and Animals.

### 2.1.2 Materials

Six face images were black-and-white photographs of volunteers with neutral expressions. The images were processed using Adobe Photoshop 5.0, uniformly adjusted to  $256 \times 256 \text{ pixels}$  ( $9.1^\circ \times 9.1^\circ \text{ visual angle in the experiment}$ ), with matched brightness ( $3.7 \text{ cd/mm}^2$ ) and contrast (RMS contrast = 0.51). Faces retained only the portion from chin

to forehead, with the distance between pupils equalized for each face and the nose position adjusted to the center of the image.

Dynamic masking stimuli were presented before and after the face images. The masking stimuli were created using OpenGL 2.0 and were the same size as the face images. The dynamic masking stimuli consisted of multiple frames of static masking stimuli. The first frame was composed of several rectangular blocks with random size, position, and grayscale, stacked together. Each subsequent frame added additional rectangular blocks of different sizes, positions, and grayscale on top of the previous frame, covering 10% of the original image area. These masking images were presented at a frequency of 60 Hz.

A top-view image of a seated human figure was used to introduce the other-perspective. The image size was  $13.6^{\circ} \times 13.6^{\circ}$ .

### 2.1.3 Procedure and Design

In each trial, a dynamic masking stimulus was first presented at the center of the screen. Then, at a random time point between 0.5-1 s, a human figure image appeared on the left or right side of the masking stimulus (the position of the human figure was balanced across trials). The human figure could either face toward or away from the central masking stimulus. At a random time point between 0.2-1.2 s after the human figure appeared, the masking stimulus disappeared and a face image was presented at the location of the masking stimulus. The face orientation could be: toward the self (i.e., upright from the participant's perspective), toward the human figure (if the human figure appeared on the left, a face rotated  $90^{\circ}$  clockwise was considered facing the human figure; the same applied to the right side), or toward the opposite side of the human figure (if the human figure appeared on the left, a face rotated  $90^{\circ}$  counterclockwise was considered facing the opposite side; the same applied to the right side). The face image lasted 66.67 ms before disappearing, followed immediately by a dynamic masking stimulus to eliminate visual aftereffects. Participants' task was to judge the orientation of the face and respond with different keys for the three orientations (spacebar for faces oriented toward self, "1" key for faces oriented toward the human figure, and "2" key for faces oriented toward the opposite side of the human figure). When they could not see clearly, they were instructed to respond based on intuition. After each response, participants received feedback on whether their answer was correct or incorrect. The experiment consisted of a practice phase and a formal experimental phase. The practice phase included 48 trials. The formal experimental phase included 432 trials, divided into four blocks. In two blocks, the human figure faced the central stimulus, and in the other two blocks, the human figure faced away from the central stimulus. The four blocks were conducted in an "ABBA" order, with the starting block type balanced across participants. Appropriate rest was provided between blocks. Each block contained 108 trials, with 36 trials for each of the three face orientation conditions (toward self, toward human figure, and toward opposite side). Each face image used in the experiment appeared with equal probability in each

minimal condition. Figure 1 [Figure 1: see original paper]A shows the trial flow diagram for a block where the human figure faces the face, using the human figure on the left side as an example. Figure 1B shows schematic diagrams of different human figure presentation conditions. Experiment 1 used a 2 (human figure orientation: facing vs. back)  $\times$  3 (face orientation: toward self vs. toward human figure vs. toward opposite side) within-subjects design.

## 2.2 Results

Participants' accuracy rates under different human figure orientation and face orientation conditions were calculated. Statistical tests on accuracy rates were completed in SPSS 20.

A 2 (human figure orientation)  $\times$  3 (face orientation) repeated measures ANOVA revealed that the main effect of human figure orientation was not significant,  $F(1, 22) = 3.84$ ,  $p = 0.063$ ,  $p^2 = 0.15$ . The main effect of face orientation was significant,  $F(2, 21) = 49.50$ ,  $p < 0.001$ ,  $p^2 = 0.83$ . Post-hoc tests using Bonferroni correction showed that accuracy for recognizing faces oriented toward self ( $M = 0.98$ ,  $SE = 0.0060$ ) was significantly higher than for faces oriented toward the human figure ( $M = 0.80$ ,  $SE = 0.019$ ),  $SE = 0.018$ ,  $p < 0.001$ , 95% CI of the difference = [0.13, 0.22], and also significantly higher than for faces oriented toward the opposite side ( $M = 0.761$ ,  $SE = 0.022$ ),  $SE = 0.022$ ,  $p < 0.001$ , 95% CI of the difference = [0.16, 0.27]. Accuracy for faces oriented toward the human figure was significantly higher than for faces oriented toward the opposite side,  $SE = 0.013$ ,  $p = 0.012$ , 95% CI of the difference = [0.0080, 0.077].

The interaction between human figure orientation and face orientation was significant,  $F(2, 21) = 8.30$ ,  $p = 0.002$ ,  $p^2 = 0.44$ . Analysis of simple main effects revealed that in the condition where the human figure faced the face, accuracy for recognizing faces oriented toward the human figure ( $M = 0.83$ ,  $SE = 0.021$ ) was significantly higher than for faces oriented toward the opposite side ( $M = 0.76$ ,  $SE = 0.021$ ),  $SE = 0.016$ ,  $p < 0.001$ , 95% CI of the difference = [0.036, 0.12]. However, in the condition where the human figure faced away from the face, there was no significant difference in accuracy between faces oriented toward the human figure ( $M = 0.77$ ,  $SE = 0.022$ ) and faces oriented toward the opposite side ( $M = 0.77$ ,  $SE = 0.025$ ),  $SE = 0.015$ ,  $p = 1$ , 95% CI of the difference = [-0.032, 0.046]. From another perspective, for faces oriented toward the human figure, accuracy when the human figure faced the face was significantly higher than when the human figure faced away,  $SE = 0.019$ ,  $p = 0.004$ , 95% CI of the difference = [0.022, 0.10]. For faces oriented toward self, there was no significant difference in accuracy between the human figure facing the face condition ( $M = 0.98$ ,  $SE = 0.0040$ ) and the human figure facing away condition ( $M = 0.97$ ,  $SE = 0.0090$ ),  $SE = 0.0070$ ,  $p = 0.429$ , 95% CI of the difference = [-0.0090, 0.019]. Similarly, for faces oriented toward the opposite side, there was no significant difference in accuracy between the two human figure orientation conditions,  $SE = 0.016$ ,  $p = 0.570$ , 95% CI of the difference = [-0.024, 0.042].

The results of the repeated measures ANOVA are shown in Figure 2 [Figure 2: see original paper].

### 2.3 Discussion

Through Experiment 1, we first replicated previous research findings that individuals are best at recognizing upright faces, possibly due to expertise effects (Gauthier & Tarr, 1997) or the unique holistic processing mechanism of upright faces (Tanaka & Farah, 1993). More importantly, we found that when the human figure faced the face, recognition performance for faces oriented toward the human figure was better than for faces oriented toward the opposite side. This indicates that the presence of the human figure in the scene affected participants' processing of leftward and rightward facing faces. When the human figure faced away from the face, this effect disappeared, and recognition performance for faces oriented toward the human figure decreased to the same level as for faces oriented toward the opposite side. This result demonstrates that participants' visual perspective taking of the human figure affected face recognition.

Participants spontaneously adopted the human figure's perspective, thereby obtaining an embodied visual experience from that perspective. When the human figure faced the face, this embodied visual experience influenced participants' face recognition: because face processing has an upright advantage effect, if the face was upright from the human figure's perspective, the upright face visual experience obtained through perspective taking could facilitate face recognition. Conversely, if the face was inverted from the human figure's perspective, the inverted face visual experience obtained through perspective taking would not facilitate face recognition. This result is consistent with findings from Surtees et al. (2016) using direction-specific numbers as visual stimuli and Ward et al. (2019) using direction-specific letters as visual stimuli.

Through Experiment 1, we demonstrated that this face recognition paradigm can sensitively detect experimental effects brought about by spontaneous visual perspective taking. Next, we will systematically vary the timing of face presentation based on this paradigm and manipulate temporal variables to explore the dynamic change process of the face recognition effect triggered by this visual perspective taking.

### 3 Experiment 2

Through Experiment 1, we verified that spontaneous visual perspective taking can facilitate the processing of upright faces from others' perspectives. Based on the hypothesis in the introduction, if perspective taking of others' viewpoints and processing of self-perspective information is an alternating dynamic process, then when participants tilt cognitive resources toward other-perspective information processing at a certain moment, we should observe improved recognition of upright faces from others' perspectives, possibly accompanied by weakened recognition of upright faces from self-perspective. Conversely, when participants tilt

cognitive resources toward self-perspective information processing, the opposite pattern should emerge. Therefore, by observing how participants' recognition performance changes over time under these two face orientation conditions, we can investigate behavioral oscillation phenomena in visual perspective taking.

In Experiment 2, we followed the design logic of classic behavioral oscillation paradigms by using the presentation of specific cues to initiate a particular state in participants' behavioral oscillation, aligning all participants to this state as a starting point in each trial, and then exploring the subsequent behavioral oscillation process between different states. This allows us to obtain a complete behavioral oscillation curve by setting different probe time points across trials. For example, in Landau and Fries (2012), researchers used an exogenous attention cue appearing on one side of the visual field to adjust participants' attention focus to that side in each trial, and then explored subsequent behavioral oscillation of attention between the two visual fields, thereby synchronizing the onset of attention oscillation across all trials using the cue presentation time as the starting point. In Experiment 2 of this study, we used the presentation of the human figure image in the scene to initiate participants' processing of other-perspective information, using the human figure presentation time point as the starting point for recording oscillation states to ensure a uniform initial state across all trials, thereby achieving synchronization of oscillation onset. Based on this, we obtained a complete behavioral oscillation curve of self and other perspective information processing by setting different probe time points across trials.

Thirty university students participated in Experiment 2, with a mean age of 21.47 years ( $SD = 2.40$ ), including 9 males. All participants had normal or corrected-to-normal vision and no known neurological or visual disorders. Participants signed informed consent before the experiment and received compensation upon completion. The experimental protocol was approved by the Peking University Ethics Committee and Committee for the Protection of Humans and Animals.

The masking stimuli and top-view seated human figure images used in the experiment were identical to those in Experiment 1. For face images, because we found in Experiment 1 that participants' recognition of upright faces from self-perspective was much better than other face orientations, we added Gaussian white noise with a mean of 0 and variance of 0.05 to all upright faces from self-perspective in Experiment 2 to increase recognition difficulty. This prevented excessive ceiling effects in upright face recognition from causing loss of information in the data.

### 3.1.3 Procedure and Design

In each trial, a dynamic masking stimulus was first presented at the center of the screen. Then, at a random time point between 0.5-1 s, a human figure image facing the center appeared on the left or right side of the masking stimulus (the

position of the human figure was balanced across participants). At a certain time point between 0.2-1.2 s after the human figure appeared (the agent-face SOA), the masking stimulus disappeared and a face image was presented at the location of the masking stimulus. The face orientation could be either toward self or toward the human figure. Specifically, 30 equidistant SOA conditions were set within the 0.2-1.2 s interval, with 33.33 ms between each adjacent SOA condition. The face image lasted 66.67 ms before disappearing, followed immediately by a dynamic masking stimulus to eliminate visual aftereffects. Participants' task was to judge the orientation of the face and respond with different keys for the two orientations ("1" key for faces oriented toward self, "2" key for faces oriented toward the human figure). The practice phase included 30 trials, with feedback on correctness after each response. The experimental phase included 720 trials, divided into 6 blocks with appropriate rest between blocks. Each block contained 120 trials, with 60 trials each for faces oriented toward self and toward the human figure, and 2 trials for each specific SOA condition. Each face image used in the experiment appeared with equal probability in each minimal condition. No feedback was provided during the experimental phase; participants were instructed to respond based on intuition when they could not see clearly. Figure 3 [Figure 3: see original paper] shows the trial flow diagram for Experiment 2. The experiment included two within-subject independent variables: face orientation (toward self vs. toward human figure) and the time interval from human figure presentation to face presentation (agent-face SOA), which included 30 equidistant conditions.

### 3.2 Results

Data from 4 participants whose accuracy in any face condition exceeded 95% were excluded, as these data had strong ceiling effects that could not effectively reflect dynamic changes in behavioral performance (the statistical test results of Fourier transform were consistent before and after excluding these participants). Data from 26 participants were retained for further analysis. Fourier transform-related analyses were performed using MATLAB 2018a, and other analyses were performed using SPSS 20.

Based on the experimental results, we could plot line graphs of each participant's accuracy in recognizing faces oriented toward self and toward the human figure over time. Figure 4 [Figure 4: see original paper]A shows the mean accuracy of all participants across different face orientation conditions and different agent-face SOA conditions. To transform time-domain information into frequency-domain information, for each participant's two curves, after mean-subtraction translation, Hanning window processing, and zero-padding at the beginning and end of the signal (Huang et al., 2015), we performed fast Fourier transform. The Fourier-transformed amplitude-frequency response results from all participants were averaged to obtain Figure 4B. Permutation tests were used to examine the amplitude-frequency response results. Specifically, for each participant, the accuracy rates under different SOA conditions were randomly shuffled, and the

above steps were repeated to obtain one random amplitude-frequency response result. This random calculation was repeated 200 times to obtain an amplitude distribution with a sample size of 200 at each frequency point, thereby obtaining the threshold for  $p < 0.05$  at each frequency point. Multiple comparison correction was then applied, selecting the largest threshold among all frequency points as the significance standard for all frequency points. The results found a significant oscillation frequency of about 1 Hz for the accuracy curve of recognizing faces oriented toward the human figure. Although there was also a peak around 1 Hz for the accuracy curve of recognizing faces oriented toward self, it did not reach significance. The permutation test results are also marked in Figure 4B.

However, because the sampling interval of agent-face SOA was only 1 second, 1 Hz means that the data in the sampling interval contains only one cycle, making the test at 1 Hz not sufficiently reliable. Next, we hoped to obtain more reliable information through multiple comparisons between the two curves. Through Fourier transform, we identified low-frequency information as our region of interest, so we smoothed the two curves to filter out high-frequency noise. The specific smoothing method was to average the accuracy of each point and its two preceding and following points (equivalent to averaging accuracy within 166.65 ms) and use this as the new accuracy for that point. To make the trends of the two curves comparable across different segments, we subtracted the overall mean from each curve (equivalent to translation processing), making the overall mean of both processed curves equal to 0. The translated and smoothed curves are shown in Figure 4C.

Paired-sample t-tests were conducted on the normalized recognition accuracy for faces oriented toward self versus toward the human figure at each SOA condition, with a significance criterion of  $p < 0.05$ . The results showed that in the 0.2-0.5 s interval, recognition accuracy for faces oriented toward self was higher than for faces oriented toward the human figure, while in the 0.7-1 s interval, the effect reversed, with recognition accuracy for faces oriented toward the human figure being higher than for faces oriented toward self. The significance test results are marked in Figure 4C.

Experiment 2 introduced the independent variable of the interval between human figure presentation and face presentation to obtain curves showing recognition of the two face orientations as a function of interval time. Based on this, we found that participants' accuracy in recognizing faces oriented toward the human figure showed a low-frequency oscillation at 1 Hz, and a weaker similar effect was observed for recognizing faces oriented toward self.

To further explore the relative relationship between the performance trends of participants recognizing the two types of faces, we wanted to conduct pairwise comparisons of participants' performance in recognizing different faces at different interval levels. However, unlike previous studies investigating behavioral oscillation, in this study the overall accuracy curve for recognizing faces oriented toward self was higher than that for recognizing faces oriented toward the hu-

man figure. This is because in previous studies, the two oscillating conditions were often completely equivalent (e.g., left visual field vs. right visual field (Landa & Fries, 2012), leftward priming vs. rightward priming (Huang et al., 2015), etc.). However, in this study, the two oscillating parties were self-perspective and other-perspective, and information processing under self-perspective had obvious advantages over processing under other-perspective. Even though we blurred faces oriented toward self to reduce this recognition advantage and avoid ceiling effects, the phenomenon that processing accuracy under self-perspective was always higher than under other-perspective still occurred, which was consistent with our results in Experiment 1. Therefore, to eliminate interference from the natural advantage of self-perspective information processing and enable comparison between the two curves to reflect the relative relationship of changing trends, we translated the two accuracy curves so that they had the same mean. Further tests showed that, under the premise of ensuring the same mean for both curves, within 0.2-0.5 s after the human figure appeared (introducing other-perspective), participants showed an advantage in recognizing faces oriented toward self, while around 0.7-1 s, participants showed an advantage in recognizing faces oriented toward the human figure, reflecting the enhancement of spontaneous visual perspective taking effects. However, this advantage gradually disappeared afterward. For the results obtained in Experiment 2, there were two possible hypotheses: First, the effect generated by visual perspective taking has a specific time window—that is, around 0.7-1 s after others' perspective is introduced, individuals are more inclined to spontaneously adopt others' perspectives, while outside this time window, individuals are less affected by others' perspectives. Second, visual perspective taking is a behavioral oscillation process—after others' perspective is introduced, individuals' adoption of others' perspectives shows periodic dominance (frequency about 1 Hz), thus showing relative fluctuations in recognition accuracy. However, because the SOA time range in Experiment 2 was relatively narrow, only one cycle of oscillation could be detected. Therefore, Experiment 2 alone was insufficient to verify which hypothesis was correct.

### 4 Experiment 3

Experiment 3 was designed to test whether the phenomenon found in Experiment 2 represents a single time window or a continuous oscillation process. If the advantage time window of spontaneous visual perspective taking is unique, then the advantage of others' perspective processing will not reappear within the extended SOA range. If this is a continuous oscillation process, the advantage of others' perspective processing will appear again within the extended SOA range.

Twenty-seven university students participated in Experiment 3, with a mean age of 22.11 years ( $SD = 3.02$ ), including 9 males. All participants had normal or corrected-to-normal vision and no known neurological or visual disorders. Participants signed informed consent before the experiment and received com-

pensation upon completion. The experimental protocol was approved by the Peking University Ethics Committee and Committee for the Protection of Humans and Animals.

The experimental materials used in Experiment 3 were identical to those in Experiment 2. The only difference in experimental procedure settings from Experiment 2 was that the agent-face SOA duration was extended from 0.2-1.2 s to 0.2-2.2 s. Similarly, 30 equidistant time points were taken within this interval as 30 SOA conditions, so the time difference between each adjacent SOA condition was 66.67 ms.

## 4.2 Results

Using the same data exclusion criterion as in Experiment 2—excluding data from participants whose accuracy in any face condition exceeded 95%—we excluded data from 6 participants (the statistical test results of Fourier transform were consistent before and after excluding these participants). Data from 21 participants were retained for further analysis. Figure 5 [Figure 5: see original paper]A shows the average results of all participants' accuracy in recognizing the two types of faces as a function of time.

In Experiment 3, we used the same smoothing method as in Experiment 2 (also averaging 5 points, but in Experiment 3 this was equivalent to averaging accuracy within 333.35 ms) to reduce high-frequency noise interference. To enable comparison between the two curves to reflect the relative relationship of changing trends and to facilitate subsequent Fourier transform, we performed the same translation processing as in Experiment 2—subtracting the overall mean from each curve (making the mean of both curves equal to 0). The smoothed and translated average results are shown in Figure 5B. Paired-sample t-tests were conducted on the normalized recognition accuracy for the two face types at each SOA condition, with a significance criterion of  $p < 0.05$ . The results showed that participants exhibited a time window of advantage for recognizing faces oriented toward the human figure around 0.8-0.9 s (0.7-1 s in Experiment 2), followed by a reversal of advantage where recognition of faces oriented toward self reached superiority. Benefiting from the extended SOA range in Experiment 3, we subsequently observed a second cycle of advantage switching. The paired t-test results are marked in Figure 5B.

Fast Fourier transform was performed on each participant's two curves, and the mean of the amplitude response results is shown in Figure 5C. Permutation tests on the results found that both the accuracy curves for recognizing faces oriented toward the human figure and toward self had a significant low-frequency oscillation of about 1 Hz, which was consistent with the results found in Experiment 2. The permutation test results are also marked in Figure 5C.

In Experiment 3, we obtained more robust behavioral oscillation results of about 1 Hz. Next, we determined the temporal relationship between the two face recognition advantages by comparing the phase relationship of the two curves. For

each participant's data, Fourier transform was used to extract phase information for both curves in the 0.5-1.5 Hz range, and the phase difference between the two curves was compared. The data are shown in Figure 5D. The mean phase difference across all participants was  $186.96^\circ$ , with a standard deviation of 73.98. Rayleigh's test was used to examine the distribution of the data, showing that the phase difference did not follow a uniform distribution on the circle ( $p = 0.040$ ) but was concentrated around  $180^\circ$ .

Experiment 3 replicated the results of Experiment 2. After the perspective-taking target appeared, participants first showed an advantage in self-perspective information processing, and then around 0.8-0.9 s, the effect reversed, showing a shift of processing advantage to others' perspectives. This result further supported the dynamic changes in processing advantages between self and other perspectives based on Experiment 2.

More importantly, by extending the agent-face SOA duration, we found that the advantage alternation between self and other perspectives continued, showing multiple reversals of advantage. The results of Experiment 3 supported the second hypothesis we proposed after completing Experiment 2—that this oscillation phenomenon is continuously present, not just a single time window. An even more interesting finding was that through Fourier transform, we found that both the accuracy curves for face recognition under self and other perspectives had an oscillation frequency of about 1 Hz, and there was a phase difference of about  $180^\circ$  between them. This means that improved recognition accuracy for upright faces from others' perspectives is accompanied by decreased recognition accuracy for upright faces from self-perspective, and vice versa. This demonstrates that when information from both self and other perspectives needs to be processed simultaneously, individuals do exhibit a rhythmic switching processing pattern.

## 5 General Discussion

This study explored the dynamic information processing of self and other perspectives in social situations where others are present by combining high temporal resolution behavioral oscillation detection methods with an implicit visual perspective taking experimental paradigm. The study included three experiments. Experiment 1 first verified that this innovative paradigm could detect spontaneous visual perspective taking, which can facilitate the processing of upright faces from others' perspectives. Subsequent Experiments 2 and 3 manipulated a new independent variable based on Experiment 1: the interval time between the appearance of the perspective-taking target and the face stimulus (agent-face SOA). The results showed that recognition accuracy for upright faces from self and other perspectives exhibited a dynamic, cyclical change process, with both showing behavioral oscillation phenomena at about 1 Hz and a phase difference of about  $180^\circ$  between them. These results indicate that information processing under self and other perspectives is a process of alternating dominance.

### 5.1 Embodiment of Visual Perspective Taking

Although Experiment 1 only served as a pre-experiment to validate the effectiveness of the paradigm, we still obtained interesting findings. In recent years, researchers have generally believed that visual perspective taking relies on embodied processing mechanisms (Kessler & Thomson, 2010; Surtees et al., 2013; Gardner & Potts, 2010): participants imagine transferring their body to the position of the perspective-taking target, thereby obtaining an immersive visual experience from others' perspectives. Therefore, this visual experience shares many similarities with visual input directly obtained by participants. Studies have found that this visual experience obtained through perspective taking can also produce visual aftereffects (Yuan et al., 2017) and facilitate the recognition of direction-specific figures (Ward et al., 2019). The results of Experiment 1 found that perspective taking can also facilitate individuals' recognition of upright faces from others' perspectives, even though these faces were not upright from self-perspective. This undoubtedly provides new evidence for the embodied processing of visual perspective taking. Based on the obvious direction specificity of face recognition, only by embodiedly obtaining the visual experience of upright faces from others' perspectives can the facilitative effect on face recognition be manifested.

### 5.2 Behavioral Oscillation of Self and Other Perspective Information Processing

Of course, the most important findings of this study are in Experiments 2 and 3. The experimental results showed that both the recognition accuracy for upright faces from others' perspectives and from self-perspective exhibited rhythmic oscillation phenomena as agent-face SOA increased, and the two showed a reciprocal relationship. This means that in interpersonal interaction situations where both others' and self-perspectives exist simultaneously, the allocation of cognitive resources to the two perspectives is a dynamic process. At certain moments, cognitive resources are concentrated on other-perspective information processing, temporarily improving recognition accuracy for upright faces from others' perspectives while temporarily reducing recognition accuracy for upright faces from self-perspective. At other moments, cognitive resources are transferred to self-perspective information processing, improving recognition accuracy for upright faces from self-perspective while reducing recognition accuracy for upright faces from others' perspectives. This switching frequency is around 1 Hz, and participants are not subjectively aware of this switching in cognitive resource allocation.

Why does the brain choose this temporally separated processing method for self and other perspectives rather than processing both perspectives simultaneously? As mentioned earlier, in social interaction, individuals need to make real-time judgments about self and others' perspectives, emotions, beliefs, and other information, and compare similarities and differences to make interactions with others smoother and more efficient. However, individuals' processing of self and

other information often shares the same neural representations, so simultaneous processing of self and other information can easily cause confusion between them. Separating the two processing procedures in time according to certain rhythmic information can effectively avoid this confusion, and by identifying the phase, the brain can effectively distinguish whether the currently processed information is self-related or other-related. On the other hand, the number of neurons in the brain is limited. Through temporal separation, the same neurons can be reused when processing different information, enabling more economical completion of multiple cognitive processes. This processing mode is not limited to self and other information processing. In fact, the discovery of more and more behavioral oscillation phenomena suggests that this may be a universally adopted neural resource-saving processing method in the brain (Miller & Buschman, 2013).

However, the behavioral oscillation frequency for self and other perspective processing found in this study is around 1 Hz, belonging to the Delta frequency band. In previous studies that found behavioral oscillation, the frequencies mainly concentrated in the 4-8 Hz Theta band (Landau & Fries, 2012; Huang et al., 2015), with some belonging to the 8-12 Hz Alpha band (Zhang et al., 2019; Erlikhman & Caplovitz, 2017). The main reason for this difference may lie in the different cognitive processes. The behavioral oscillations in the Theta and Alpha bands mentioned above mainly occur in more basic cognitive processes such as attention and priming, while the behavioral oscillation found in this study exists in the more complex social cognitive process of visual perspective taking. Completing this perspective-taking process may require the participation and integration of multiple cognitive processes including attention, object recognition, and mental imagery, thus requiring longer processing time, which means smaller oscillation frequency.

### 5.3 Neural Basis of Behavioral Oscillation

From the perspective of neural oscillation, studies have shown that Delta band neural oscillations in the TPJ may be closely related to individuals' social cognitive functions (Donaldson et al., 2018). Combined with the results of this study, this suggests that the rhythmic activity of the TPJ may be the neural basis for generating behavioral oscillations in self and other perspective processing. On one hand, many studies have found that the TPJ plays an important role in self-other distinction (Bukowski, 2018; Seymour et al., 2018; Sowden & Catmur, 2015; Wang et al., 2016), even considering the TPJ as a core brain region and information hub when various parts of the brain work together to process self and other information (Seymour et al., 2018). Quesque and Brass (2019) believe that the TPJ's function of distinguishing self from others is general and universal, manifested at various levels including perception, action, and mentalizing. Damage to or interference with the TPJ can cause individuals to experience "out-of-body" experiences (Blanke & Arzy, 2005) and other difficulties in self-other distinction (Silani et al., 2013; Uddin et al., 2006). On the other hand,

many studies have also found that the TPJ participates in switching processes in cognitive processing, which is reflected both in attention reorienting (Corbetta & Shulman, 2002; Serences et al., 2005; Dugué et al., 2018) and in switching between self and others' beliefs and perspectives in social cognitive processes (Mitchell, 2008; Corbetta et al., 2008). Therefore, we speculate that the TPJ may play the role of a “switch” with a fixed rhythm. In social situations requiring self-other distinction, the working frequency of this switch is set at around 1 Hz. Under its modulation, individuals' processing of information from self and other perspectives shows rhythmic switching. Even based on the TPJ' s important role in attention reorienting, and the enhancement of Theta activity in the TPJ and its involved ventral attention network during attention tasks (McDermott et al., 2017; Proskovec et al., 2018), we can also speculate that the behavioral oscillation phenomena found in attention processes in previous studies also originate from the “switch” function of the TPJ, but for different cognitive processing procedures, the TPJ endows different switching rhythms. Of course, these hypotheses require more brain imaging research to prove.

## 6 Conclusion

Through an innovative experimental paradigm, this study found that information processing from self and other perspectives in social scenes where others are present exhibits a behavioral oscillation phenomenon at about 1 Hz. As a basic psychological process in social cognition, visual perspective taking, these research findings can help us understand how individuals simultaneously process self and other information and accurately distinguish between them during social interaction. Future research combining brain imaging can also help us find the neural mechanisms behind this behavioral oscillation phenomenon. On the other hand, the results of this study also show that behavioral oscillation phenomena not only exist in basic cognitive processes such as attention but also exist in rhythmic processing modes in more complex social cognitive processing. This is an important supplement to our understanding of brain processing modes. We have more reason to believe that based on the brain' s inherent rhythmic neural activity, transforming two or more simultaneously appearing targets or processing objects into temporally separated periodic processing may be the most universal, economical, and effective processing method favored by the brain and preserved by evolution.

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