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Conscious and Unconscious Processing of Ensemble Statistics Oppositely Modulate Perceptual Decision-Making

Dingrui Liu, Wenjie Liu, Xiangyong Yuan, and Yi Jiang
State Key Laboratory of Brain and Cognitive Science, Center for Excellence in Brain Science and Intelligence Technology, Institute of Psychology, Chinese Academy of Sciences
Department of Psychology, University of Chinese Academy of Sciences
Chinese Institute for Brain Research, Beijing, China

Our visual system possesses a remarkable ability to extract summary statistical information from groups of similar objects, known as ensemble perception. It remains elusive whether the processing of ensemble statistics exerts influences on our perceptual decision-making and what roles consciousness and attention play in this process. In a series of experiments, we demonstrated that the processing of ensemble statistics can exert significant modulation effects on our perceptual decision-making, which is independent of consciousness but relies on attentional resources. More intriguingly, the conscious and unconscious ensemble representations respectively induce repulsive and attractive modulation effects, with the unconscious effect susceptible to the temporal separation and the distinction between the inducers and the targets. These results not only suggest that the conscious and unconscious ensemble representations engage different visual processing mechanisms but also highlight the distinct roles of consciousness and attention in ensemble perception.

Public Significance Statement

This study demonstrates that the summary statistics of the conscious and unconscious nontarget ensembles oppositely bias the perceptual judgments of the targets (a repulsion or an attraction effect). Although both effects rely upon available attentional resources, only the unconscious attraction effect is dependent on the simultaneity and the similarity between the targets and the nontargets. These results contribute to the comprehensive understanding of ensemble perception and the functional roles of consciousness and attention.

Keywords: ensemble perception, summary statistics, consciousness, attentional load

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In a complex visual scene, it seems impossible to perceive everything precisely at a glance because of the limited capacity of our visual system (Cohen et al., 2016; Luck & Vogel, 1997; McClelland & Bayne, 2016). However, we are capable of rapidly accessing the summary statistics, such as the mean and the variance, of the stimulus set in the scene along a variety of dimensions including not only the low-level and middle-level (e.g., orientation, hue, size; see

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Yi Jiang https://orcid.org/0000-0002-5746-7301
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The data for this article are available at https://osf.io/nqmzj/.

Correspondence concerning this article should be addressed to Yi Jiang, State Key Laboratory of Brain and Cognitive Science, Center for Excellence in Brain Science and Intelligence Technology, Institute of Psychology, Chinese Academy of Sciences, 16 Lincui Road, Beijing 100101, China. Email: yijiang@psych.ac.cn

Chetverikov et al., 2017; Dakin & Watt, 1997; Dan, 2001; Hansmann-Roth et al., 2019, 2021; Joo et al., 2009) but also the high-level visual features (e.g., emotional expression, facial identity; see Haberman et al., 2009; Haberman & Whitney, 2007, 2011; Han et al., 2021; Peng et al., 2020). This ability to extract the summary statistics from groups of similar objects is referred to as ensemble perception or summary representation (Alvarez, 2011; Hubert-Wallander & Boynton, 2015; Whitney & Yamanashi Leib, 2018).

Previous studies have shown that ensemble perception can be characterized to some extent as an automatic, compulsory process (Fischer & Whitney, 2011; Haberman & Whitney, 2007; Oriet & Brand, 2013; Parkes et al., 2001; Tanrikulu et al., 2020), suggesting that the summary statistics can be extracted rapidly even without intention. The automaticity of ensemble perception raises the possibility that the summary statistics of multiple groups are able to be extracted simultaneously. This is exemplified in a study carried out by Chong and Treisman (2005b), in which the accuracy of judging the mean size of the designed-color circles intermingled with other color circles was immune to whether the designed color was cued beforehand. Such characteristic of ensemble representation may profoundly preclude us from unbiasedly extracting the summary statistics of a single set of items when facing multiple sets in real-world scenes, as the ensemble perception of different sets may occur simultaneously. Hence, it is of great significance to find out the interaction between multiple-ensemble perception, or put it another way, whether the ensemble processing of the nontargets would bias our perceptual judgments of the targets.

More critically, researchers have been debating over decades whether ensemble perception can take place independent of awareness (Joo et al., 2009; Parkes et al., 2001; Van Opstal et al., 2011; Ward et al., 2016) or attention (Alvarez & Oliva, 2008; Bronfman et al., 2014; Chong & Treisman, 2005a; Dakin et al., 2009; Jackson-Nielsen et al., 2017). As it is almost impossible to probe the ensemble representation when the targets are rendered invisible, elucidating the interaction between multiple ensemble representations poses an opportunity to reconcile the controversial role of conscious awareness in ensemble perception. In the present study, we adopt a modified contextual paradigm in which the contextual influences of the conscious and unconscious summary statistics on the ensemble perceptual judgments of the targets are directly assessed and compared. According to a well-known theory of consciousness, the Global Neuronal Workspace theory, stimulus-specific information will be amplified and reencoded only when it gains access to consciousness (Atmanspacher, 2006; Dehaene et al., 2011; Salti et al., 2015). Moreover, only stimuli with high visibility can be modulated in a top-down, strategic manner (de Lange et al., 2011). In other words, it is expected that only the conscious, but not the unconscious, ensemble representation ignites the top-down, strategic processing of the visual system, which may lead to differential influences of the conscious and unconscious summary statistics of the nontargets on the ensemble perception of the targets. The present study, therefore, experimentally examined this hypothesis and further explored the important factors, such as attentional resources, temporal separation, and stimulus similarity, that are possibly involved in these interactions so as to comprehensively delineate the cognitive mechanisms underlying the ensemble representation.

Design

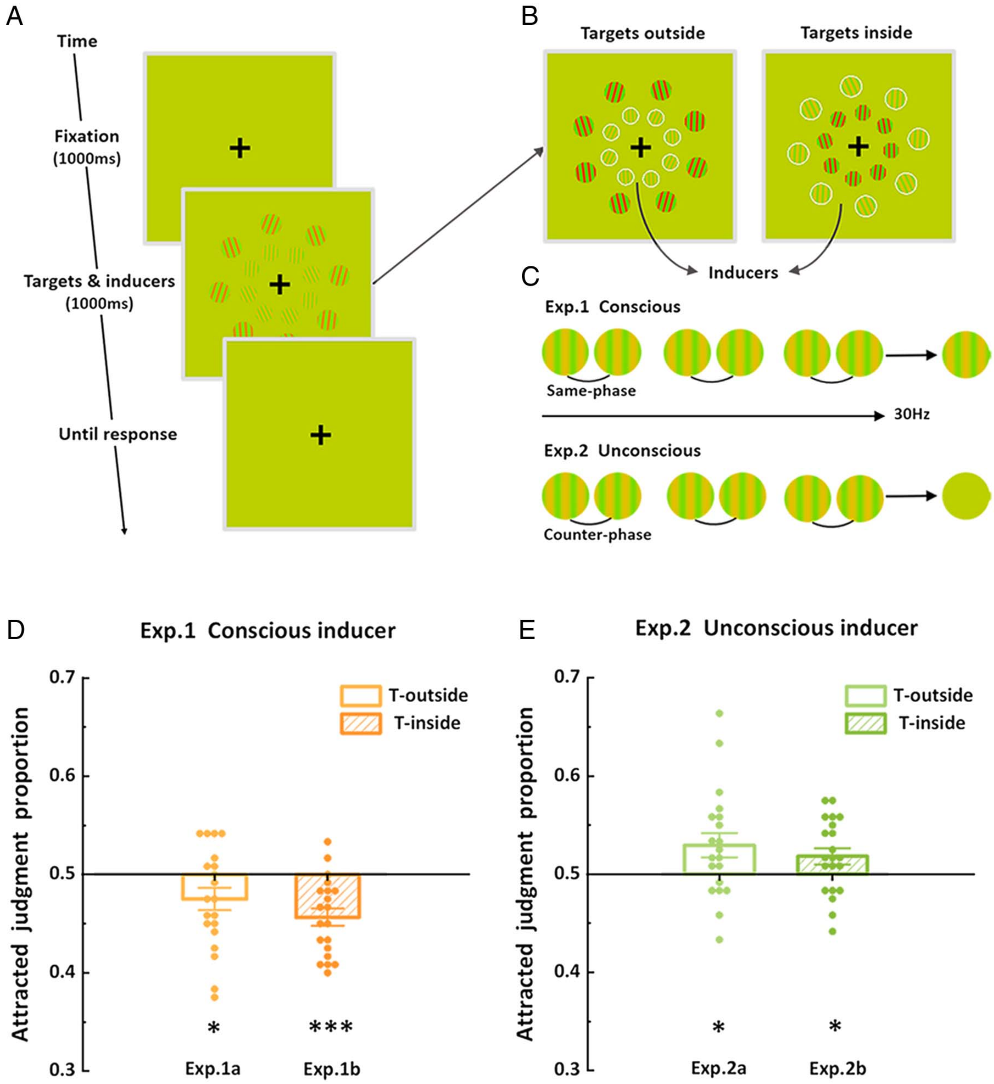
In a series of experiments, two arrays of gratings were arranged in concentric circles, with one array of the gratings (i.e., inducers) rendered visible or invisible, and the participants were instructed to judge the average orientation of the other array of the gratings (i.e., targets), as shown in Figure 1A–C. The visibility of the inducers was manipulated by a critical flicker–fusion frequency method, in which two isoluminant colors alternatively flickering at frequencies over 25 Hz would be perceptually fused into one color (Hoshiyama et al., 2006; Jiang et al., 2007; Lu et al., 2012; Shady et al., 2004). In the invisible condition, the two counterphase chromatic (red-green and green-red) gratings alternated at a flicker frequency of 30 Hz so that they were fused into a percept of static yellow with the stripes completely invisible. In the visible condition, the same-phase (red-green or green-red) rather than the counterphase chromatic gratings were presented, thus making the red and green stripes visible (Figure 1C). Such method could ensure that except for the perception of the stimuli, the physical features, such as luminance, contrast, and spatial frequency, were identical between the visible and invisible conditions. Experiments 1 and 2 first explored whether conscious and unconscious ensemble statistics would differentially modulate another ensemble perceptual judgment as expected. Experiments 3–5 then tested how attentional load, temporal separation, and stimulus similarity affected these interactions. Through a series of experiments, we proposed and discussed the possible cognitive mechanisms.

Method

Participants

A total of 214 naïve participants recruited from Chinese colleges and universities took part in the study, and each was allowed to participate in only one of the experiments. Eleven participants were excluded due to the following reasons. Briefly, eight were excluded (one each in Experiments 1a and 2b; two each in Experiments 1b, 2a, and 5a) because they made more than two incorrect responses in catch trials; one in Experiment 3b was excluded as he always pressed the same key in the noncatch trials and two participants in Experiments 2a and 5b were excluded because they failed to pass the

Figure 1
Procedure, Stimuli, and Results of Experiments 1 and 2



Note. (A) Sample trial sequence from Experiments 1 and 2. (B) Stimulus arrangement. In Experiments 1a and 2a, the targets were positioned on the outer circle, whereas in Experiments 1b and 2b, they were positioned on the inner circle. The inducers were circumscribed in white for illustration only, positioned correspondingly on the inner or outer circle. (C) CFF paradigm. In Experiment 1, the visible inducers were generated by presenting chromatic gratings of the same phase. In Experiment 2, the invisible inducers were generated by rapidly flickering two counterphase, chromatic gratings at 30 Hz. The proportions of participants' orientation judgments attracted to the average orientation of the inducers in Experiments 1 (D) and 2 (E). CFF = critical flicker–fusion frequency. See the online article for the color version of this figure.
$^{*}p < .05$. $^{***}p < .001$.

awareness check (see the Data analysis section, for more details). Finally, there remained 203 Chinese young adults (78 males, age range 18–30, mean age 22 years old), with 20 (5–10 males) in each experiment, except 21 (8 males) in Experiment 2b and 22 (7 males) in Experiment 3b. The sample size was determined based on a two-tailed G*Power calculation, using the one-sample *t* test with power of 0.8 and an effect size *d* of 0.7. Considering that no previous studies had the identical experimental design as the current one, it was difficult to estimate the appropriate effect size in advance, we therefore decided to choose an intermediate effect size of 0.7. This calculation yielded a recommended sample size of 19, and we increased the sample size to ~20 in each experiment. All participants had normal or corrected-to-normal vision and gave written, informed consent in accordance with procedures approved by the institutional review board of the Institute of Psychology, Chinese Academy of Sciences.

Stimuli and Procedure

All the stimuli were generated by MATLAB (The MathWorks, Natick, MA) and presented using the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997) on an LCD monitor (1,920 × 1,080 resolution; 60 Hz refresh rate) at a viewing distance of 57 cm. The gratings presented were all chromatic with red and green phases, distributed within a 7.0° × 7.0° yellow area (red, green, and blue = [134, 151, 0]).

Experiments 1 and 2

In Experiments 1 and 2, there were 16 chromatic gratings evenly arranged on two concentric circles (Figure 1B). The gratings on the inner circle (2.14° diameter) had a visual angle of 0.54° (5.56 cycles per degree), whereas the gratings on the outer circle (3.90° diameter) had a visual angle of 0.70° (5.71 cycles per degree). The inducers consisted of eight gratings positioned either on the inner circle (Experiments 1a and 2a) or the outer circle (Experiments 1b and 2b). They were rendered visible in Experiment 1 by alternatively presenting two same-phase red-green gratings at 30 Hz, but rendered invisible against the yellow background in Experiment 2 by alternatively presenting two counterphase red-green gratings at 30 Hz (Figure 1C). We manipulated the average orientation of the inducers to examine how it modulated the orientation ensemble perception of the eight target gratings. There were three average orientations of the inducers, left-tilted (anticlockwise), right-tilted (clockwise), and vertical. In the left-tilted condition, four gratings of the inducers had an orientation of 1°, whereas the other four gratings had an orientation of −25°. In the right-tilted condition, four gratings of the inducers had an orientation of 25°, whereas the other four gratings had an orientation of −1°. In the vertical condition, all gratings had the same, vertical orientation.

The targets were composed of eight gratings that were spatially separate from the inducers (Figure 1B). The orientation of each grating was selected randomly from 1° to 25° clockwise or anticlockwise from the vertical with two constraints. First, the average of them was always vertical. Second, four of them should be left-tilted, and the other four right-tilted. Thus, if the average orientation of the targets was consistently perceived as tilted toward left or right, it might be regarded as being affected by the inducers.

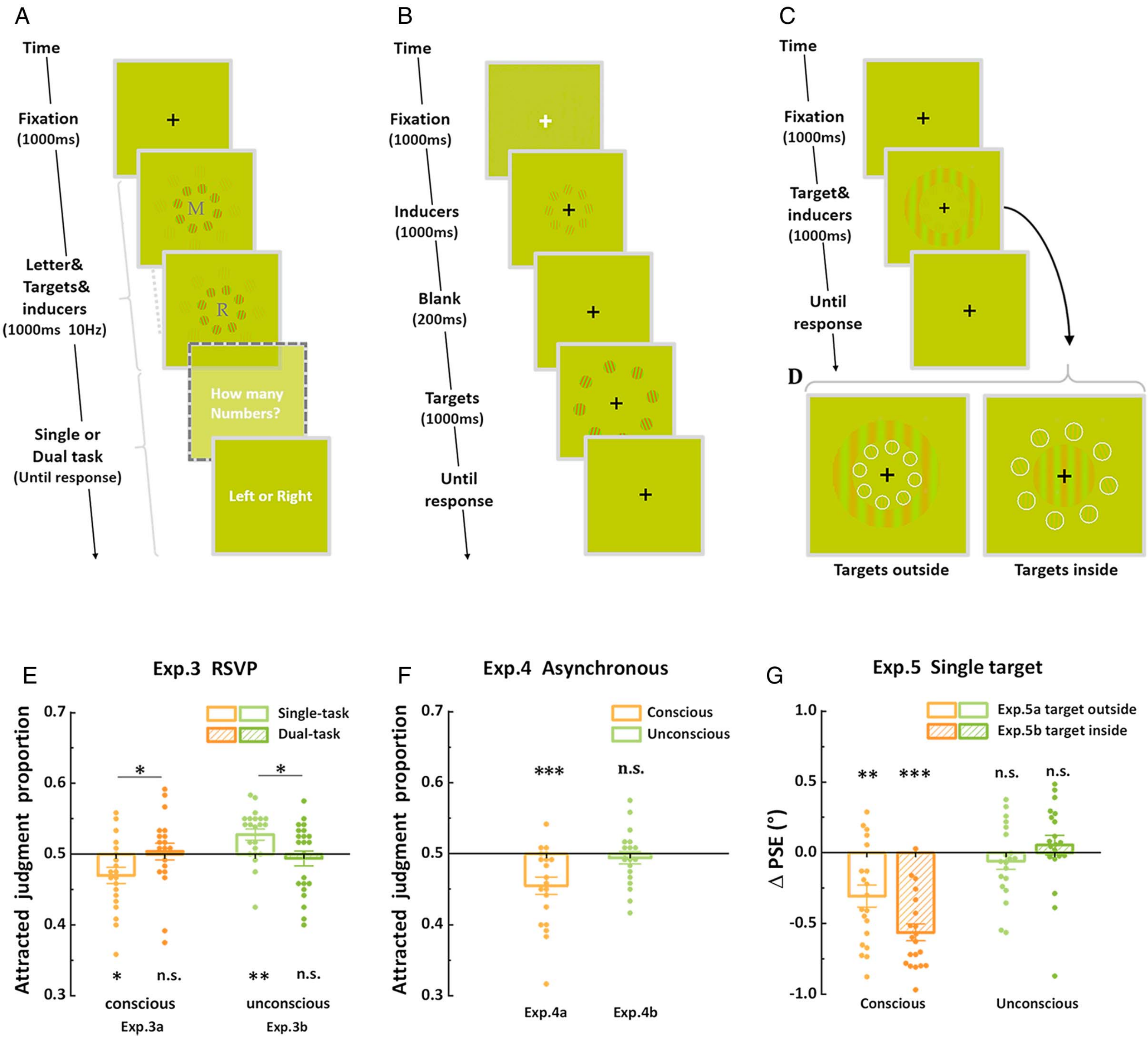
As illustrated in Figure 1A, each trial began with a cross fixation (0.65° × 0.65°) of 1,000 ms, followed by the inducers and the targets, simultaneously presented for another 1,000 ms. After that, participants were instructed to judge the average orientation of the targets (left-tilted or right-tilted) as accurately as possible by pressing the left or right arrow key. There were 60 trials for each condition of the inducers, resulting in 180 trials in total. To avoid random guessing, we assigned additional 24 catch trials, in which the orientation of the target was all 25° or −25°, and participants ought to have no difficulty giving a correct answer in these trials. All the procedures were the same in Experiments 1 and 2, except the following in Experiment 2. First, participants were asked to skip the current trial by pressing the up arrow key if they saw anything else besides the targets within the yellow area. Second, at the end of the experiment, participants had to complete a 60-trial two-alternative forced choice task for awareness check, in which they tried their best to guess the average orientation of the invisible inducers. These designs assessed both the subjective and the objective invisibility of the inducers and ensured that the inducers were assigned attention and made completely invisible to the screened participants.

Experiment 3

Different from Experiments 1 and 2, the targets were always positioned on the inner circle in Experiment 3, and a letter stream was presented in the center at a speed of 10 Hz during the display of the inducers and the targets (Figure 2A). The stream was made up of capital letters (0.80° in height) randomly sampled from "ACDEGHKMNRSTUVXY," into which zero, one, or two numbers randomly selected from "234679" were inserted. And participants were instructed to report the appearance times of the numbers. This rapid serial visual presentation (RSVP) task could consume plenty of attentional resources (Joseph et al., 1997; Kikuchi et al., 2002; Seno et al., 2011), thereby we investigated the role of attention in the modulation effect of the summary statistics of the inducers on the ensemble perception of the targets with a dual-task procedure. In the single-task condition, participants were instructed to ignore those rapidly presented letters and only judge the average orientation of the target gratings on the inner circle. In this condition, no attention should be paid to the letter stream so that the attentional load was low for the ensemble perception of the targets and the inducers. We expected to observe a comparable modulation effect of the inducers, similar to those found in Experiments 1 and 2. In the dual-task condition, participants were instructed to report both the appearing times of the numbers and the average orientation of the target gratings, and they were told in advance that the RSVP task was their primary task, whereas the orientation judgment task was the secondary. This ensured that the letter stream depleted the available attentional resources as much as possible so that we could evaluate the modulation effect under high attentional load.

Each participant performed two blocks, one for the single-task condition and the other for the dual-task condition, with

Figure 2
Procedure, Stimuli, and Results of Experiments 3–5



Note. (A) The procedure in Experiment 3. In the dual-task condition, participants were instructed to report both the appearance times of the numbers and the average orientation of the targets, while in the single-task condition, participants only needed to judge the average orientation of the targets. Sample trial sequence from Experiments 4 (B) and 5 (C). (D) Stimulus arrangement. The gratings circumscribed in white were the inducers (for illustration only). The proportions of participants' orientation judgments attracted to the average orientation of the inducers in Experiments 3 (E) and 4 (F). (G) ΔPSE in Experiment 5. PSE = point of subjective equality; RSVP = rapid serial visual presentation. See the online article for the color version of this figure.
n.s. $p > .05$. * $p < .05$. ** $p < .01$. *** $p < .001$.

the order counterbalanced across subjects. In Experiment 3, the vertical inducers were not included anymore so that each block consisted of 132 trials including 12 catch trials, equally assigned for the left-tilted and right-tilted inducers. All the designs and procedures were the same in Experiments 3a and 3b, except that the inducers were visible in Experiment 3a and rendered invisible in Experiment 3b. The trial-by-trial subjective evaluation and postexperiment awareness check were performed as in Experiments 1 and 2.

Experiment 4

The design and procedure of Experiment 4 were similar to those of Experiments 1 and 2, except that a brief temporal gap was introduced between the display of the inducers and the targets. As illustrated in Figure 2B, each trial began with a white, cross fixation, which turned black after 1,000 ms to inform the participants the current trial began and they should focus their attention. The inducers displayed for 1,000 ms. After they disappeared, there was a 200 ms temporal gap followed by the targets that were presented for 1,000 ms duration. The inducers were always positioned on the inner circle and set to be visible in Experiment 4a and rendered invisible in Experiment 4b. In Experiment 4a, participants could see the inward and outward grating arrays appearing in sequence and judged the average orientation of the second grating array; but in Experiment 4b, they could merely see the target gratings presented shortly after the fixation turned black and judged the average orientation of this grating array.

Experiment 5

Different from the above experiments, the target in Experiment 5 was substituted by a single grating, which appeared in an annulus (2.68°–4.18°) outside the inducers in Experiment 5a and in a circle (2.14° in diameter) surrounded by the inducers in Experiment 5b (Figure 2D). The target had five possible orientations, −2°, −1°, 0°, 1°, or 2°, and a psychophysical task was applied to assess the perceptual orientation of the target, modulated by the inducers' average orientation (left-tilted or right-tilted). Participants performed two blocks: in the first block, the inducers were invisible, and in the second block, they were visible. Each block consisted of 220 trials, with 20 trials for each experimental condition and 20 catch trials in which the target was either 25° or −25°. Each trial followed the same procedure as in Experiments 1 and 2 (Figure 2C).

Statistics and Reproducibility

In the experiments where the inducers were invisible (Experiments 2, 3b, 4b, and the invisible block of Experiment 5), participants' awareness of the inducers was assessed based on both objective and subjective criteria. First, we excluded the participants whose accuracy in the awareness check fell out of the range 37.35%–62.65%, calculated according to a binomial test against 50% (95% confidence interval for 60 trials). Then, for the remaining participants, we excluded the trials in which they subjectively reported to see any other things within the yellow area beside the targets (no more than 1% trials in total).

As participants were only required to judge the average orientation of the targets (Experiments 1–4) or the orientation of the single target (Experiment 5), the judgments ought to be immune to the average orientation of the inducers if the inducers' summary statistics do not modulate the perception of the targets. By contrast, if the summary statistics indeed exert modulation effects, the perceptual orientation of the targets is expected to be attracted to or repelled from the average orientation of the left-tilted or the right-titled inducers. To quantify the potential modulation effect, in Experiments 1–4 where the average orientation of the targets was always vertical, we calculated the proportion of participants' orientation judgments attracted to the average orientation of the inducers (hereinafter referred to as attracted judgment proportion). The judgment is deemed as attraction when participants perceived the targets orienting toward the same direction as the average orientation of the inducers. Then two-tailed one-sample *t* tests with 95% confidence were used to compare the attracted judgment proportion with the baseline (50%). A p value <.05 was considered statistically significant. If there was a significant difference between them, it denoted that the inducers' summary statistics modulated the ensemble processing of the targets. In the psychophysical task of Experiment 5, we calculated for each participant the proportions that the target was judged as right-tilted under each inducer condition (left-tilted or right-tilted). Then we fitted them with a Boltzmann sigmoid function $f(x) = 1/(1 + \exp[-(x-x_0)/\omega])$, where x_0 corresponds to the point of subjective equality (PSE), at which participants perceived the target as vertical. The larger the PSE, the more likely the target was judged left-tilted than its original orientation (Supplemental Figure S1). In both the visible and invisible blocks, we subtracted the PSE under the left-tilted inducers from the PSE under the right-tilted inducers (i.e., ΔPSE). The statistical analyses were conducted on the ΔPSE. If a two-tailed one-sample *t* test showed the ΔPSE significantly differed from zero, it indicated that the inducers' summary statistics influenced the orientation judgments of the targets.

Transparency and Openness

We report how we determined our sample size, all manipulations, and all measures in the study. Data were analyzed using SPSS Version 22.0 and G-power Version 3.1. All data are available at (https://osf.io/nqmzj/; Liu et al., 2022). The materials and analysis codes are available to other researchers upon request. This study's design and analysis were not preregistered.

Results

Prior to reporting the main results, we conducted two supportive analyses. First, in the awareness check of all experiments that included invisible inducers, the screened participants (see the Method section for the inclusion criteria in detail) could neither perceive the inducers nor discriminate the average orientation of the inducers above chance level, mean accuracy ± *SD*, Experiment 2a: 0.497 ± 0.058, $t(19) = -0.26$, $p = .800$, 95% CI = [−0.031, 0.024]; Experiment 2b: 0.490 ± 0.053, $t(20) = -0.89$, $p = .386$, 95% CI = [−0.035, 0.014]; Experiment 3b: 0.519 ± 0.054, $t(21) = 1.66$, $p = .112$, 95% CI = [−0.005, 0.043]; Experiment 4b: 0.483 ± 0.061, $t(19) = -1.22$, $p = .236$, 95% CI = [−0.045, 0.012];

Experiment 5a: 0.498 ± 0.060, $t(19) = -0.09$, $p = .927$, 95% CI = [−0.030, 0.027]; Experiment 5b: 0.498 ± 0.048, $t(19) = -0.23$, $p = .818$), 95% CI = [−0.025, 0.020], which confirmed that the inducers could not be consciously perceived by the participants in these experiments. Second, we demonstrated that there was no bias in participants' judgments of the average vertical targets (left-tilted or right-tilted) when the average orientation of the inducers was vertical. In Experiments 1, 2, and 4, the proportion of the target judged as left-tilted was not significantly deviated from 50% in the vertical inducers condition, $M \pm SD$, Experiment 1: 0.515 ± 0.075, $t(39) = 1.23$, $p = .227$, 95% CI = [−0.009, 0.038]; Experiment 2: 0.511 ± 0.112, $t(40) = 0.63$, $p = .533$, 95% CI = [−0.024, 0.046]; Experiment 4: 0.491 ± 0.083, $t(39) = -0.70$, $p = .489$, 95% CI = [−0.036, 0.017].

Conscious and Unconscious Summary Statistics Exert Differential Modulations on Ensemble Perception

Experiments 1 and 2 examined how the summary statistics of visible and invisible stimuli modulated the ensemble perception of another group of spatially separated stimuli. We therefore manipulated the visibility of the inducers and instructed the participants to judge the average orientation of the targets (actually vertical on average). The inducers were visible in Experiment 1 while invisible in Experiment 2, positioned either on the inner circle (Experiments 1a and 2a) or the outer circle (Experiments 1b and 2b). If the summary statistics indeed exerted a significant modulation effect, participants' orientation judgments would be biased by the average orientation of the titled inducers instead of fluctuating around vertical. We calculated the proportion of the average orientation of the targets being judged as attracted to the average orientation of the inducers (i.e., attracted judgment proportion), and found it was significantly lower than 50% in Experiment 1, Experiment 1a: 0.475 ± 0.051, $t(19) = -2.18$, $p = .042$, 95% CI = [−0.049, −0.001], *Cohen's d* = 0.490; Experiment 1b: 0.457 ± 0.039, $t(19) = -4.94$, $p < .001$, 95% CI = [−0.062, −0.025], *Cohen's d* = 1.103; see Figure 1D, whereas significantly higher than 50% in Experiment 2, Experiment 2a: 0.529 ± 0.056, $t(19) = 2.37$, $p = .028$, 95% CI = [0.003, 0.055], *Cohen's d* = 0.518; Experiment 2b: 0.518 ± 0.038, $t(20) = 2.21$, $p = .039$, 95% CI = [0.001, 0.035], *Cohen's d* = 0.474; see Figure 1E. These results showed that irrespective of the positions of the inducers and the targets, the orientation ensemble of the vertical targets was repelled from the average orientation of the visible inducers, while attracted to the average orientation of the invisible inducers. These findings were further verified when applying another paradigm to manipulate the visibility of the inducers, that is, the continuous flash suppression paradigm in which the to-be-suppressed stimuli were monocularly presented to one eye and masked by colored dynamic noise that was simultaneously presented to the other eye (see the Supplemental Materials, for more details). They together demonstrated that the summary statistics of the visible and invisible inducers can differentially modulate the ensemble processing of the targets.

Abundant Attentional Resources Are Indispensable for Both Conscious and Unconscious Modulation Effects

According to previous studies, there were two conflicting views about the role of attention in ensemble perception. One claimed that directed attention is not necessary (Alvarez & Oliva, 2008, 2009; Bronfman et al., 2014; Ward et al., 2016), whereas the other held that attention is able to modulate ensemble perception (Dakin et al., 2009; McNair et al., 2017). Experiment 3 then investigated whether and how attentional resources affected the observed modulation effects. The findings could also assist in delineating the role of attention in conscious and unconscious ensemble perception. We found that in the single-task condition, where participants were only required to judge the average orientation of the targets, the average orientation of the visible and invisible inducers biased the ensemble perception of the targets' orientation toward opposite directions (Figure 2E), consistent with the findings of Experiments 1 and 2. The attracted judgment proportion was significantly lower than 50% when the inducers were visible in Experiment 3a, 0.470 ± 0.051, $t(19) = -2.63$, $p = .016$, 95% CI = [−0.054, −0.006], *Cohen's d* = 0.588, whereas significantly higher than 50% when the inducers were invisible in Experiment 3b, 0.528 ± 0.036, $t(21) = 3.58$, $p = .002$, 95% CI = [0.012, 0.044], *Cohen's d* = 0.778.

However, in the dual-task condition, where participants had to simultaneously perform the average orientation judgment and the RSVP task (i.e., counting the numbers inserted in the letter stream), the modulation effect was severely impaired irrespective of whether the inducers were visible (Experiment 3a) or invisible (Experiment 3b). The attracted judgment proportion did not significantly differ from 50% in both experiments, Experiment 3a: 0.504 ± 0.053, $t(19) = 0.32$, $p = .756$, 95% CI = [−0.021, 0.029]; Experiment 3b: 0.494 ± 0.050, $t(21) = -0.57$, $p = .574$, 95% CI = [−0.028, 0.016]. Since the participants all exhibited high performance in the RSVP task (with a mean accuracy of 81.48% in Experiment 3a and 81.79% in Experiment 3b), it then confirmed that in this dual-task condition, the attentional load was relatively high for the ensemble perception of the targets and the inducers. Furthermore, similar results were found even if we calculated the attracted judgment proportion only for the correct trials of the RSVP task. These results suggest that available attentional resources are indispensable to the ensemble perception and/or the modulation effects.

Differential Influences of Temporal Separation on Conscious and Unconscious Modulation Effects

The above experiments revealed that with sufficient attentional resources, the ensemble perceptual orientation of the targets was repelled from the average orientation of the visible inducers (i.e., the repulsive modulation effect), whereas attracted to the average orientation of the invisible inducers (i.e., the attractive modulation effect). It is possible that the attracted modulation effect may be due to the inability of the participants to segregate the invisible inducers from the targets. In Experiment 4, we tested this hypothesis by introducing a brief temporal gap between the presentation of the inducers and the targets. The results revealed that the attracted judgment proportion was still significantly lower than 50% when the inducers were visible in Experiment 4a, 0.455 ± 0.055, $t(19) = -3.65$, $p = .002$, 95% CI = [−0.071, −0.019], *Cohen's d* = 0.818, whereas the attracted judgment proportion was not significantly different from 50% when the inducers were rendered invisible in Experiment 4b, 0.494 ± 0.038, $t(19) = -0.68$, $p = .505$, 95% CI = [−0.024, 0.012], see Figure 2F. In other words, the attractive modulation effect triggered by invisible summary statistics would be abolished when the inducers and the targets were temporally separated, whereas the repulsive modulation effect triggered by visible summary statistics was immune to such temporal separation. It thus implied that the attractive modulation effect from unconscious ensemble is more fragile than the repulsive modulation effect from conscious ensemble, considering the former strongly relying on the temporal integration between the targets and the invisible inducers. It further suggested the attractive and repulsive modulation effects might engage bottom-up and top-down mechanisms of the visual system separately.

Conscious and Unconscious Modulation Effects Differentially Depend on Target–Inducer Similarity

According to Experiment 4, the attractive but not the repulsive modulation effect was based on the premise that the invisible inducers and the targets might be perceptually inseparable. Another effective method to disrupt perceptual grouping and induce perceptual separation is to change the stimulus similarity (Yuan et al., 2015). To further confirm that the perceptual separation differentially affects the attractive and repulsive modulations, in Experiment 5, we manipulated the similarity (or the perceived distinction) between the inducers and the targets by substituting the group of target gratings with a single target grating and instructing participants to perform a simple orientation discrimination task instead, which further enlarged the distinction between the targets and the inducers. In this psychophysical task, we calculated a ΔPSE index by subtracting the PSE under the left-tilted inducers from the PSE under the right-tilted inducers in both the visible (ΔPSE_v) and invisible (ΔPSE_i) conditions. The results showed that, irrespective of whether the target position was outside (Experiment 5a) or inside (Experiment 5b) the inducer, there was no significant difference between ΔPSE_i and zero, mean $\Delta PSE_i \pm sd$, Experiment 5a: −0.059 ± 0.261, $t(19) = -1.01$, $p = .326$, 95% CI = [−0.181, 0.063]; Experiment 5b: 0.054 ± 0.310, $t(19) = 0.78$, $p = .447$, 95% CI = [−0.091, 0.199]; see Figure 2G, suggesting that the unconscious modulation effect was not evident when the inducers were rendered invisible. By contrast, when the inducers were visible, there was a significantly negative ΔPSE_v, mean $\Delta PSE_v \pm SD$, Experiment 5a: −0.306 ± 0.348, $t(19) = -3.93$, $p = .001$, 95% CI = [−0.469, −0.143], *Cohen's d* = 0.879; Experiment 5b: −0.563 ± 0.265, $t(19) = -9.49$, $p < .001$, 95% CI = [−0.687, −0.439], *Cohen's d* = 2.125, indicating the persistence of the conscious modulation effect. These results reaffirmed that the unconscious modulation effect, dependent on perceived target–inducer simultaneity and similarity, may rely on a different mechanism from the conscious modulation effect.

Discussion

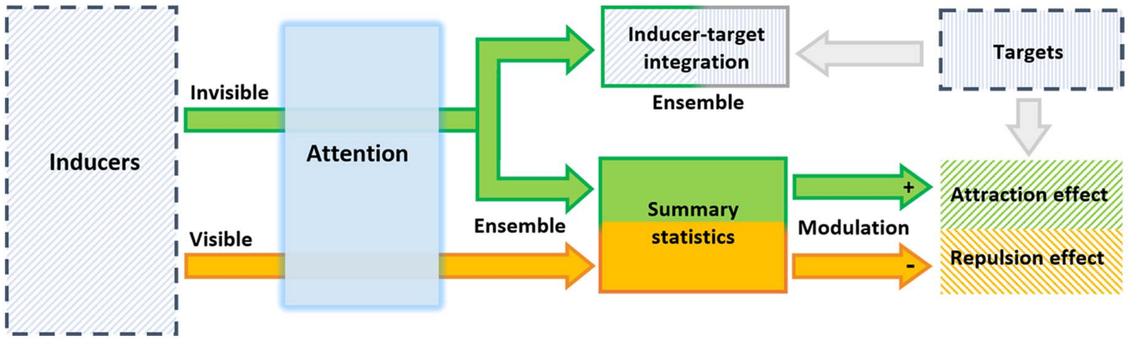
Through a series of experiments, the present study demonstrated that processing of conscious and unconscious ensemble statistics differentially and even oppositely affect our perceptual decision-making. First, participants' ensemble judgments of the targets tended to be repelled from the conscious summary statistics of the visible inducers (Experiment 1) but attracted to the unconscious summary statistics of the invisible inducers (Experiment 2). Second, both the conscious and unconscious modulation effects disappeared under high attentional load (Experiment 3), indicating the necessity of sufficient attentional resources in triggering the interaction between multiple ensemble representations or even the occurrence of ensemble perception. Third, the unconscious modulation effect was highly susceptible to the target–inducer temporal separation (Experiment 4) and distinction (Experiment 5), whereas the conscious modulation effect was immune to these factors. Taken together, these findings suggest that the conscious and unconscious ensemble representations may engage different visual processing mechanisms (e.g., the bottom-up and top-down mechanisms), which in turn exert dissociable influences on perceptual decision-making and highlight the distinct roles of awareness and attention in ensemble perception (see Figure 3, for a schematic illustration).

Dissociable Influences From Conscious and Unconscious Ensemble Representations

The dissociable modulation effects (i.e., repulsion and attraction) induced by the conscious and unconscious ensemble representations at first glance seem to resemble some properties of the tilt illusion (Gibson, 1937). In the classic tilt illusion, the presence of an oriented surround stimulus biases the perceived orientation of a simultaneously presented target (Clifford, 2014). The target appears repelled away from the inducer in orientation between 0° and 50° but appears rotated toward the inducer when it is between 75° and 80°. Many variations have been extended around the

Figure 3

A Schematic Illustration of the Proposed Mechanism for the Unconscious and Conscious Modulation Effects



Note. The invisible inducers exert an unconscious attractive modulation effect on the perceptual decision-making of the targets, whereas the visible inducers exert a conscious repulsive modulation effect. The unconscious attraction effect may result from the ensemble process of the inducer–target integration, that is, the invisible inducers are represented as part of the targets unintentionally. Alternatively, the summary statistics of the inducers and the targets are separately extracted and then interact with each other to modulate the perceptual judgments. The modulation effects can operate differently for the unconscious and conscious ensemble representations. Although both of these modulation effects strongly rely on attentional resources, the unconscious modulation effect depends on the simultaneity and the similarity between the inducers and the targets, whereas the conscious modulation effect is largely immune to these factors. See the online article for the color version of this figure.

classical tilt illusion (Clifford & Harris, 2005; Motoyoshi & Hayakawa, 2010; Tomassini & Solomon, 2014; Yuan et al., 2017), in which a remarkable finding is that the repulsion effect can survive after the removal of the oriented surround grating from awareness (Clifford & Harris, 2005; Motoyoshi & Hayakawa, 2010) but the attraction effect requires awareness (Tomassini & Solomon, 2014). This is however different from the present study in which the attractive modulation effect appeared when the inducers were rendered invisible. In addition, each item of the inducers was set to be slightly tilted away from the vertical orientation, corresponding to the orientation range in the repulsive tilt illusion condition. Therefore, the models proposed to explain the tilt illusion, such as the lateral inhibition theory (Blakemore et al., 1970, 1973), the normalization theory (Gibson, 1937), and the gain control model (Solomon & Morgan, 2006), cannot be directly applied to account for the dissociable modulation effects observed in the present study, especially to the attractive modulation effect.

A recent study has shown that the figure-ground modulation is awareness-dependent (Huang et al., 2020). Accordingly, we inferred that the participants might be unable to distinguish the invisible inducers from the targets in the present study when the inducers and the targets were perceptually similar to each other and presented simultaneously. As a result, when the participants extracted statistical information from the targets, the invisible inducers may be represented as part of the targets unintentionally, hence their judgments were unavoidably attracted to the inducers' summary statistics. This is consistent with our findings that the attractive modulation effect disappeared when the inducer–target integration was disrupted by inserting a brief temporal gap (Experiment 4b) or altering the target–inducer similarity (Experiment 5b). In this sense, the attractive modulation effect may simply reflect an ensemble process of the inducer–target integration rather than a "modulation" process (Figure 3). On the other hand, the "modulation" account, which suggests that the summary statistics of the invisible inducers and the visible targets are separately extracted in the first step, and then the ensemble representation of the targets incorporates that of the inducers at the decision-making stage, is also plausible (Figure 3). In this sense, the attractive modulation effect is somewhat like a consequence of "information leakage" in that the ensemble judgment of targets is intermingled with the unconscious readout of the surrounding summary statistics. Although it is uncertain which account is superior to the other, both suggest a bottom-up mechanism underlying the attractive modulation effect. Furthermore, they both indicate ensemble perception can take place even if the stimuli cannot be consciously perceived.

So as to the repulsive modulation effect, it manifests as the conscious summary statistics of the inducers first being extracted and then modulating the perceptual judgment of the targets. Some may argue that according to the lateral inhibition theory (Blakemore et al., 1970, 1973), the perceptual orientation of each target grating among the arrays is affected by its nearby gratings, so that the repulsive modulation effect may be solely caused by the lateral inhibition between the target items and the inducer items, rather than by an ensemble process before the modulation. However, the results in Experiment 4a contradict this argument by showing that the asynchronously presented inducers also repulsively biased the ensemble perception of the targets. This indicates that the participants automatically extracted the summary statistics of the inducers, which further affected the summary statistics of the subsequently presented targets. Therefore, these results together support that the summary statistics of multiple conscious ensembles may be extracted independently but interact with each other within a relatively flexible temporal window. In other words, the repulsive modulation effect observed in the conscious ensemble perception may additionally engage a top-down cognitive mechanism, which is quite different from the unconscious ensemble perception. But notably, although the conscious and unconscious modulation effects seem to be accounted for by two different mechanisms, we do not negate that these mechanisms are related or even interdependent. Since consciousness is routinely measured by the visibility that can be treated as either a continuous or a binary variable, it is possible that the top-down and bottom-up mechanisms may be involved in a more general network, in which the response pattern is continuously adjusted as a function of visibility.

Distinct Roles of Awareness and Attention in Ensemble Perception

As mentioned in the *introduction*, it has long been a concerned topic whether the occurrence of ensemble perception is independent of awareness (Joo et al., 2009; Parkes et al., 2001; Van Opstal et al., 2011; Ward et al., 2016) or attention (Alvarez & Oliva, 2008; Bronfman et al., 2014; Chong & Treisman, 2005a; Dakin et al., 2009; Jackson-Nielsen et al., 2017). By demonstrating robust modulation effects of conscious and unconscious ensemble perception on the perceptual judgment, the present study suggests that the perceptual awareness of the stimuli may not be necessary for ensemble perception to take place. On the other hand, by demonstrating that the statistics of unattended ensembles (irrespective of the stimulus visibility) cannot exert significant influences on the perceptual judgment, the present study lends support to the notion that attention is indispensable to ensemble perception.

Different from previous studies that used ensemble perception as a direct measurement to examine the role of attention, the present study probed this issue by measuring the modulation effect of the summary statistics of attended or unattended ensembles on the perceptual judgment. By this means, the potential confusion caused by the task-relevant effect can be largely avoided. More crucially, we adopted a high-attention-load task accompanied by the perceptual judgment task, thereby little attention resources could be available to the ensemble perception of the inducers. In this case, the vanished repulsive and attractive modulation effects reflect that the summary statistics cannot be successfully extracted from the unattended inducers irrespective of their visibility. Compared with previous findings (Alvarez & Oliva, 2009; Bronfman et al., 2014; Jackson-Nielsen et al., 2017), our results thus more convincingly point to the conclusion that attention is indispensable to ensemble perception.

On the whole, our findings contribute to the classic topic of the relationship between attention and consciousness from the perspective of ensemble perception. Different from the initial view that attention is sufficient and/or necessary for consciousness (Posner, 1994; Rensink et al., 1997), the present study provides compelling evidence for a functional dissociation between visual awareness and top-down attention (Koch & Tsuchiya, 2007; Watanabe et al., 2011), which also fills the knowledge gap in the role of consciousness and attention in ensemble perception.

Constraints on Generality

The present study mainly focused on the ensemble perception of a low-level visual feature (i.e., orientation). Considering that the ensemble perception of many low-level visual features, such as orientation, color, and size, depends on how proximal these features are in representational space (Attarha et al., 2014; Attarha & Moore, 2015; Haberman et al., 2015), the current findings are likely to generalize, to a large extent, to the other low-level visual features.

The supplemental experiment (see Supplemental Material, for details) reported quite similar results despite variations in the apparatus, paradigm, and stimulus parameters, suggesting these variations would not hinder the replication of the present study. However, the difficulty of judging the inducers' summary statistics is of great importance because correctly reading out the summary statistics of the inducers is the premise of the observed modulation effects. For a successful replication, the orientation settings of the inducers should be adjusted to a degree that the participants judge the average orientation with high accuracy. In addition, participants should be with normal color vision and cognitive ability, and there is no reason to expect that the results depend on other characteristics of participants, materials, or experimental context.

Conclusion

The present study demonstrates that perceptual decision-making on summary statistics may engage two different mechanisms in the visual system, a bottom-up mechanism that underlies the attractive modulation effect from the unconscious summary statistics, and both bottom-up and top-down mechanisms that undergird the repulsive modulation effect from the conscious summary statistics. Furthermore, our results also lend new support to the distinct roles of awareness and attention in ensemble perception: awareness acts as a "guide," which determines how to utilize the extracted summary statistics cognitively, whereas attention acts as a "switch," which determines whether to extract the summary statistics from ensemble stimuli (see Figure 3, for a schematic illustration).

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