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Attention without awareness: Attentional modulation of perceptual grouping without awareness

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Abstract

Perceptual grouping is the process through which the perceptual system combines local stimuli into a more global perceptual unit. Previous studies have shown attention to be a modulatory factor for perceptual grouping. However, these studies mainly used explicit measurements, and, thus, whether attention can modulate perceptual grouping without awareness is still relatively unexplored. To clarify the relationship between attention and perceptual grouping, the present study aims to explore how attention interacts with perceptual grouping without awareness. The task was to judge the relative lengths of two centrally presented horizontal bars while a railway-shaped pattern defined by color similarity was presented in the background. Although the observers were unaware of the railway-shaped pattern, their line-length judgment was biased by that pattern, which induced a Ponzo illusion, indicating grouping without awareness. More importantly, an attentional modulatory effect without awareness was manifested as evident by the observer's performance being more often biased when the railway-shaped pattern was formed by an attended color than when it was formed by an unattended one. Also, the attentional modulation effect was shown to be dynamic, being more pronounced with a short presentation time than a longer one. The results of the present study not only clarify the relationship between attention and perceptual grouping but also further contribute to our understanding of attention and awareness by corroborating the dissociation between attention and awareness.

Keywords Visual awareness · Perceptual organization · Attention · Divided attention and inattention

Perceptual grouping and attention

A daunting task for the visual system is to construct a three-dimensional world from the condensed two-dimensional information attained from the retinal surfaces. The process by which the visual system disambiguates miscellaneous contours, colors, and movements and gathers them into meaningful units or objects is commonly referred to as *perceptual grouping*. Investigation of perceptual grouping can be traced back to Gestalt psychology (Westheimer, 1923). Gestalt psychologists proposed a set of principles by which multiple stimuli could be grouped and viewed as one unit. According to the principle of *similarity*; for example, stimuli with similar features, such as similar shapes or colors, could be grouped together.

Early theories of visual information processing assert that perceptual grouping is a basic visual process that occurs prior to the involvement of attention (Julesz, 1981; Neisser, 1967; Treisman, 1982). Attention can be viewed as a cognitive process that, when one is confronted with a large amount of information in an environment, selectively prioritizes some of information.[1] A potential function of perceptual grouping is to coarsely organize the visual scene into a smaller number of units, so attention can be selectively allocated to one or some of the units. This has been empirically supported by

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[1] In psychology, a well-cited conceptual definition of attention is provided by James (1890, pp. 403-404): "Every one knows what attention is. It is the taking possession by the mind, in clear and vivid form, of one out of what seem several simultaneously possible objects or trains of thought. Focalization, concentration, of consciousness are of its essence. It implies withdrawal from some things in order to deal effectively with others." Although the operational definitions of attention vary greatly across different studies, they generally involve a selective process to prioritize some units over others, which is consistent with James's assertion that "it implies withdrawal from some things in order to deal effectively with others."

studies that demonstrated effects of perceptual grouping on attention (Kasai & Takeya, 2012; Kerzel, Born, & Schonhammer, 2012; Vatterott & Vecera, 2015). Therefore, it is a reasonable conjecture that perceptual grouping occurs prior to attention. However, the preattentive view of perceptual grouping has been challenged by a substantial number of studies (Ben-Av, Sagi, & Braun, 1992; Han, Jiang, Mao, Humphreys, & Gu, 2005; Han, Jiang, Mao, Humphreys, & Qin, 2005; Mack, Tang, Tuma, Kahn, & Rock, 1992; Rock, Linnett, Grant, & Mack, 1992; Zaretskaya, Anstis, & Bartels, 2013). Among these studies, some showed a *modulatory* effect of attention on perceptual grouping. For example, Han, Jiang, Mao, Humphreys, and Qin (2005) presented their subjects with stimulus arrays, where local elements were evenly arranged or grouped into columns or rows based on the principle of proximity or similarity. The grouping-related neural activities, indexed by subtracting EPRs to the grouped stimulus from those to the evenly arranged pattern, were weakened when the stimulus array fell outside the attended area in the visual field.

Beyond being simply *modulatory,* some research has shown that attention is a *necessary* condition for perceptual grouping. For example, in studies conducted by Mack, Rock, and their colleagues (Mack & Rock, 1998; Mack et al., 1992; Rock et al., 1992), observers were required to make responses to a certain stimulus in a visual display while another pattern defined by proximity or luminance similarity grouping was presented in the background but was irrelevant to the stimuli to which the observer was intentionally responding. At the end of the task, a significant number of observers reported not seeing the grouping pattern in the background. That is, without attention deployed to the pattern, grouping does not occur.

Perceptual grouping and awareness

While evidence of attention as a *modulatory* or a *necessary* factor for perceptual grouping was emerging, another line of research provided contradictory evidence: Perceptual grouping occurs without attention as long as one can measure it without, or prior to, awareness. For example, patients with *visual extinction* are characterized by an impaired capacity to simultaneously process multiple stimuli due to a lesion of the parietal lobe. They can detect a single stimulus presented to either visual field but fail to detect a contralesional stimulus when it is presented simultaneously with an ipsilesional stimulus (Baylis, Driver, & Rafal, 1993). Thus, this disorder is considered a deficit in attentional selection. Despite the impaired mechanism for attentional selection, patients with visual extinction have shown preserved capacity in processes related to object recognition (for a review, see Driver, 1995). There is evidence that grouping between the stimuli on the contralesional and ipsilesional sides can improve the processing of stimuli on the contralesional side (Conci et al., 2009; Gilchrist, Humphrey, & Riddoch, 1996; Mattingley, Davis, & Driver, 1997; Rappaport, Riddoch, & Humphrey, 2011; Ward, Goodrich, & Driver, 1994). In these studies, the grouping process affected whether they could enter awareness, so this grouping process must have occurred prior to awareness. For the grouping process that occurred prior to awareness, patients with attentional deficit still preserve this capacity.

With the general, nonclinical population, a number of studies have used implicit measurements to provide evidence that perceptual grouping can occur without attention (Lo & Yeh, 2008; Moore & Egeth, 1997; Russell & Driver, 2005). For example, Moore and Egeth (1997) presented their observers with two horizontal bars and tasked them with judging which of the two bars appeared to be longer than the other. While the observer paid attention only to the bars, black and white discs were displayed in the background. The black discs could be grouped to form a railway-shaped pattern against the background of white discs. In the critical trial, the two horizontal bars were equal in length, but the railway-shaped disc array in the background induced a Ponzo illusion, prompting the observer to report one bar to be longer than the other.[2] The majority of the observers did not report seeing a railway-shaped pattern in the background. However, their line-length judgment was still biased by the pattern in the background. Thus, perceptual grouping by color similarity can occur without attention when grouping is measured in an implicit way. Using an identical method, Lo and Yeh (2008) further demonstrated that perceptual grouping without awareness is a dynamic process: Grouping by orientation similarity could not be completed within a 200-ms presentation time, but the grouping effect emerged with a 500-ms presentation time, even when the observer was still unaware of the grouping pattern.

To reiterate, whether a grouping process requires attention seems to depend on how awareness is involved. For the explicit grouping, or grouping with awareness, attention is important, but grouping per se does not necessarily require attention if one can measure it in an implicit way.

Aim of this study

This study aims to test how attention modulates perceptual grouping without awareness. As mentioned earlier, the effect of attention on perceptual grouping was shown to be *modulatory* in some studies (Ben-Av et al., 1992; Han, Jiang, Mao, Humphreys, & Gu, 2005; Han, Jiang, Mao, Humphreys, & Qin, 2005) and *necessary* in others (Mack & Rock, 1998; Mack et al., 1992; Rock et al., 1992). However, if one can measure perceptual grouping without awareness,

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[2] For an illustration, readers can refer to Fig. 1, which is very similar to the stimuli used in Moore and Egeth's (1997) study with two exceptions: First, the railway-shaped pattern was formed by black discs; second, there was no letter in the center.

attention is not necessary (e.g., Lo & Yeh, 2008; Moore & Egeth, 1997). The question remains: With an implicit measurement, can attention nevertheless modulate perceptual grouping? Previous studies demonstrating modulatory effects of attention on perceptual grouping might have conflated the effects of attention with those of awareness, so the modulatory effect might only be restricted to perceptual grouping with awareness instead of perceptual grouping in general. To examine how attention modulates perceptual grouping, one has to test the attentional modulation effect on perceptual grouping without awareness.

Key concepts in this study

Awareness, in this study, is operationally defined by whether or not the observer can report the presence of a certain stimulus. Such an operational definition is based on the conceptual definition of *access consciousness* in the literature of consciousness: the mental representations accessible for reasoning, action control, or verbal reporting (Block, 1996). In this study, awareness was manipulated using a task similar to the one used in Moore and Egeth's (1997) study. Observers judged the relative lengths of the two horizontal lines while a railway-shaped grouping pattern was presented in the background. Only data from observers who failed to report the background pattern were included in the analysis. This was designed to test perceptual grouping without awareness because observers could not report the railway-shaped grouping pattern. After completing one block of trials to test grouping without awareness, the observers were asked about the background railway-shaped grouping pattern, and thus they became aware of this pattern. They then repeated the same task for another block, and the findings from this were used to test perceptual grouping with awareness.

Another key concept in this study is attention, which can be viewed as a cognitive function that selectively prioritizes some of the available information. In order to induce differential prioritization for different items in the visual display, a commonly used method is to make some items more relevant to the observer's goal than others. Therefore, goal relevance could be a useful method for manipulating attention, which has been intensively studied by Folk, Remington, and their colleagues (Folk, Leber, & Egeth, 2008; Folk, Remington, & Johnston, 1992; Irons & Remington, 2013). In the study of Folk et al. (2008), for example, observers viewed series of letters in a rapid serial visual presentation (RSVP). The task was to identify the letter of a designated color, but a nonletter stimulus affected the performance when it was marked by the attended color. In this scenario, attention was captured by a nontarget stimulus because it was marked by the goal-contingent color. Interestingly, recent studies showed that attention could be captured by invisible nontargets (Ansorge, Kiss, & Eimer, 2009; Lamy, Alon, Carmel, & Shalev, 2015), which provided empirical basis for this present study to investigate attentional effects without awareness. In the current study, in addition to the line-length judgment, the observer was required to detect a color in an RSVP letter stream, which was the same or different than the color of the railway-shaped grouping pattern. Presumably, the railway-shaped grouping pattern could capture attention when it was formed by the to-be-searched color. By changing the color of the railway-shaped grouping pattern, attention could be manipulated.

In Experiment 1, where the presentation was short, the undetected railway-shaped pattern biased the observer's line-length judgment to a larger extent when the grouping was based on the attended color rather than the unattended color. Therefore, attention modulated perceptual grouping, and this modulatory process occurred without awareness. However, this attentional effect was reduced in Experiment 2, where the presentation was long. A possible explanation for this will be presented in the General Discussion section.

Experiment 1

An experimental setting similar to the one developed by Moore and Egeth (1997) was used in this study. The critical stimuli, which might or might not possess the attended color, were presented in the background, while the observer was conducting another task that was irrelevant to the critical stimuli.

Method

Participants The two experiments in this study were approved by the Research Ethics Committee for Human Subject Protection of National Chiao Tung University, and all of the participants gave their written consent before participating. In this experiment, 54 people (20 males) ages approximately 20–30 years, were recruited. All participants reported having normal or corrected-to-normal vision. None of the participants was aware of the purpose of this experiment.

Stimuli The experiment was controlled using a MacBook Air and programmed in MATLAB r2013b with Psychtoolbox–3 extensions (Brainard, 1997; Pelli, 1997). Visual stimuli were displayed on a 22-inch CRT monitor (Mitsubishi i-TECH iF2200 NF CRT Monitor) with a spatial resolution of 1024 × 768 and a refresh rate of 100 Hz. Participants sat in a dimly lit room and used a chin rest to maintain a viewing distance of 60 cm.

The stimuli used in this experiment are shown in Fig. 1. A trial began during which a white fixation cross appeared at the center of the display, with each of its arms subtending at a 0.5° visual angle. The fixation cross was presented for 1,000 ms,

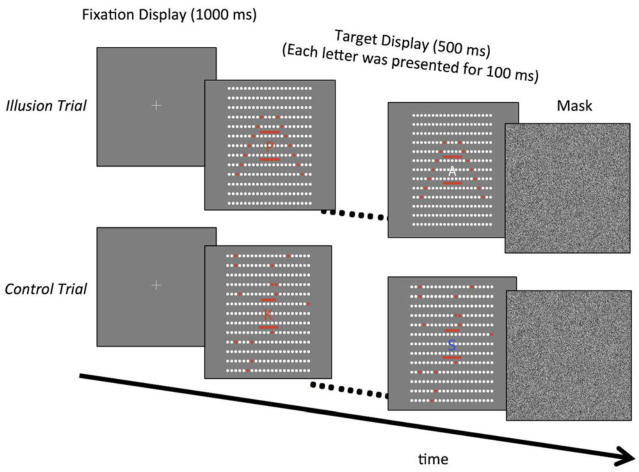

Fig. 1 Stimuli presented in an illusion trial (upper panel) or a control trial (lower panel) in Experiment 1. A trial started with the fixation display, followed by the target display, which comprised background discs, two horizontal bars, and centrally presented letters. Five letters were presented consecutively at the center of the visual display, with each one presented for 100 ms. The target display was then masked by the mask display. (Color figure online)

followed by the target display, which was composed of a gray background and 273 discs arranged in an array of 13 rows and 21 columns. The radius of each disc was 0.3°, and the center-to-center distance between neighboring discs was 0.8° horizontally and 1.3° vertically.

In the target display of an *illusion trial* (see Fig. 1, upper panel), 14 of the 273 discs were colored, with red (CIE x, y = .61, .34, luminance = 40.29 cd/m^2) for half of the trials and green (CIE x, y = .28, .59, luminance = 39.75 cd/m^2) for the other half. The rest of the discs were white (CIE x, y = .28, .29, luminance = 184.26 cd/m^2). The colored discs were arranged in a way that resembled either an upright or an inverted *V*. In the target display of a *control trial* (see Fig. 1, lower panel), there were also 14 colored discs (red for half of the trials and green for the other half), but the locations of these were random. In addition to the discs, there were two horizontal bars around the center of this display with a separation of 5.5°. In an *illusion trial*, the two horizontal bars were both 4° in length and 0.5° in width. In a *control trial*, the two horizontal bars had equal widths of 0.5°, but their lengths were different; they could be 3.8° versus 3.6°, 4.0° versus 3.8°, 4.2° versus 4.0°, or 4.4° versus 4.2°. The location of the longer bar, which could be on the top or bottom, was randomized across the trials. The color of the two horizontal bars was always the same as that of the colored discs in the background.

At the center of the target display, there was an RSVP letter stream. Each RSVP stream was composed of five letters, with each letter presented for 100 ms. The letters could be any English letter from *A* to *Z*, selected randomly without replacement, and the colors could be white (CIE x, y = .28, .29, luminance = 184.26 cd/m^2), black, yellow (CIE x, y = .46, .46, luminance = 101.03 cd/m^2), or blue (CIE x, y = .15, .07, luminance = 19.98 cd/m^2), selected randomly with replacement. In addition to these four colors, the letter stream contained one red letter (CIE x, y = .61, .34, luminance = 40.29 cd/m^2) in half of the trials and one green letter (CIE x, y = .28, .59, luminance = 39.75 cd/m^2) in half of the trials. For each trial, whether or not a red letter was presented was irrelevant to whether or not a green letter was presented. Therefore, some trials contained a red letter but not a green one, some trials contained a green letter but not a red one, some trials contained both, and some trials contained neither. The temporal serial position of the target (whether the target was presented as the first, second, third, fourth, or fifth letter) was randomized across the trials. The letter font was Menlo, and letters were 1.6° in width and 2.1° in height. The target display was followed by a mask display comprising random white and black dots.

Procedure The participants performed two two-alternative forced-choice tasks. The primary task was the line-length judgment task, where they had to orally report which of the two horizontal bars appeared to be longer than the other. Possible responses for this task were "upper" or "lower" and were given in Chinese.

The secondary task was the color-detection task, where half of the participants had to report whether a red target was presented in the central RSVP letter stream, and the other half had to report whether a green target was presented. Possible responses for this task were "yes" or "no" and were given in Chinese.

The participants made oral answers to both the primary task and the secondary task, with four possible responses: upper/yes, upper/no, lower/yes, or lower/no (all given in Chinese). The experimenter repeated their answers back to them to confirm their responses and then wrote them down. After completing one trial, the experimenter pressed a key to initiate the next trial.

The experimental procedure is illustrated in Fig. 2. The practice block was composed of 10 control trials. The pre-inquiry block contained 64 trials that were made up of half illusion and half control trials. For the illusion trials, the colored discs in the background formed an upright *V* (half red/half green) in half of the trials and an inverted *V* (half red/half green) in the other half. For the control trials, the colored discs in the background were red in half of the trials and green in the other half. Whether the central letter stream contained a red or a green letter was irrelevant to the background color.

Following the pre-inquiry block was the inquiry block, where the participants were questioned about the background. The first three trials were control trials. These were followed by an illusion trial, which was referred to as the first inquiry trial. After the participant completed the two tasks for this trial, the experimenter asked the participant the following questions: (1) Did you notice an upright *V* or an inverted *V* in the

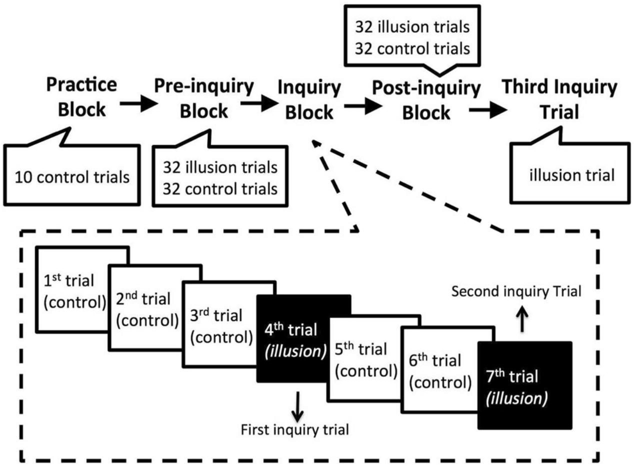

Fig. 2 Schematic illustration of the experimental procedure

background? (2) If there was a *V* in the background, do you think that it was an upright *V* or an inverted *V*? (When asked this question, the participant was shown a piece of paper on which an upright *V* and an inverted *V* were portrayed.) (3) How sure are you about your choice? (A rating of 1 indicated *not sure at all*, 2 indicated *somewhat sure,* and 3 indicated *absolutely sure.*) After the first inquiry trial, the participant responded to the next two control trials without being questioned by the experimenter. In the seventh trial, which was referred to as the second inquiry trial, the participant was asked the same three questions again.

After the inquiry block, the participant completed the post-inquiry block, which was exactly the same as the pre-inquiry block. After completing the post-inquiry block, the participant was asked to shift his or her attention to the background in the third inquiry trial. In this trial, the participant simply reported whether the background contained an upright or an inverted *V* and gave his or her confidence rating. Participants were not queried about the horizontal bars or the central letters.

Half of the participants were presented with an upright *V*, an inverted *V*, and an upright *V*, respectively, in the first inquiry, second inquiry, and third inquiry trials; the other half was presented with an inverted *V*, an upright *V*, and an inverted *V*, respectively, in the first inquiry, second inquiry, and third inquiry trials. The colors of the discs in the three trials were either green or red and were randomly assigned.

After the participants completed the third inquiry trial, they were questioned again about whether they had noticed the background *V* pattern before being informed of its presence by the experimenter. A positive answer led to the exclusion of the participant's data.

Results

Thirteen participants reported seeing a *V* in the pre-inquiry block, so their data were excluded from further analyses.

Line-length judgment How attention modulated perceptual grouping without awareness was indexed by how a differently colored undetected background pattern affected the line-length judgment task. Therefore, it was essential that the participants be able to judge the relative length of two lines properly. In order to confirm that the participants were not guessing, their line-length judgment performance in the 64 control trials was analyzed (in the pre-inquiry block and the post-inquiry block). In these trials, one bar was indeed physically longer than the other. The accuracy data for each individual were subject to a binomial z test,[3] and the criterion was set to $p < .05$ to indicate whether the line-length judgments for a given individual were indeed significantly higher than chance. The data from five participants were excluded based on this criterion. For the remaining 36 participants (14 males), their mean accuracy of line-length judgment for control trials was 77%, and all of the subsequent analyses' results were based on their illusion trials, where the two centrally presented horizontal bars were physically equal in length.

The critical dependent variable was the illusion-induced bias, which was the percentage of illusion-consistent responses. An illusion-consistent response was one in which the participant reported that the bar at the converging side of the *V* pattern (the upper side of an inverted *V* or the lower side of an upright *V*) was longer.

Two measurements of the illusion-induced biases were used: Conditional illusion-induced biases were calculated by only including the trials where the color-detection task was correct. The incorrect trials were excluded as participants might have failed to attend to the target color in those trials; unconditional illusion-induced biases were calculated by including all the trials irrespective of the performance in the color-detection task. Possibly, the participants were indeed paying attention to the designated color throughout the whole experimental session, even when they occasionally made mistakes for the color-detection task.

The conditional illusion-induced biases (see Fig. 3), based on 76% of trials with correct color-detection responses, were subjected to a repeated-measures analysis of variance (ANOVA) with two factors: (1) *Block*, as an indicator of *awareness* (the pre-inquiry block, where the participants could not report the background railway-shaped pattern, versus the post-inquiry block, where the participants reported having noticed the background railway-shaped pattern), and (2) *color relevance*, as an indicator of *attention* (the *task-relevant color* condition, where the railway-shaped pattern in the background was formed by the to-be-searched color, versus the *task-irrelevant color* condition, where the railway-shaped

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[3] For large n (e.g., $n > 30$), one can approximate the binomial distribution with a normal distribution ($\mu = p, \sigma = \sqrt{p(1-p)}$), where p is the proportion of correct responses). Therefore, the z test can be used to test the null hypothesis of a given binomial dataset having a mean of 0.5 (the chance level).

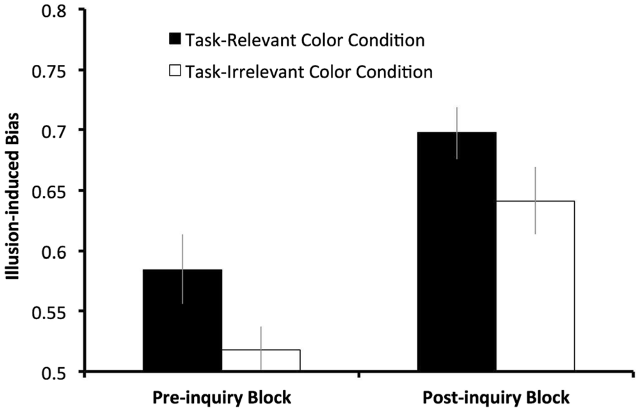

Fig. 3 Averaged illusion-induced biases, defined by the percentage of reports of the line-length judgment task in accordance with the Ponzo illusion, in different conditions in Experiment 1. This figure is based on the conditional measurement, where only the trials with correct color-detection performance were included. The error bar indicates one standard error

pattern was formed by a color irrelevant with the task goal). The mean illusion-induced biases in the *task-relevant color* and *task-irrelevant color* conditions were 58% (*SE* = 2.85%) and 52% (*SE* = 2.00%) in the pre-inquiry block and 70% (*SE* = 2.18%) and 64% (*SE* = 2.78%) in the post-inquiry block (50% refers to the chance level). There were significant main effects of *color relevance,* $F(1, 35) = 10.52$, $p = .003$, $\eta_p^2 = .23$, and *block,* $F(1,35) = 28.22$, $p < .001$, $\eta_p^2 = .45$, without an interaction, $F(1, 35) = 0.07$, $p = .79$, $\eta_p^2 = .002$. For *block*, the illusion-induced bias was higher in the post-inquiry block than in the pre-inquiry block regardless of the color of the discs in the background. For *color relevance*, the illusion-induced bias was higher in the *task-relevant color* condition than in the *task-irrelevant color* condition, regardless of whether or not the participant was aware of the railway-shaped pattern in the background.

For the unconditional illusion-induced biases, consistent results were observed: The unconditional illusion-induced biases in the *task-relevant color* and *task-irrelevant color* conditions were 60% (*SE* = 2.13%) and 54% (*SE* = 2.16%) in the pre-inquiry block and 69% (*SE* = 2.18%) and 63% (*SE* = 2.85%) in the post-inquiry block. There were significant main effects of *block,* $F(1, 35) = 20.28$, $p < .001$, $\eta_p^2 = .37$) and *color relevance,* $F(1, 35) = 8.00$, $p = .008$, $\eta_p^2 = .19$, but no significant interaction between the two, $F(1, 35) = .003$, $p = .96$, $\eta_p^2 < .001$. Both conditional and unconditional measurements yield consistent analysis results. To avoid lengthy data description, all of the following discussions are based on the conditional measurement of data analysis unless otherwise stated.

The aim of this study was to examine the effect of attention on undetected perceptual grouping. Therefore, the critical comparison was the illusion-induced bias between the *task-relevant color* and *task-irrelevant color* conditions in the pre-inquiry block, which were 58% and 52%, with the difference reaching statistical significance, $t(35) = 2.30$, $p = .03$, Cohen's $d = 0.39$. A similar pattern was observed in the post-inquiry block, where the illusion-induced bias was 70% in the task-relevant color condition and 64% in the task-irrelevant color condition, with the difference reaching statistical significance, $t(35) = 2.14$, $p = .04$, Cohen's $d = 0.36$, as well.

If one assumes that the participant no longer needed to actively attend to a particular color after the target appeared, one should expect that serial target position would have had an influence on the effect of attention on grouping. In other words, a later serial target position should predict a higher illusion-induced bias in the *task-relevant color* condition. To test this, the correlation coefficient between the serial target position and the illusion-induced bias in each condition for each participant was calculated, and then these coefficients were subjected to *t*-test analyses to examine whether they were significantly different than zero. In order to include a large number of trials, this analysis was based on the unconditional measurement, where all the trials were included, regardless of the performance on the color-detection task. The correlation coefficients in the *task-relevant color* condition and *task-irrelevant color* condition were −.07, $t(35) = 1.28$, $p = 0.21$, Cohen's $d = -0.22$, and .03, $t(35) = 0.45$, $p = 0.66$, Cohen's $d = 0.08$, in the pre-inquiry block, and −.01, $t(35) = 0.16$, $p = 0.88$, Cohen's $d = -0.03$, and −.03, $t(35) = 0.38$, $p = 0.71$, Cohen's $d = -0.06$, in the post-inquiry block. None of the values were significantly different than zero. A possible explanation for the lack of correlation is that attention could not disengage from the attended color within the time window of 500 ms. Even for trials in which the target was presented at the first serial position, attention on the designated color might have persisted until the last letter was presented.

Color-detection task and other perceptual indices For the color-detection task, the average accuracy across the pre-inquiry block and the post-inquiry block was 76% for the illusion trials and 77% for the control trials. The accuracy of reporting the background *V* as inverted or upright was 39%, 75%, and 100%, respectively, in the first inquiry, second inquiry, and third inquiry trials, and the corresponding confidence rating results were 1.17, 1.89, and 2.94 (out of 3).

Discussion

In this experiment, an attentional modulation effect on perceptual grouping was demonstrated: Perceptual grouping based on the attended color biased the line-length judgment more than perceptual grouping based on an unattended color. More importantly, the grouping modulation effect did not require awareness as attentional effects were observed both in the pre-inquiry block and in the post-inquiry block.

Experiment 2

In Experiment 1, it had been shown that the attentional modulation effect did not require awareness. However, if attention and awareness were only minimally involved—as in the case of the task-irrelevant color condition in the pre-inquiry block—the illusion-induced bias was 52%, which was not significantly higher than the chance level of 50%, $t(35) = 0.88$, $p = .39$, Cohen's $d = 0.15$. One possible reason for the insignificance of the illusion-induced bias is that perceptual grouping requires either attention or awareness. Alternatively, perceptual grouping could occur with neither attention nor awareness, but the presentation time in Experiment 1 was simply too short; this is based on Lo and Yeh's (2008) finding that processes without awareness can be time dependent.

In this experiment, the presentation time was increased in order to examine whether the effect of perceptual grouping could emerge even when attention and awareness were minimally involved.

Method

Participants Forty participants, ages approximately 20–30 years, were recruited (19 were males). All reported having normal or corrected-to-normal vision. None of the participants were aware of the purpose of this experiment.

Stimuli and procedure The stimuli and procedure were identical to those in Experiment 1, except for the exposure duration of the target display, which was adjusted to 800 ms. For the central RSVP stream, each trial comprised eight letters, with each letter presented for 100 ms.

Results

Seven observers reported seeing the railway-shaped pattern prior to the inquiry block, and thus, their data were excluded from further analyses.

Line-length judgment In the cases of the 33 participants (14 males) who were not aware of the railway-shaped pattern in the pre-inquiry block, their line-length judgment performances for the control trials (the two horizontal bars were indeed different in length) were all significantly higher than the chance level, according to z tests for individual participants (ps < .05). The mean accuracy of their line-length judgment performances for the control trials was 86%.

In this experiment, the illusion-induced bias in the task-irrelevant color condition in the pre-inquiry block was 64% (conditional measurement), which was significantly higher than the chance level of 50%, $t(32) = 5.95$, $p < .001$, Cohen's $d = 1.05$. In the condition where only minimal attention and awareness were involved, the railway-shaped pattern in the background nevertheless significantly biased line-length judgment performance.

The illusion-induced biases in all conditions were subjected to a repeated-measures ANOVA. For the conditional illusion-induced biases (see Fig. 4), which were based on 82% of trials with correct color-detection responses, the mean illusion-induced biases in the task-relevant color condition and the task-irrelevant color condition were 65% (SE = 2.69%) and 64% (SE = 2.32%) in the pre-inquiry block, and 72% (SE = 2.89%) and 74% (SE = 2.79%) in the post-inquiry block. There was a significant effect of *block,* $F(1, 32) = 10.04$, $p = .003$, $\eta_p^2 = .24$, but no significant effect of *color relevance,* $F(1, 32) = 0.11$, $p = .75$, $\eta_p^2 = .003$, or interaction of the two, $F(1, 32) = 0.59$, $p = .45$, $\eta_p = .02$. For the unconditional illusion-induced biases, the result pattern was consistent: The mean illusion-induced biases in the task-relevant color condition and the task-irrelevant color condition were 64% (SE = 2.20%) and 62% (SE = 2.44%) in the pre-inquiry block, and 72% (SE = 2.61%) and 73% (SE = 2.70%) in the post-inquiry block. There was a significant effect of *block,* $F(1, 32) = 17.03$, $p < .001$, $\eta_p^2 = .35$, but there was no significant effect of *color relevance,* $F(1, 32) = 0.15$, $p = .71$, $\eta_p = .005$, or interaction of the two, $F(1, 32) = 0.77$, $p = .39$, $\eta_p^2 = .02$. All the following descriptions of illusion-induced biases were based on the conditional measurement only.

Color-detection task and other perceptual indices For the color-detection task, the average accuracy across the pre-inquiry block and the post-inquiry block was 82% for the illusion trials and 84% for the control trials. The accuracy of reporting the background V as being inverted or upright was 55%, 88%, and 100%, respectively, in the first inquiry, second inquiry, and third inquiry trials, and the corresponding confidence rating results were 1.15, 2.30, and 2.94 (out of 3).

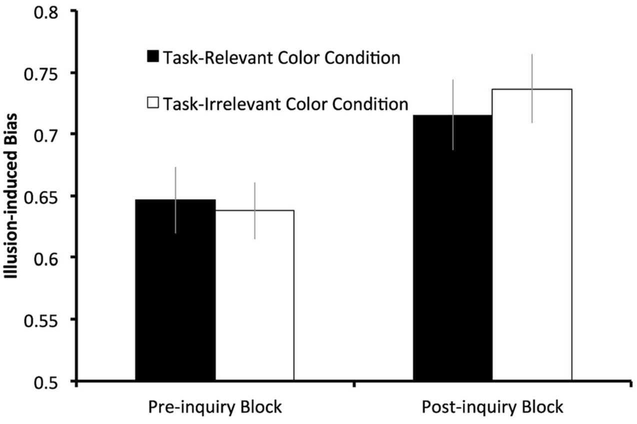

Fig. 4 Illusion-induced bias, defined by the percentage of reports of the line-length judgment task in accordance with the Ponzo illusion, in different conditions in Experiment 2. This figure is based on the conditional measurement, where only the trials with correct color-detection performance were included. The error bar indicates one standard error

Cross-experimental analysis To examine the effect of processing time (500 ms vs. 800 ms), the data of the two experiments were collapsed (the conditional measurement only) and subjected to an ANOVA, with *presentation time* as a between-subject factor. The analysis revealed an interaction between *presentation time* and *color relevance*, $F(1, 67) = 6.28$, $p = .01$, $\eta_p^2 = .09$, consistent with the finding that the attentional effect was significant only in Experiment 1 (500 ms) but not the present experiment (800 ms). For awareness, there was no significant interaction between *presentation time* and *block*, $F(1, 67) = 1.01$, $p = .32$, $\eta_p^2 = .01$, suggesting a constant effect of awareness across different processing times.

The effect of presentation time was particularly important for the task-irrelevant color condition, where the illusion-induced bias increased from 52% in Experiment 1 (500 ms) to 64% in Experiment 2 (800 ms) in the pre-inquiry block, $F(1, 67) = 15.63$, $p < .001$, $\eta_p^2 = .19$, and increased from 64% in Experiment 1 (500 ms) to 74% in Experiment 2 (800 ms) in the post-inquiry block, $F(1, 67) = 5.82$, $p = .02$, $\eta_p^2 = .08$. For the task-relevant color condition, the increase of processing time did not exert any significant effect as the illusion-induced biases in Experiments 1 and 2 were 58% and 65% in the pre-inquiry block, $F(1, 67) = 2.47$, $p = .12$, $\eta_p^2 = .04$, and 70% and 72% in the post-inquiry block, $F(1, 67) = 0.25$, $p = .62$, $\eta_p^2 = .004$. Thus, the reduction of the attentional effect by the increased presentation time was mainly caused by the increased illusion-induced bias in the task-irrelevant color condition rather than by decreased bias in the task-relevant color condition.

Discussion

In the condition where minimal attention and awareness were involved, the railway-shaped pattern significantly biased the observers' line-length judgment. Therefore, perceptual grouping can occur with minimal attention and awareness as long as sufficient time is provided. However, the illusion-induced bias in the task-relevant color condition did not increase accordingly, resulting in a reduction of the attentional effect.

General discussion

In the literature, attention has been shown to be a modulatory factor (e.g., Ben-Av et al., 1992; Han, Jiang, Mao, Humphreys, & Gu, 2005; Han, Jiang, Mao, Humphreys, & Qin, 2005; Zaretskaya et al., 2013) or a necessary factor (Mack & Rock, 1998; Mack et al., 1992; Rock et al., 1992) for perceptual grouping. However, the view of attention as a necessary factor for perceptual grouping has been challenged by recent studies that demonstrate perceptual grouping without attention with implicit measurements (e.g., Conci et al., 2009; Mattingley et al., 1997; Moore & Egeth, 1997; Russell & Driver, 2005). Following the same rationale, the attentional modulation effects on perceptual grouping shown in previous studies may only be applicable to grouping with awareness. However, the present study argues against this, indicating that attention modulates perceptual grouping even without awareness of the grouping pattern.

The function of attention

A curious finding in the present study was the reduction of attentional effect as the presentation time increased. This was caused by the increased illusion-induced bias when the grouping was based on an unattended color. For grouping based on the attended color, increasing processing time did not significantly increase the illusion-induced bias. Possibly, grouping with attention had reached asymptote with the 500-ms presentation time, but grouping without attention had not; thus, an increase of presentation time could only raise the grouping effect in the latter case but not the former one. In other words, attention accelerates the grouping process. With attention, the effect of grouping can reach asymptote earlier.

The function of awareness

If attention accelerates the grouping process so the illusion-induced bias reached asymptote earlier, the asymptote value was set by the state of awareness. Without awareness, the grouping pattern could only bias the line-length judgment task to a very limited extend. In the case of the pre-inquiry block in the present study, the maximum biasing effect (which occurred with an 800-ms presentation time) was 65%. In the post-inquiry block, where awareness was involved, the maximum biasing effect increased to 74%.

Why did the grouping pattern bias the line-length judgment performance more with awareness than without awareness? The data of the present study cannot answer this question directly. One speculation is provided as follows. The visual information processing can be viewed as a combination of two streams (Lo & Yeh, 2011): The *awareness* stream processes stimuli of which the observer is aware, and the *unawareness* stream processes other stimuli. In the pre-inquiry block, the fact that the railway-shaped pattern and the two target bars were processed in different streams limited the interactions, and thus, the maximum effect that the unaware background pattern could exert on the aware target bars was low. In the post-inquiry block, both the railway-shaped pattern and the two targets were processed in the awareness stream, which facilitated their interactions, so the maximum effect that the background pattern could exert on the target bars was high. In both the pre-inquiry block and the post-inquiry block, attention could accelerate the grouping process so that the illusion-induced bias could reach the maximum value sooner.

Grouping and attention

Does grouping require attention? The results of present study suggest that it does not, as is made evident by the above-chance illusion-induced bias observed in the condition where minimal attention and awareness were involved. However, attention could nevertheless modulate perceptual grouping by accelerating the grouping process.

One series of studies argued that perceptual grouping includes multiple types of distinct processes, some of which require little or no attention while some require more (Kimchi & Razpurker-Apfeld, 2004; Razpurker-Apfeld & Pratt, 2008; Trick & Enns, 1997). Kimchi and Razpurker-Apfeld (2004), for example, demonstrated that grouping involving clustering elements with the same feature required little attention. In contrast, the process whereby the grouping pattern is represented as a holistic figure that is segregated from the background required attention. The present study provides an alternative view for this. The crucial difference between different types of grouping may not be their different demands of attention but different processing times. The railway-shaped pattern in this study was formed by elements integrated into a holistic figure that was segregated from the white discs, so it should be an attention-demanding process, according to Kimchi and Razpurker-Apfeld's (2004) study. However, when a longer time was provided, the grouping process involving the formation of the railway-shaped pattern could also be complete with minimal awareness and attention, as demonstrated in Experiment 2.

The results of the present study can be interpreted with the theoretical framework proposed by Roelfsema and his colleagues (Roelfsema, 2006; Roelfsema, Lamme, & Spekreijse, 2000): Perceptual grouping can be mediated by feedforward connections from low visual cortical areas to high visual cortical areas; this is called *base grouping*. Neurons in the low visual areas have their preferred locations and features. When they send inputs to high visual areas, the high visual areas integrate the information to form a more complex representation. In the case of the present study, the grouping in the task-irrelevant color condition in the pre-inquiry block might be mediated via this type of *base grouping*. This process does not require awareness, as suggested by Lamme (2003) that processing mediated by feedforward neural connections is not accompanied by awareness. In addition to feedforward connections, representations of high visual areas, attention, or awareness trigger recurrent connections (horizontal and feedback connections) that might serve to modulate perceptual grouping, which can account for how attention and awareness facilitated perceptual grouping.

Dissociation between awareness and attention

In the present study, attention was manipulated by means of instructing the observers to prioritize one color over others via the color-detection task. Awareness, on the other hand, is defined by the observer's ability to report the presence of a certain stimulus. As more and more researchers devote themselves to the scientific study of consciousness, miscellaneous paradigms to render stimuli invisible have been developed (for a review, see Kim & Blake, 2005). In these methods, the index of awareness or consciousness was also based on the observer's subjective reports. In recent years, a technique known as the *continuous flashing stimulation* (CFS) paradigm (Jiang, Costello, Fang, Huang, & He, 2006; Kanai, Tsuchiya, & Verstraten, 2006; Tsuchiya & Koch, 2005; van Boxtel, Tsuchiya, & Koch, 2010) has been used intensively. In CFS, the critical stimulus is projected to one eye, and a series of high-contrast masks is projected to the other. Due to the suppression from the high-contrast masks, the critical stimulus can be rendered invisible. If the critical stimulus still affects the observer's performance on another task, one can infer that this effect occurs without awareness. In this method, whether a given stimulus is invisible or not depends on the observer's subjective report. One might argue that the observer might not report what he or she really perceives, so the subjective report may not be a good index of awareness. Nonetheless, it is still very commonly used.

Awareness and attention have long been considered as inseparable psychological processes (Posner, 1994). One reason for this is that one possible consequence of being deprioritized, or unattended, is a lack of awareness (Mack et al., 1992; Rock et al., 1992). However, the view of inseparability between attention and awareness has been challenged recently (e.g., Lamme, 2003). Empirical evidence for the dissociative effects of attention and awareness has been demonstrated in low-level visual effects, such as the tilt aftereffect (Kanai et al., 2006), color afterimages (van Boxtel, Tsuchiya, & Koch, 2010), luminance afterimages (Brascamp, van Boxtel, Knapen, & Blake, 2010), and shape identification for localized stimuli (Schmidt & Schmidt, 2010; Tapia, Breitmeyer, Jacob, & Broyles, 2013). These effects generally involved early visual processing stages. Possibly, the effects of attention and awareness are independent in early visual processing stages but are correlated in more advanced processing stages, as suggested by Brascamp et al. (2010). However, this present study provides evidence for the notion that attention and awareness can be dissociated up to the level of perceptual grouping.

Limitations of the present study

Perceptual grouping may include multiple distinct processes that occur at various levels in the visual system (Palmer, Brooks, & Nelson, 2003; Yu & Franconeri, 2015). The design of this study is based on the grouping principle of color similarity, so the underlying mechanisms inferred from the results of the present study are presumably only applicable for grouping by color similarity. What could be observed if a different type of grouping was used? This is an empirical issue. A reasonable conjecture is that different time courses might be observed. In the present study, perceptual grouping by color similarity reached its maximum effect at 500 ms with attention and at 800 ms without attention. Had a different type of grouping been used, a different pair of presentation times might have been needed to demonstrate the dynamics of attention and perceptual grouping.

One should also note that the attentional effect observed in this study resulted from a particular type of attention. As stated earlier, attention is a selective mechanism that prioritizes some stimuli over others. This prioritization effect can be applied to a particular region in the visual field, namely, space-based attention (Eriksen & Yeh, 1985; Posner, Snyder, & Davidson, 1980), or to a group of stimuli that share a common feature, namely, feature-based attention (Bichot, Rossi, & Desimone, 2005; Lo & Holcombe, 2014; Lo, Howard, & Holcombe, 2012; Martinez-Trujillo & Treue, 2004; Sàenz, Buracas, & Boynton, 2003; Treue & Martinez-Trujillo, 1999). The present study focuses only on feature-based attention, as attention was manipulated by instructing observers to prioritize a certain feature. Therefore, one could argue that the finding might not be applicable for space-based attention. This could be an empirical issue worthy of future investigation.

Conclusion

The relationship between perceptual grouping and attention has long been a hotly debated topic. Attention has been shown to be a modulatory factor in some studies and a necessary factor in others. However, that attention is a necessary condition has been challenged by recent studies that investigated perceptual grouping without awareness. To clarify the relationship between attention and perceptual grouping, this study aimed to test whether attention can modulate perceptual grouping without awareness, and positive results were manifested. Furthermore, the attentional modulation effect was dynamic, being significant with a shorter presentation time but not a longer one. A possible mechanism has been provided: The state of awareness sets a maximum level of how perceptual grouping affects the observer's task at hand and attention accelerates the grouping process.

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