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Subliminal attentional modulation in crowding condition

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Abstract

In the crowding phenomenon, recognition of a visual target is impaired by other similar visual stimuli (distracters) presented near the target. This effect may be due largely to insufficient resolution of spatial attention. We showed that attention could subliminally enhance orientation selective adaptation to illusory lines in the crowding condition where target-distractor separation is beyond the limit of spatial resolution of attention. Despite the traditionally held close link between attention and awareness, here we provided evidence for subliminal attentional modulation for orientation stimuli that could not have been consciously perceived.

Keywords: Subliminal attentional modulation; Crowding; Adaptation; Illusory line; Awareness

1. Introduction

Identification of a target stimulus in the peripheral visual field is impaired when flanked by other similar stimuli (visual distractors) presented in its close proximity. This phenomenon is called 'crowding' (Toet & Levi, 1992; Wilkinson, Wilson, & Ellemberg, 1997). The crowding effect persists even if the observer knows which stimulus the target is and task performance drops to chance level under severely crowded conditions despite unlimited exposure time.

Conventionally, the reduced sensitivity to targets embedded in a field of similar items is termed 'lateral masking' and is often attributed to lateral inhibition between neighboring neurons at early stages of visual processing (Chastain, 1983). Some researchers have tried to interpret the crowding effect in terms of ordinary lateral masking (Mansfield, Legge, & Ortiz, 1998; Townsend, Taylor, & Brown, 1971; Wolford & Chambers, 1984). According to this theory, visual information of the crowded target is blocked in the early sensory level by flanking distractors.

Recently, evidence has been provided showing that crowding is not an example of ordinary lateral masking. Contrary to the assumption that ordinary masking should lead to signal disappearance by blocking feature detection, it has been shown that 'feature integration' does occur in crowding conditions. These studies argue that crowded features are detected and integrated over an inappropriately large area in the peripheral visual field, thus rendering the sensory signal ambiguous (Levi, Hariharan, & Klein, 2002; Pelli, Palomares, & Majaj, 2004).

In line with the idea that crowding is not a simple consequence of lateral masking, He, Cavanagh, and Intriligator (1997) suggested that crowding effect may be due to insufficient 'spatial attentional resolution'. He, Cavanagh, and Intriligator (1996) studied orientation selective adaptation in the crowding condition

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and showed that crowding is a high-level phenomenon occurring at the level of attentional selection rather than at early sensory levels. In their experiments they asked human observers to report the orientation of a single grating in the periphery of their visual field flanked by other similar gratings. In such a crowding condition the observers were no longer aware of the orientation of the target stimulus. However, orientation selective adaptation (a V1 phenomenon) was not affected by the presence of flankers. They suggested that crowding happens in higher visual cortical areas and restricts the availability of visual information to explicit conscious perception. That local processing is unimpaired by crowding although local signals cannot reach consciousness could be explained by the theory of 'obligatory pooling' (Parkes, Lund, Angelucci, Solomon, & Morgan, 2001). This theory asserts that the signal arising from the peripherally presented target is pooled with those arising from the distractors before reaching awareness.

In our previous studies, we addressed the question whether attributes of visual stimuli other than first-order orientation (grating) can be processed in the crowding condition. We showed that crowding does not impair orientation selective adaptation to illusory lines (Rajimehr, Montaser-Kouhsari, & Afraz, 2003) and adaptation to the apparent motion (Rajimehr, Vaziri-Pashkam, Afraz, & Esteky, 2004). These works provide further evidence for the idea that crowding is a high-level phenomenon occurring later than the preliminary stages of cortical processing involved in the detection of illusory contours and apparent motion.

He et al. (1996, 1997) proposed that crowding occurs at cortical levels involved in attentional selection. They argue that the smallest region of the visual field that could be isolated by attention is much coarser than the smallest details resolvable by vision. Therefore, multiple similar objects spaced more finely than the limit of attentional resolution cannot be individuated by attention for further processing. However, attention may 'subliminally' enhance the processing of visual information of the crowded item when the target-distractor separation is beyond the spatial resolution limit of attention.

The effects of attentional modulation have been shown in various sensory levels (e.g. Motter, 1993). Thus, adaptation is expected to depend on attention at some sensory levels. For example, attention has modulatory effects on the motion aftereffect (Chaudhuri, 1990; Lankheet & Verstraten, 1995; Rees, Frith, & Lavie, 1997), figural aftereffect (Shulman, 1992; Suzuki, 2001; Yeh, Chen, DeValois, & DeValois, 1996), stereoscopic depth aftereffect (Rose, Bradshaw, & Hibbard, 2003) and tilt aftereffect (Spivey & Spirn, 2000). It has been also shown that adaptation to illusory lines is attenuated in conditions of 'inattention' (either when spatial or object-based attention is drawn away from adapting stimuli) (Montaser-Kouhsari & Rajimehr, 2004), though adaptation to illusory lines does occur in the crowding condition (Rajimehr et al., 2003). Thus, it is conceivable that subliminal attentional modulation may take place selectively for crowded illusory lines. In this work, we demonstrated direct evidence for subliminal attentional modulation in the crowding condition by measuring orientation selective adaptation to crowded illusory lines when subjects performed a foveal attentive task during the adaptation period. We expected weaker adaptation when attention was drawn away from the crowding display. Our hypothesis was confirmed by the analysis of data.

2. Methods

Four subjects, three males and one female, aged between 19–28 years, participated voluntarily in the experiment. All subjects were trained psychophysical observers with normal or corrected-to-normal vision. All were naive to the purpose of the experiment.

The stimuli were programmed in Delphi V.6, on a Pentium III 800 MHz PC. Images were displayed on a RGB color monitor, 800 H × 600 V pixel resolution, 85 Hz frame rate (795FT Plus, LG: Korea). Subjects were placed in a dark room with their heads fixed on a chin and forehead rest and viewed the displays binocularly. The distance between eyes and the monitor screen was 50 cm. Each subject completed 4 blocks, composed of 50 trials each. Data was analyzed using SPSS V.11.

We used the paradigm introduced by Rajimehr et al. (2003) to study the orientation selective adaptation to illusory lines. Fig. 1 demonstrates the temporal succession of visual stimuli in a typical trial. Each trial began with the presentation of a fixation point (red dot) for 800 ms followed by four seconds of adapting stimulus presentation (adaptation phase) immediately succeeded by the test stimulus presentation for 580 m (test phase; fixation point: green). The trial ended with a two-second period of blank screen as inter-trial interval.

Adapting and test stimuli were illusory contours. Each illusory contour was constructed by two line gratings (both oriented either 45° or 135°) abutting each other with a phase shift ('abutting gratings'). In each grating patch, there was a vertical or horizontal illusory border between the two sets of gratings. Each patch subtended 2.86° of visual angle and had 4 real lines with 0° of tilt angle (i.e., angle between two line gratings) and 0° of lateral alignment (i.e., the lateral misalignment between two line gratings). Line spacing (distance between two lines in each grating) was 0.45° and line width was 0.11°.

In the adaptation phase of the crowding condition the adapting target patch was presented along with three flanking distracter patches: one located above and the

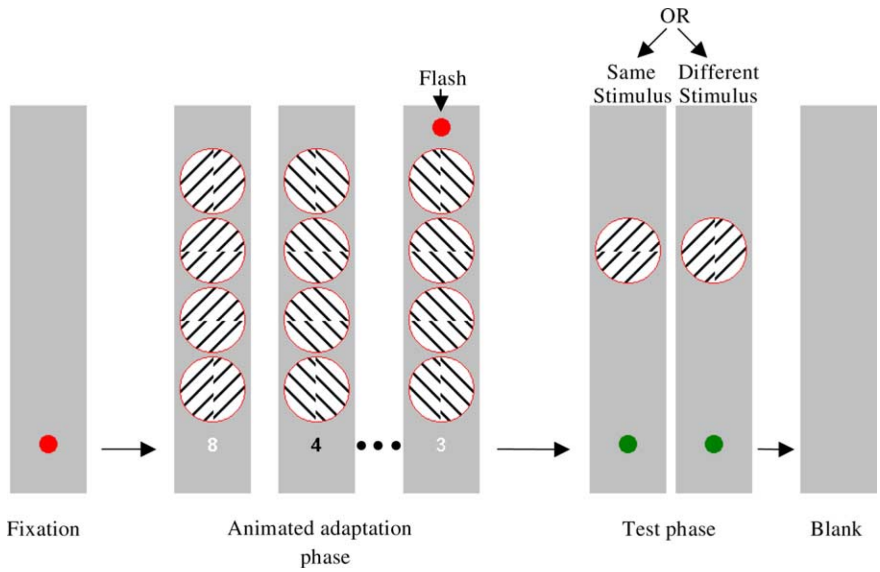

Fig. 1. Schematic diagram demonstrating the temporal succession of visual stimuli in a typical trial. Each trial consisted of three phases: fixation phase, animated adaptation phase and test phase. Blank screen was presented during inter-trial interval for 2 s. Adapting and test stimuli were abutting gratings presented above the fixation point. In the adaptation phase, the adapting target patch was embedded among three flanking distractors; one located above and the other two located below the target. Durations of adaptation and test phases were 4 s and 580 ms, respectively. The fixation point was a small red dot during the adaptation phase that turned to green in the test phase. Digit stimuli were presented at the fixation point. A flash stimulus was presented at the top of crowding display, 500 ms before the end of the adaptation period. The orientation of test illusory line was either the same or different from that of adapting illusory line. (For interpretation of the references in color in this figure legend, the reader is referred to the web version of this article.)

other two located below the target (see Fig. 1). The eccentricity of the target patch was 8.5° above the fixation point. Center-to-center distance between two adjacent patches in the radial array was 3°.

Since we intended to study the 'pure' adaptation to 'illusory' lines, orientation specific adaptation of the 'real' grating lines should have been avoided as well as retinal adaptation. To rule out the effects of lower level adaptations, an animated stimulus display was used in the adaptation phase. In this animation, the orientation of real lines inside the adapting target and distractor patches changed to orthogonal orientation repeatedly (seven times in every four seconds of the adaptation phase) while the orientation of illusory lines remained the same (see Fig. 1). As a result, there was no adaptation to real lines while our stimuli could still induce the perception of illusory lines with constant orientations during the four seconds of adaptation phase. The orientations of illusory lines in target and distractor patches were constant within each trial and were randomized across trials.

The test stimulus was presented after the animated adaptation phase at the same location as the adapting target (see Fig. 1). The orientation of the test illusory line was either the same or different from that of the illusory line in the adapting target.

Observers were asked to fixate on the fixation point, maintain their fixation through the trial and report the orientation of the illusory line in the test patch at the end of each trial by pressing one of the two alternative keys on the keyboard.

Based on subject's task in the adaptation period, the experiment consisted of two attentional conditions. In 'full attention' condition no stimulus was presented at the fixation point and subjects were instructed to covertly attend to the location of adapting target stimulus throughout the adaptation phase although they could not precisely individuate it. In 'poor attention' condition a stream of randomly chosen black or white digits appeared at the fixation point (frequency = 2 Hz). Numbers were chosen from 2 to 9 and subtended about $0.22 \times 0.57°$. The color of digits was either black or white. Subjects were asked to make odd–even judgments for each 'black' digit presented in the stream by pressing one of the two alternative keys on the computer keyboard. Trials where the average performance (percent correct) of the digit task was below 75% were excluded in the analysis of data. At 500 ms before the end of the adaptation period, a flash stimulus was presented at the top of the crowding display. This flash enabled subjects to easily disengage their attention from the fixation point and get ready for orientation discrimination of the test illusory line. A 'text cue' was presented at the beginning of each trial that determined the attentional condition to be presented.

We had to ensure that in the crowding condition, the orientation of the illusory line in the target patch was completely crowded (i.e. subjects were at chance level). Therefore, in a control experiment, the magnitude of crowding for illusory lines of the target patch was measured. Stimuli, crowding condition and the experimental procedure were exactly identical to those in the previous experiment, but no digits were presented at the fixation point and the test stimulus was not displayed. Subjects were asked to report the orientation of the illusory line in the target patch at the end of each trial. To ensure severe crowding (unresolvable by extended duration of stimulus presentation), subjects were allowed to view the crowded stimuli for four seconds.

3. Results

Two adaptation conditions were defined: 'same adapt-test' where adapting and test illusory lines had the same orientations and 'different adapt-test'. We measured the effects of adaptation condition and attentional condition ('full attention' or 'poor attention') on the performance of illusory line-orientation discrimination in the test phase. Using a two way ANOVA, the pure effect of adaptation was significant ($F(1,3) = 25.48$, $P < 0.01$). However, the pure effect of attention was not significant ($F(1,3) = 0.27$, $P > 0.05$). This result shows that the overall performance (average percent correct of 'same adapt-test' and 'different adapt-test') is statistically equal for the 'full attention' (74.97%) and the 'poor attention' (76.58%) conditions.

The interaction between attentional and adaptation conditions was significant ($F(1,3) = 13.36$, $P < 0.01$). Post Hoc analysis (Scheffe' test) revealed that the percent correct of 'different adapt-test' (orthogonal orientation) was significantly higher than 'same adapt-test' (same orientation) in the 'full attention' condition ($P < 0.01$). This finding demonstrates a robust orientation selective adaptation to the illusory line in the 'full attention' condition (Fig. 2). Whereas, difference between percent corrects of 'different adapt-test' and 'same adapt-test' was not significant in the 'poor attention' condition ($P > 0.05$) indicating that orientation selective adaptation to the illusory line is almost absent in the 'poor attention' condition (see Fig. 2).

The results of the control experiment demonstrated that our stimulus arrangement was capable of producing a robust crowding effect. Performance of subjects in discriminating the orientation of target illusory lines dropped to chance level in the crowding condition (Fig. 3). There was no significant difference between percentage of correct responses and chance level (50% correct) for each subject (P value > 0.05 using χ^2 test, $d' = 0.178$, Criterion = 0.139).

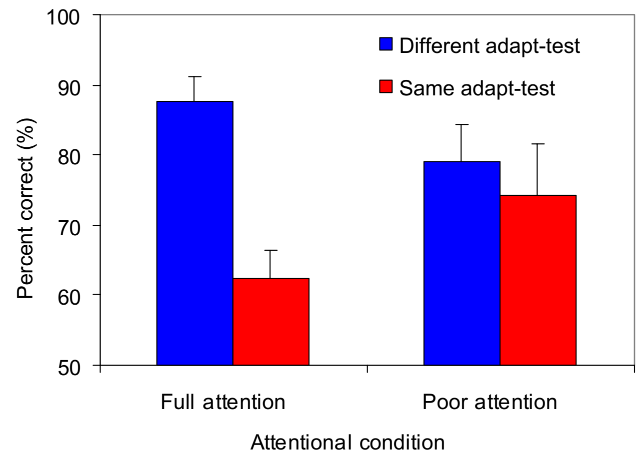

Fig. 2. There were two adaptation conditions: 'same adapt-test' where adapting and test illusory lines had the same orientations and 'different adapt-test'. Percent correct of 'different adapt-test' was significantly more than 'same adapt-test' in 'full attention' condition. Difference between percent corrects of 'different adapt-test' and 'same adapt-test' was not significant in 'poor attention' condition. Error bars represent one standard error of mean.

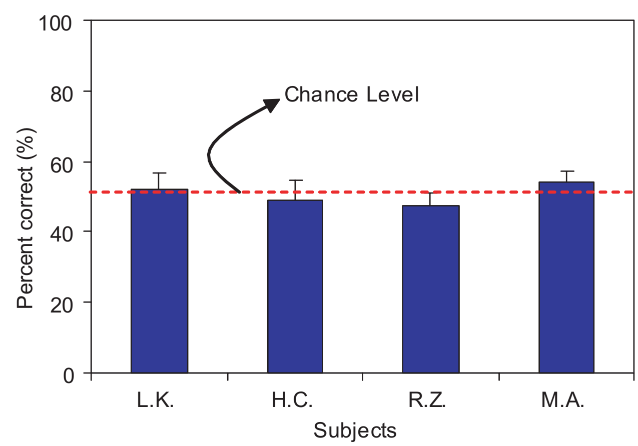

Fig. 3. In the control experiment, performance of each subject in discriminating the orientation of target illusory lines dropped to chance level in the crowding condition. Error bars represent one standard error of mean.

4. Discussion

The results clearly demonstrated that orientation selective adaptation to illusory lines in the crowding condition was enhanced when visual spatial attention was directed to the location of the adapting target stimulus. A control experiment showed that the performance of subjects in discriminating the orientation of target illusory lines embedded among flanking distractors dropped to chance level even when the crowding display was presented for four seconds (duration equal to adaptation phase in the main experiment); therefore, the adapting target stimulus in the main experiment could not have been individuated by attention. It seems likely that attention subliminally modulates and enhances adaptation to illusory lines even if we cannot select the crowded item attentively for further processing and have no conscious perception of it.

We restricted our analysis to trials where the performance of odd–even judgment task at the fixation point was above 75% correct. We used this criterion to make sure that subjects had adequately engaged their attention in the fixation point in the 'poor attention' condition.

In 'poor attention' condition, an additional task with high attentional demands was performed at the fixation point. At the end of adaptation phase, subjects were instructed to shift their attention toward the location of test stimulus and report the orientation of the test illusory line, which was presented only for 580 ms. Since there was no delay between adaptation and test phases, subjects might not have had enough time for task switching and shift of attention toward the test stimulus location. A pilot study confirmed this speculation by showing that overall performance was significantly enhanced when a brief flash was added above the stimulus array immediately before the test phase enabling the subjects to disengage their attention from the foveal task and shift towards the test stimulus location. Thus, addition of the flash ruled out the potential explanation of the lack of adaptation (i.e., no statistical difference between percent corrects for 'different adapt-test' and 'same adapt-test') due to slower shifting of attention in 'poor attention' condition. Further analysis showed that both attentional conditions had similar overall performance confirming that the flash stimulus presented before the end of adaptation phase was effective in disengagement of attention from the fixation point.

Two factors are responsible for attentional enhancement of adaptation to illusory line orientation. Discrimination of test illusory line orientation improved when adapting target and test illusory lines were orthogonal and declined when orientations of adapting target and test illusory lines were the same. Impaired performance in the 'same adapt-test' trials could be explained by classical theories of adaptation. If we assume that there are neurons or neuronal populations responding to illusory lines presented at their preferred orientation, the adaptation to illusory lines could be due to repeated firing of these neurons when the stimulus (illusory contour) is presented for a long exposure time. Continuous neural firing decreases the orientation sensitivity maximally at the adapting orientation (i.e. for 'same adapt-test' stimuli). As a possible theory for attentional modulation, the firing of neurons at the attended location is increased by attention (Treue, 2001). Continuous firing of neurons at higher rates accelerates the process of neuronal fatigue and leads to a stronger effect of adaptation (i.e., steeper decline in the percent correct of 'same adapt-test' in 'full attention' condition). Enhanced orientation discrimination for 'different adapt-test' could by explained by sharpening neuronal orientation selectivity after adaptation to orthogonal orientation (Dragoi, Sharma, Miller, & Sur, 2002) and attention may accentuate this sharpening of neuronal selectivity (Spitzer, Desimone, & Moran, 1988; Lee, Itti, Koch, & Braun, 1999; Murray & Wojciulik, 2004). However, there is some evidence indicating that attention does not affect orientation tuning functions (McAdams & Maunsell, 1999; Treue & Martinez Trujillo, 1999).

Classically V2 area is considered as the first stage in the processing of illusory contours (Peterhans & von der Heydt, 1982; von der Heydt, Peterhans, & Baumgartner, 1984). However, some works suggest that illusory contours could be coded by cells in V1 (Grosof, Shapley, & Hawken, 1993; Sheth, Sharma, Rao, & Sur, 1996). We excluded the possibility of adaptation to illusory lines in visual areas lower than V1 using 'animated adaptation paradigm'. Therefore, subliminal attentional modulation of orientation selective adaptation to illusory lines may occur in V1 and V2 areas. There is ample evidence showing the effects of attentional modulation in early sensory levels such as V1 (Ito & Gilbert, 1999; Motter, 1993; Roelfsema, Lamme, & Spekreijse, 1998) and V2 (Bender & Youakim, 2001; Luck, Chelazzi, Hillyard, & Desimone, 1997; Motter, 1993; Reynolds, Chelazzi, & Desimone, 1999). There is also an fMRI data indicating increased activation in early visual cortex at the attended location even when no target is presented (Ress, Backus, & Heeger, 2000). Therefore, attention to the target's location might increase the low-level response to the target (and subsequently its adaptation) even though it does not lead to a selection of the target sufficient for its identification. Consistent with this fMRI data, our experiment provides a psychophysical evidence for attentional modulation in the absence of awareness.

Traditionally, attention and consciousness have been closely linked (O'Regan & Noe, 2001; Posner, 1994). However, our results demonstrated the attentional modulation of the target, independently of whether that led to awareness of the target. We suggest that, in certain circumstances, attentional modulation occurs selectively for a visual stimulus (or attributes of stimulus) while subjects have no explicit conscious perception of that stimulus. Further investigations are needed to explore the mechanisms of subliminal attentional modulation.

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