Awareness is the key to attraction: Dissociating the tilt illusions via conscious perception

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The tilt illusion is a compelling example of contextual influence exerted by an oriented surround on a target’s perceived orientation. A vertical target appears to be tilted away from a $15^\circ$ oriented surround but appears to be tilted toward a $75^\circ$ tilted surround. We tested the claim that these biases result from distinct sensory processes: a low-level repulsive process and a higher-level attractive process. If this claim were correct, then surround visibility would be a requirement for attraction, but it would not necessarily be a requirement for repulsion. Indeed, Motoyoshi and Hayakawa (2010) have demonstrated that repulsion can survive removal of the surround from phenomenal awareness using adaptation-induced blindness. Here we sought to test this prediction by measuring the orientation biases in a parafoveally presented Gabor patch surrounded by tilted gratings after 20-s adaptation. The adapting stimulus was an annularly windowed plaid composed of vertical and horizontal jittering gratings. Observers were instructed to maintain fixation throughout the trial and report whether the Gabor appeared to be tilted clockwise or anticlockwise of vertical. They also had to indicate whether the surround was visible after adaptation. Postadaptation biases were then compared with those obtained in a control experiment without dynamic adaptation. We found large repulsive biases induced by $15^\circ$ oriented surrounds, but no attractive biases were induced by $75^\circ$ tilted surrounds. This result shows that attractive effects do require visual awareness and thereby provides robust evidence for the existence of two separate mechanisms mediating the phenomenology of the tilt illusions.

Introduction

The tilt illusion (Figure 1a) is a well-known phenomenon of simultaneous orientation contrast in which the orientation of a line is misperceived when presented within a tilted surround. Gibson and Radner (1937, p. 453) first noticed that a slightly tilted line “appears progressively less tilted during the course of perception,” positing a shift of the “visual reference axes” toward the line’s orientation. A similar explanation is possible for the tilted illusion (Gibson, 1933). In this case, the tilted surround (the inducer) attracts whichever subjective reference axis (either horizontal or vertical) is closest. This normalization will decrease the surround’s apparent tilt, but it may increase the apparent tilt of the target it surrounds. When the surround has a relatively small tilt (e.g., $15^\circ$) away from vertical, a vertical target will appear to have a tilt in the opposite direction. This repulsion is known as the direct effect. When the surround has a relatively large tilt (e.g., $75^\circ$) away from vertical, a vertical target will appear to have a tilt in the same direction. This attraction is known as the indirect effect. However, without ad hoc modification, Gibson’s normalization theory cannot account for the fact that the indirect effect is weaker than its direct counterpart (Figure 1b).

Blakemore, Carpenter, and Georgeson (1970) proposed an alternative explanation of the direct effect based on lateral inhibition between neurons selective for similar orientation. If both this model and Gibson’s were correct, then the direct effect should be larger because it reflects the sum of two processes. The indirect effect reflects only normalization.

Morant and Harris (1965) offered a similar suggestion for the difference in magnitude between direct and indirect versions of the tilt after-effect (Figure 1c). The tilt after-effect and the tilt illusion show many parametric similarities, and it has been debated whether they could be accounted for by a common mechanism.
Rich empirical evidence seems to favor this hypothesis (Magnussen & Kurtenbach, 1979; Sekuler & Littlejohn, 1974; Tolhurst & Thompson, 1975), suggesting that the tilt illusion should be thought of as the result of some sort of fast adaptation. In particular, asynchronous presentations of test and inducer increase the illusions (both direct and indirect effects) when the inducer is visible for a proportionally longer time (Sekuler & Littlejohn, 1974; Harris & Calvert, 1989; Wenderoth, van der Zwan, & Johnstone, 1989; Wolfe, 1984). This is also observed in the tilt after-effect (Wenderoth & Johnstone, 1988) and is consistent with the visual system adapting to the inducing context (Corbett, Handy, & Enns, 2009). Bearing this in mind, we can safely extend Morant and Harris’ idea to the simultaneous domain of tilt illusion.

Evidence consistent with a unique cause of the indirect effect is its relative immunity to contrast manipulations (Wenderoth & Johnstone, 1988). This finding can also be taken as evidence against its mediation by low-level mechanisms, which should be sensitive to contrast.

Another piece of evidence linking the indirect effect to high-level mechanisms is Wenderoth and Johnstone’s report that a square frame surrounding the stimulus abolishes the indirect effect. Because the frame’s contours are relatively far away from the central target grating, its effect seems unlikely to be
mediated by the relatively short-range lateral connections between neurons in the primary visual cortex (Wenderoth & Johnstone, 1987).

The rod-and-frame effect (Asch & Witkin, 1948) offers a suggestive parallel to the functional properties of the tilt illusion. When a vertical rod is presented within a tilted square, its orientation appears distorted systematically in a fashion similar to the tilt illusion (Beh, Wenderoth, & Purcell, 1971): It shows both direct and indirect effects for small (about 15°) and large (about 75°) rod-frame angular distances, respectively (Beh et al., 1971). The interesting aspect of this illusion is that, given the shape of the surround and the distance of its borders from the rod, the misperception cannot be readily accounted for by the interplay of V1 simple cells (Beh et al., 1971; Wenderoth & Beh, 1977; Wenderoth et al., 1989). Hence, the direct effect in the rod-and-frame illusion is likely to lie on mechanisms dealing with more global features than oriented contours. Even more interestingly, the reported direct and indirect effects have about the same magnitude (about 1.3°; Beh et al., 1971) similarly to what posited by Gibson’s normalization (Gibson & Radner, 1937). The existence of an indirect effect also for an illusion mediated by global orientation mechanisms provides indirect support to the idea that the repulsive effect of the tilt illusion may result from the linear combination of high- and low-level components.

A growing body of evidence shows that orientation contextual illusions can occur also when the inducing stimulus is suppressed from awareness (Clifford & Harris, 2005; He & MacLeod, 2001; Pearson & Clifford, 2005). In a recent work, Motoryoshi and Hayakawa (2010) demonstrated that after adaptation to a drifting grating, static gratings often become invisible. They named this effect adaptation-induced blindness (AIB), and they also reported the direct effect’s immunity to a lack of phenomenal awareness. Given the presumed localization of direct and indirect effects at two different levels, we reasoned that the manipulation of visual awareness could be a suitable mean to characterize such a dissociation, the assumption being that mechanisms responsible for the indirect effects involve activity in visual areas at least as high as those mediating conscious vision. We would then expect an angular function similar to that predicted by a lateral inhibition model (Figure 1) with only a repulsive component for the inducer’s orientations close to the vertical. Hence, we measured the tilt illusion after removing the oriented surround stimuli from phenomenal awareness by using the paradigm of adaptation-induced blindness (Figure 2). Postadapta-
tion biases were then compared with those obtained in a control experiment without dynamic adaptation. The results confirm our expectations, showing that only the indirect effect requires visual awareness and thereby provide robust evidence for the existence of two separate mechanisms mediating the phenomenology of the tilt illusions.

Methods

Main experiment

Observers

Four naïve observers took part in the experiment (three women and one man) aged between 27 and 38 years and with corrected-to-normal vision.

Apparatus

Stimuli were presented using Matlab and the Psychtoolbox routines (Brainard, 1997; Pelli, 1997) on a 20-in. calibrated LCD display controlled by an Apple iMac via an ATI Radeon HD 26,000 PRO card (refreshing rate of 60 Hz) having an eight-bit gray-scale resolution. Each pixel subtended approximately 0.02° of visual angle, at a viewing distance of 60 cm. Observations were carried out in a lighted room. Data analysis was conducted using Mathematica and PSYCHOMETRICA (Watson & Solomon, 1997).

Stimuli

At a viewing distance of 60 cm, the inducer and target diameters subtended 10° and 5.2° of visual angle, respectively. The inducer and target were separated by a 30-arc-min gap, and all contours were smoothed via a raised cosine filter subtending 7.8 arc min. Each of these sinusoidal gratings had a spatial frequency of 1.5 c/° and a spatial phase φ, randomly chosen from the interval (−π, +π). The Michelson contrasts of target and inducer were 0.99 and 0.59 of their maxima, respectively. These values were chosen to obtain a reliable invisibility of the inducer as assessed in a pilot experiment. The inducer was always present, and its orientations were drawn from the set {±15°, ±75°}. These specific orientations where chosen to maximize the magnitude of the direct and indirect effects (O’Toole & Wenderoth, 1977). The adapting mask had the same annular window as the inducer. Within this window, we presented the product of two orthogonal square-wave gratings (at ±45° with respect to vertical) at full contrast. Jitter was introduced by randomly selecting the spatial phase of each grating every 0.1 s.

Procedure

The adapting mask was centered at 3° of eccentricity either on the left or right side of the fixation point. On each trial, following 20 s of adaptation, the mask was replaced by the target and inducer at time t = 0, which ramped on and off smoothly in a Gaussian temporal window (μ = 800 ms; σ = 200 ms). Observers had to report whether the test grating appeared tilted clockwise or anticlockwise of vertical by pressing the left or right arrow key. They were also instructed to press the bar instead of the arrow keys to report cases in which the surround was visible after adaptation. If such was the case, the trial was discarded and had to be repeated. On each trial, the target’s orientation was adjusted by one of eight randomly interleaved staircases (Watson & Pelli, 1983). Two staircases were associated with each inducer’s orientation: one designed to converge on P(“ACW”) = 0.16 and the other on P(“ACW”) = 0.84. Each observer performed one session consisting of about 240 trials.

Control experiment

To quantify the effect induced by lack of visual awareness, we compared postadaptation biases with the biases measured in a control experiment, in which both the target and the inducer were visible. We therefore designed our control experiment to be identical to the main experiment, apart from the absence of the adapting jittering mask as outlined in Figure 2.

Results

We tested the role of visual awareness in both the direct and indirect effects by rendering the inducer invisible through dynamic adaptation. Observers reported the inducer as visible in only 6% of the trials. This value is comparable to the 8% reported by Motoyoshi and Hayakawa (2010), confirming the efficacy of our methods. Orientation bias was adopted to quantify the tilt illusion. That is, for each inducer’s orientation, we estimated how far the central test had to be tilted in order to appear vertical. That corresponds to the point on the psychometric curve at which the probability to respond clockwise, given a certain orientation of the test grating, equals chance level (50%).

Each point in Figure 3 (upper panels) shows the average biases of our four observers, segregated on the basis of the visibility of the inducing surround. In the control condition (visible surround), as expected, near-vertical inducers (±15°) produced repulsive biases (direct effect) of 4.5° ± 1.2° (mean ± SD), whereas near-to-horizontal inducers caused 1.6° ± 0.6° of attraction (indirect effect; Figure 3, upper panels and table). In the
postadaptation condition (invisible surround), near-vertical inducers again produced significant biases (4.7° ± 1.2°), but the near-horizontal inducers did not (0.1° ± 0.3°). Hence, when the inducer is not perceived, there is almost no evidence of attraction, but repulsion is only marginally diminished. The same pattern of results can be observed at the individual level (Figure 4). A paired \( t \)-test confirms that the effect of adaptation on the (unsigned) magnitude of the direct effect is larger than its effect on the magnitude of the indirect effect, \( t(7) = 2.19, p < 0.03 \). Therefore, our data reveal that visual awareness is required only by processes mediating the indirect effect, advocating the notion that attraction and repulsion are mediated by distinct mechanisms (Wenderoth & Johnstone, 1988).

**Discussion**

We tested the claim that the tilt illusion’s phenomenology might be accounted for by the interplay between two different mechanisms located at different stages of the visual processing stream (Morant & Harris, 1965). To isolate early stages of processing, we used AIB to remove illusion-inducing stimuli from phenomenal awareness. The rationale of using this approach is based on the idea that consciousness emerges only after elaborate perceptual processing unfolding over multiple processing levels (Erdelyi, 1974). If one of these levels is interrupted, the visual information will be unconsciously processed until that stage (Lin & He, 2009). In our specific case, by making the inducing surround unconscious, we wanted to see where the mechanisms mediating the indirect and direct effects are located in the visual hierarchy with respect to the stage where phenomenal awareness emerges.

We found that AIB was successful in eliminating the so-called indirect version of the tilt illusion but not the direct one. Adaptation is likely to decrease low-level neural responses to the surround. Hence, it could be argued that in our experiment, the indirect effect is diminished by a decrease in contrast, rather than by the
lack of awareness of the surround. However, this criticism is inconsistent with evidence showing the relative immunity of the indirect effect to contrast manipulations (Wenderoth & Johnstone, 1988).

Blakemore et al. (1970) explained the direct effect in terms of lateral inhibition between striate neurons with adjacent receptive fields and similar orientation selectivity operating on a local scale. The indirect effect, on the other hand, is believed to reflect mechanisms involved in global orientation analysis occurring, therefore, in extrastriate sites where neurons are tuned to global stimulus properties (Wenderoth & Johnstone, 1987).

The latter conclusion, however, is not completely clear-cut. In fact, there is evidence that some global processes (such as texture segmentation) are implemented as early as V1 (possibly through feedback from extrastriate areas; Lamme, van Dijk, & Spekreijse, 1993). Therefore, it is not impossible for the direct and indirect effects to be at least partly mediated by a common substrate. If this were the case, then the indirect effect could be understood as a consequence of re-entrant activity from extrastriate areas to the striate cortex (Poom, 2000). Our main finding that the indirect effect is abolished by lack of phenomenal awareness is consistent with this idea because it is believed that re-entrant connections from high-level areas to V1 could be crucial for conscious perception (Lamme, 2003). Further support comes from the finding that the direct effect saturates after 100 ms of stimulus presentation. The indirect effect, on the other hand, does not saturate until after 400 ms (Wenderoth & Johnstone, 1988).  

Multiple levels of the visual processing hierarchy might be engaged in determining the repulsive direct effect as well (Clifford & Harris, 2005; Wenderoth & Johnstone, 1987). Previous studies (Forte & Clifford, 2005; Wade, 1980) reported an incomplete interocular transfer of the direct effect. That is, the size of the effect is lessened when the inducer is presented to one eye and the test to the other (dichoptical presentation) compared with when the inducer and test are presented to the same eye (monocular presentation). The amount of interocular transfer is thought to be related to the amount of monocular and binocular neurons engaged in the processing. Therefore, this indicates that monocular neurons, mainly present in V1 (Hubel & Wiesel, 1962), are only partly responsible for the direct effect.

Taken together, these observations are consistent with Morant and Harris’ hypothesis of high- and low-level components interacting to generate the angular tuning function that describes the phenomenology of the tilt illusion. Indeed, Morant and Harris’ idea can explain the fact that low-level manipulations do not extinguish the direct effect but just reduce it to roughly
the same magnitude of its direct counterpart (Wenderoth & Johnstone, 1987). Another prediction implied by a linear combination model is that by suppressing the indirect effect, we should expect a commensurate reduction in the direct effect’s magnitude (Wenderoth et al., 1989).

Our data are at odds with this latter prediction. The fact that repulsive biases are only marginally affected by lack of awareness, however, could suggest that the interaction might be nonlinear instead of additive, as posited by Morant and Harris’ original model. For example, the tilt illusion’s angular function might result from the implementation of a max rule so that only the maximum output between the two processes contributes to the bias.

An alternative explanation could be related to the proposal of the direct effect resulting from the contribution of multiple levels of the visual hierarchy. A mounting body of psychophysical and neurophysiological evidence suggests that erasing visual stimuli from awareness only weakens but does not eradicate the corresponding neural signal (Blake, Tadin, Sobel, Raissian, & Chong, 2006; Lehky & Blake, 1991; Sobel, Blake, & Raissian, 2004). Furthermore, these weakening effects are first expressed at early levels of processing and become progressively more potent at subsequent stages (Blake & Logothetis, 2002; Freeman, Nguyen, & Alais, 2005; Nguyen, Freeman, & Wenderoth, 2001). If the repulsive effect is really based on low-level mechanisms, we can speculate that it would be subjected to a relatively small amount of suppression. High-level processes, such as those mediating the indirect effect, would instead endure a stronger suppression. Therefore, the smaller weakening observed on the direct effect would be explained in terms of different levels of suppression exerted by removing the visual stimulus from awareness.

It must be noted that our results are at odds with the conclusions of Mareschal and Clifford (2012), who reported the persistence of the indirect effect when the surround’s orientation was rendered indiscernible through rapid presentation. The major difference in our study is that our surrounds were perceptually invisible to the observers and that phenomenal awareness was assessed on a trial-by-trial basis. However, it is also possible that discrepancies could stem from the techniques employed by the two studies. Indeed, it has been reported that different methods to manipulate visual awareness could yield divergent results when applied to contextual phenomena such as visual crowding (Chakravarthi & Cavanagh, 2009; Wallis & Bex, 2011) and orientation after-effects (Apthorp, Cass, & Alais, 2011). Further investigation could clarify a possible role of different techniques in the discrepancy here observed.

Conclusions

Our results demonstrate that the neural counterparts of direct and indirect effects are likely to be found largely in V1 lateral interactions and in global extrastriate processes, respectively. More specifically, here it is shown that only the attractive indirect illusion is based on mechanisms that require visual awareness to operate.

Keywords: tilt illusion, visual awareness, adaptation, contextual interactions

Acknowledgments

This research was supported by a grant from the Engineering and Physical Sciences Research Council (EP/E064604).

Commercial relationships: none.

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Footnote

1These temporal estimates were obtained in the absence of adaptation. Examining the effect of AIB on the dynamics of the tilt illusion is beyond the scope of this article, but it is conceivable that AIB may have merely slowed the indirect effect to the point that our stimuli disappeared before it could manifest.

References


