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Last but not least

Optimising the Pinna – Brelstaff illusion

Pinna and Brelstaff (2000) presented the fascinating motion illusion shown in figure 1. By fixating the centre of the image and moving the page toward the eyes, one experiences a compelling counter-rotation of the two rings of boxes (micropatterns) composing the display. (For many people the illusion is most vivid if the display remains stationary and the head is moved toward the page.) The experience induced by the inner ring is somewhat like that of looking at a Ferris wheel whose movement is linked to your movement. The Ferris wheel is stationary when you are stationary and rotates counterclockwise when you approach it. Consider a chair directly to the right of the centre of the hypothetical Ferris wheel. As you move toward the wheel, the retinal image of the chair will move in an up-to-the-right direction from its initial position. This local path represents a combination of the centrifugal flow caused by approaching the wheel and the counterclockwise rotation of the wheel itself. Unlike the chair on the Ferris wheel, however, the micropattern directly to the right of centre in the Pinna – Brelstaff figure does not trace out an up-to-the-right path on the retina; as the distance from eye to the image decreases, the image expands on the retina and each micropattern moves along a straight-line path that connects it with the centre of the display. So, why does the illusory motion occur?

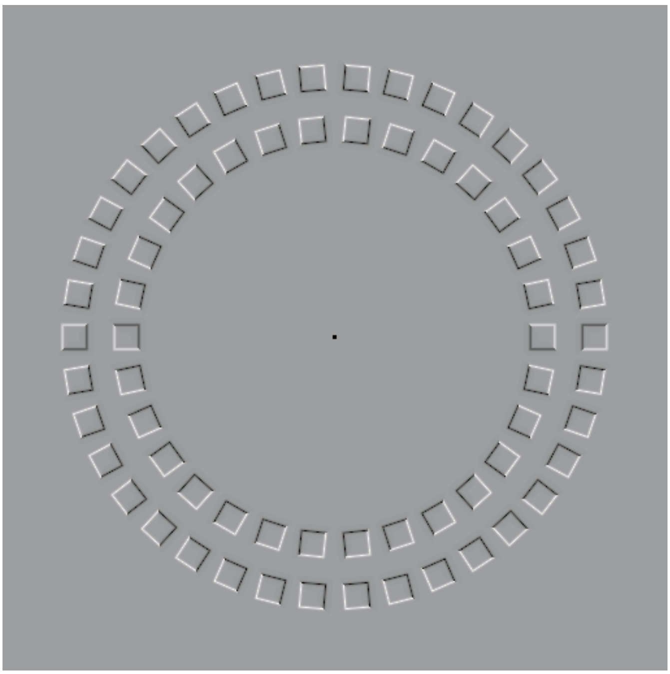

Figure 1. The Pinna – Brelstaff illusion.

As noted by Pinna and Brelstaff (2000) and Morgan (2002), the origins of this illusion may be understood by considering the nature of the direction-selective neurons at the earliest stages of visual processing. These neurons are orientation-selective and, at best, any such neuron can signal the speed with which a line of its preferred orientation

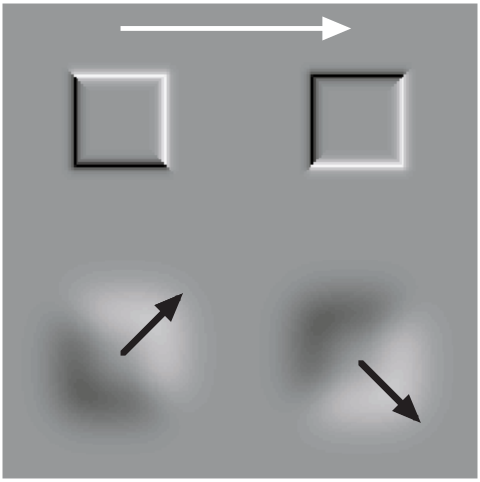

Figure 2. The two micropatterns at the top have strongly oriented low-frequency components, as shown in the blurred versions at the bottom. When these micropatterns translate to the right, they will elicit strong responses from direction-selective neurons having the direction preferences indicated by the overlaid arrows.

moves through its receptive field—this is the well known aperture problem. The top panel of figure 2 shows two micropatterns taken from the inner and outer rings of figure 1, directly to the right of fixation. When the micropatterns are blurred (as in the bottom of figure 2) to remove high spatial frequencies, one can readily see that each micropattern has a dominant orientation in the remaining low spatial frequencies. When the micropatterns translate directly to the right across the retina (as indicated by the white arrow at the top of the figure), they will elicit the strongest responses from neurons sensitive to motion up-to-the-right (figure 2, bottom left) and down-to-the-right (figure 2, bottom right); the black arrows indicate the direction selectivity of the most strongly stimulated neurons. Therefore, if we were to consider only the responses of individual low-level direction-selective neurons, our best guess about the micropattern directly to the right of fixation would be that it is moving up to the right, just as the chair on the hypothetical Ferris wheel. Thus, the responses of early visual mechanisms to the Ferris wheel chairs and micropatterns may be the same, thereby providing a basis for the illusion. However, this analysis raises another question. Why do the micropatterns (and chairs) appear to follow a circular path rather than spiral paths?

In both cases, it seems that the visual system is able to 'discount' the whole field centrifugal retinal motion caused by moving closer to an object. It is clear that the visual system does this routinely because objects typically do not appear to change in size as they move closer to us or we to them. However, to discount the centrifugal flow in the Pinna–Brelstaff figure, the visual system might actually recover the true direction of movement of each micropattern across the retina. There are a number of ways in which the ambiguous responses of direction-selective neurons may be combined to recover the true direction of local image motion (eg Adelson and Movshon 1982; Wilson et al 1992). Such computations are usually associated with neurons found in area MT of monkey visual cortex. It may be that the responses of MT neurons feed into neurons in MSTd that are selective for flow patterns associated with whole-field expansion (Duffy and Wurtz 1991). These responses may be used by some later process to discount the whole-field motion caused by the observer moving toward the surface or by the surface moving toward the observer. As mentioned, discounting such whole-field motion leads to size or object constancy and explains why we don't see the concentric rings in figure 1 getting larger as they get closer to us or shrink as they move further away (Morgan 2002). Thus, the true direction of motion of each micropattern may be recovered by combining the responses of many direction-selective units within a local region (eg Adelson and Movshon 1982; Wilson et al 1992).

On the other hand, the fact that the illusory motion is seen suggests that the visual system retains the local, direction-selective responses elicited by each micropattern and that these contribute to the sense of rotary motion within an object of stable size. As shown in figure 2, there are large differences in the motion signals arising from nearby micropatterns in the inner and outer rings of figure 1. Because the visual system is very sensitive to differences in local motions, we might expect such signals to be segregated and attributed to independently moving objects. Furthermore, it is well known that the visual system tends to group items by similarity, proximity, and common fate. Therefore, neighbouring items eliciting strong responses from similarly tuned direction-selective neurons (as would neighbouring micropatterns within one of the rings) should be grouped together and segregated from other items that are grouped in virtue of eliciting strong responses in a different set of direction-selective neurons (ie micropatterns in the other ring).

It seems, then, that low-level direction-selective mechanisms serve at least two masters: one that computes whole-field flow, and one that groups local motions within this whole-field flow. Such a scenario is consistent with the problem that motion poses to the visual system. Motion across the retina can be generated by our own movements (self-motion) or by objects moving independently of us in the environment (object motion). We are rarely absolutely stationary, so to form a representation of object motions the visual system must 'discount' retinal motions arising from self-motion.(1) (This is not to say that the visual system discounts only whole-field flows generated by self-motion.) The Pinna–Brelstaff figure appears to engage both systems.

The discussion above suggests that the Pinna–Brelstaff illusion does not depend on the precise geometric structure of its constituent micropatterns, but rather it depends on the low-frequency orientation structure in the display. This is confirmed in a new version of the illusion (figure 3) constructed from Gabor patches (Gaussian-modulated cosine waves) [see Morgan (2002) for a display having similar structure]. Gabor patches were used because they are thought to be very effective stimuli for low-level motion energy mechanisms (Adelson and Bergen 1985). Beyond demonstrating that oriented stimuli are sufficient to generate the illusion, we were interested in the Gabor parameters that produce the most effective illusory motion. The stimulus in figure 3 was derived through three experiments (described below) that manipulated the relative orientations of the Gabor patches in the two stimulus rings, their spatial frequencies, and their densities.

All patterns in our experiments were generated within a 512×512 pixel image on a high-resolution computer monitor (27 pixels cm^{-1}). The Gabor patches were positioned at 180 and 212 pixels from screen centre, which at a mean viewing distance of 57 cm correspond to 6.67 deg and 7.85 deg from fixation. (We included concentric circles as 'guides' because our initial impression was that they enhanced somewhat the illusory motion, but they are by no means a necessary condition for the illusion to occur.) The Gaussian component of each Gabor patch had a standard deviation of 6 pixels in all experiments. The phases of the two rings of Gabors were randomised and the outer ring had proportionally more patterns than the inner ring so that micropattern density in the two rings would remain the same.

During the experiments, subjects rocked back and forth over a fixed distance (20 cm) at a controlled rate while viewing each display. Subjects synchronised their motions with a fixation spot whose luminance varied in linear ramps from white-to-black-to-white over a period of 2 s. Head position was in the rest position (67 cm from

(1) A similar explanation of the Pinna–Brelstaff illusion can be found in Morgan (2002). We thank Peter Thompson for bringing this article to our attention.

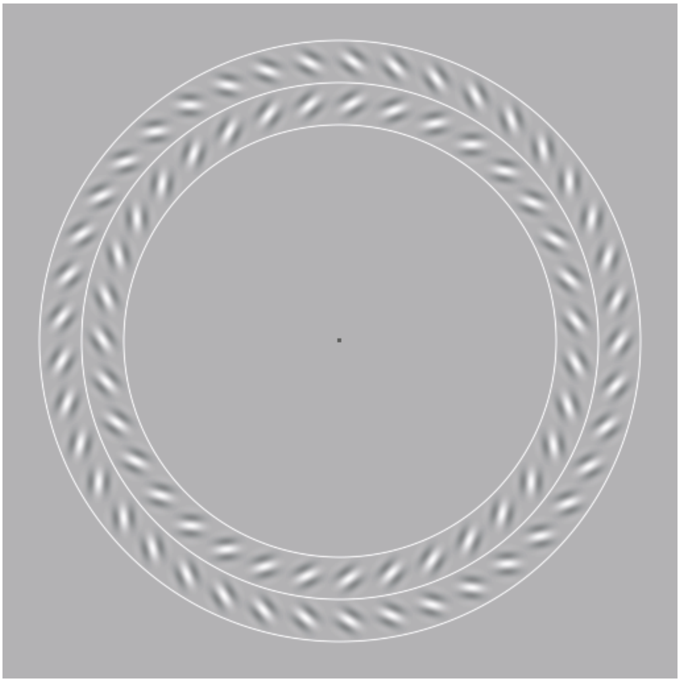

Figure 3. An optimised version of the Pinna – Brelstaff illusion.

the screen) when the spot was initially white, moved toward the forward-most position (47 cm from the screen) as the spot changed from white to black, then back toward the rest position as the spot changed from black to white. On each trial, two displays were presented in sequence (each differing only on the variable of interest) and, at the offset of the second stimulus, the subject judged whether the first or second display produced the most compelling sensation of motion. We tested nine levels of each variable for a total of ${}_9C_2 = 36$ combinations. Within a block of 36 trials, a particular pattern could be chosen as 'most effective' a maximum of eight times. All data shown below represent the averages of three blocks of trials.

In an initial test, we asked what orientation difference (between patterns in the inner and outer rings) produced the best sense of motion. Nine orientation differences were tested ranging from 0° to 180°. For a 0° difference, micropatterns in the inner and outer rings were parallel to the true direction of motion. For a 90° difference, the two patterns were oriented ±45° to the true direction of motion. For a 180° difference both were perpendicular (±90°) to the true direction of motion; in this latter case both micropatterns had the same orientation. The wavelength of the sinusoidal component of the Gabor was fixed at 12 pixels and there were 30 Gabors in the inner ring. The left panel of figure 4 shows the results of three subjects (three symbols). For all three subjects, an orientation difference of 112.5° (ie ±56.25°) produced the strongest sense of image motion.

With a fixed orientation difference of 112.5°, we then sought the optimal spatial frequency of the Gabor patch by examining nine wavelengths ranging from 4 to 32 pixels in equal logarithmic steps. The results are summarised in the centre panel of figure 4. The average results showed a peak at a wavelength of 14 pixels which, at a mean viewing distance of 57 cm, corresponds to a spatial frequency of 1.92 cycles $\deg^{-1}$.

Finally, with a fixed orientation difference of 112.5° and a fixed wavelength of 14 pixels, we varied the number of patterns in the inner ring from 4 to 72 (in equal logarithmic steps). The right panel of figure 4 shows that the strength of the illusion

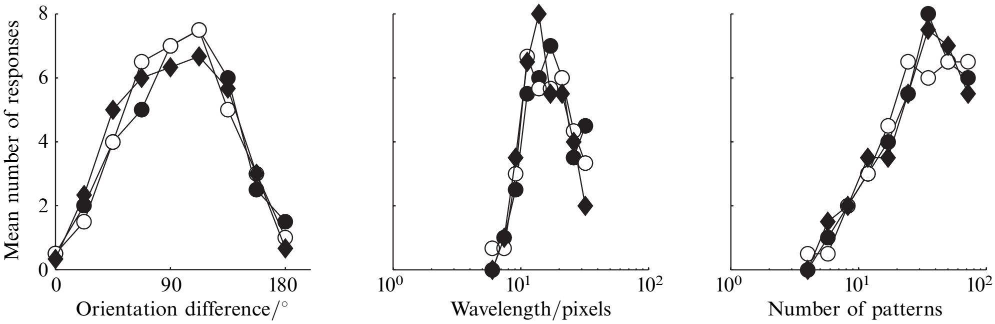

Figure 4. Results of the experiment showing the optimal choices of orientation difference, spatial frequency, and density of Gabors.

increased with the number of micropatterns and reached a peak at 35 micropatterns in the inner ring. As mentioned, figure 3 shows a pattern comprising micropatterns whose parameters and number were derived from the peaks of the curves shown in figure 4.

These results support the suggestion of Pinna and Brelstaff (2000) that the low-frequency orientation structure in their patterns generates their illusion. In other words, we have stripped down our displays to the essential information needed to generate the illusion. Our results also corroborate a qualitative observation made by Pinna and Brelstaff. Their figure 5 shows that the illusion is enhanced (relative to that shown in our first figure and theirs as well), when the squares are changed to parallelograms that increase the orientation difference in the low-frequency components of the patterns in the inner and outer rings. This is consistent with the results in the left of figure 4, which show that an orientation difference of 112.5° produces stronger illusory motion than does a pattern with a 90° orientation difference.

We note that our efforts to optimise this illusion are incomplete for two reasons. First, we tested our parameters sequentially rather than simultaneously. This was a practical consideration; testing all 27 possible combinations of three variables, each with nine levels (ie ${}_{27}C_2$), would have required more than three times as many trials. So it is possible that, within this parameter space, there exists a slightly more compelling version of the illusion. Second, there is clearly a very large parameter space that could be explored and we have examined just three stimulus dimensions that may affect the illusion. One might also investigate Gabor bandwidth, phase, and contrast, to name a few. Although more compelling versions may exist, we have shown that the low-frequency orientation structure in the original displays is sufficient to produce the illusion, and we have taken a step toward quantifying the parameters that produce the optimal illusory motion.

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