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Orientation uncertainty reduces perceived obliquity

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ABSTRACT

The influence of prejudice on perception should be greatest when certainty about stimulus identity is least. We exploited this relationship to reveal visual biases for the cardinal orientations: vertical and horizontal. Specifically, when we increased the variance of orientations in an array of grating patches, estimates of the mean became less oblique. This result is consistent with a stable prior, or prejudice, for those orientations most prevalent in natural scenes.

1. Introduction

Many contemporary theorists describe vision as form of Bayesian inference (Knill, Kersten, & Yuille, 1996). That is, our perceptions result from the combination of prior beliefs with data we gather from the environment. As an example, consider the convex appearance of concave faces (Gregory, 1970). To a Bayesian, this phenomenon suggests a belief that faces are concave with a very low probability (Yellott & Kaiwi, 1979).

The influence of prior knowledge is demonstrably greatest when certainty about stimulus likelihood is least. Possibly the earliest example was the finding that when depth cues become impoverished, the distance of any object appears closer to 2 m than it really is (Gogel, 1969). However, it is not clear whether this bias has anything to do with prior knowledge. The 2 m distance has no known behavioural relevance.

In the laboratory, behavioural relevance can be manipulated. For example, using virtual reality, Körding and Wolpert (2004) taught observers to compensate for a shift in apparent hand positions. The ability to compensate for subsequent shifts was found to vary with the fidelity of the virtual image. When that image was blurred, pointing behaviour was biased toward the shift they learned.

Rather than bias observers in the laboratory, two previous studies (Stocker & Simoncelli, 2006; Weiss, Simoncelli, & Adelson 2002) exploited the smooth and slow motions known to dominate the statistics of natural flow fields (Roth & Black, 2007), and fit a Bayesian model to the relationship between stimulus contrast and perceived speed (cf. Hammet, Champion, Thompson, & Morland, 2007; Thompson, Brooks, & Hammet, 2006). Our approach is similar, except instead of relying on noise intrinsic to the visual system, we decided to directly manipulate uncertainty by adding variance to the stimulus.

We derived our predictions from the predominance of approximately horizontal and vertical contours in our environment (Coppola, Purves, McCoy, & Purves 1998; Switkes, Mayer, & Sloan, 1978). It has already been established that humans have greater sensitivity and acuity for simple stimuli having these cardinal orientations (Appelle, 1972). A preference for motion along cardinal axes has also been demonstrated (Mansfield, 1974). These behavioural "oblique effects" are thought to be consistent with physiological studies showing that relatively few neurons are tuned to oblique orientations (Andrews & Schluppeck, 2000). What we sought to determine was whether perception actually would shift toward the cardinal orientations when confidence in the true stimulus orientation was low.

2. Methods

In our initial test of this hypothesis, we asked five normal, naïve observers to align two "comparison" dots with their estimate of the average orientation in an array of Gabor patterns. The orientation of each Gabor was randomly selected from a Gaussian distribution (see Fig. 1). We expected estimates of the mean to be closer to the closer cardinal axis. No efforts were made to restrict the contents of the room from view. We did not want to discourage observers from adopting any typical prior they might have for the orientation content of indoor scenes. Observers were asked to fixate on the centre of the iMac display on which the stimuli were presented, but this fixation was not enforced in any way.

At a viewing distance of 57 cm, each comparison dot had an angular subtense of 0.2° It was white with a luminance of 221 cd/m^2. The two dots were presented at a viewing eccentricity of 5°, on opposite sides of fixation. Observers adjusted the azimuth of the dots using two keys on the keyboard, and clicked the mouse

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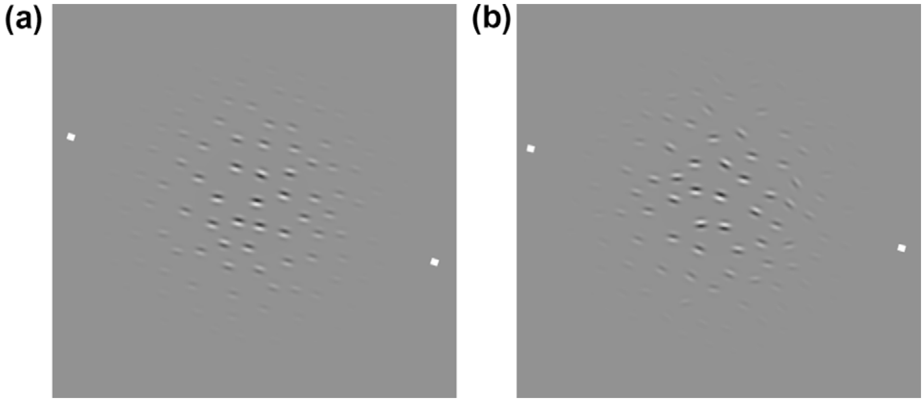

Fig. 1. Example stimuli and typical result in the main experiment. Each little oriented pattern is a Gabor. In (a) the Gabors are tilted −75° ± 2° clockwise with respect to vertical. On average, observers aligned the two white spots with an angle that was 4° farther from the nearest cardinal axis than the mean of this stimulus (i.e. −71°). In (b) the tilts are −75° ± 14°. On average, observers were unbiased in their alignments of the two white spots with the mean of this array.

button when it appeared to match that of the average orientation. There was an inter-trial interval of 1 s. In a control experiment we fixed the azimuth of the dots, and four naïve observers adjusted the orientation of the Gabor array using the same two keys. Three of these latter observers also participated in the main experiment.

Each Gabor in the array had a spatial frequency of 6.9 c/deg, a spatial phase of either $\pi/2$ or $-\pi/2$ (randomly chosen for each Gabor pattern), a space constant (σ) of 0.072°, a mean luminance of 111 cd/m^2, and a contrast of 0.99. Prior to each trial, the Gabor patterns were placed, one at a time, in a $5.7^\circ \times 5.7^\circ$ square. The placement of each Gabor pattern was random, with the constraint that no two Gabors could have centres closer than 0.43° (i.e. 6σ). The number of Gabor patterns required to fill each square was 132 ± 4. The entire array appeared within a Gaussian window, the space constant of which was 1.4°. In separate blocks, we used Gabor arrays having 0.1 s, 0.5 s, and response-terminated displays. Only response-terminated displays were used in the control experiment.

3. Results

3.1. Main experiment: response bias

In this study, we were primarily concerned with perceptual biases. In particular, we wanted to know whether the variance of orientations affected their apparent mean. However, what we measured were response biases, i.e. differences between the true mean orientation and the azimuth of the comparison dots. (NB: We use positive numbers to represent clockwise tilts. Thus positive response biases indicate responses that are clockwise with respect to unbiased responses.) Perceptual and response biases are not necessarily the same; for example, observers could have a perceptual bias towards the cardinal axis, but a response bias in the direction of making the comparison dots less vertical than the gratings. We shall start by analysing response biases only.

Our observers were remarkably precise in their estimates of orientation. When all the data were pooled without regard to observer, display duration, orientation variance or mean physical tilt, the standard deviation (SD) of response bias was just 9.8°. Nonetheless, there were a few trials, even with long durations and low orientation variance (as in Fig. 1a), for which the bias was strangely large. Perhaps on these trials, observers mistakenly clicked the mouse button, indicating alignment, before they had actually moved the comparison dots from their random starting positions. We decided to establish a rather conservative criterion for removing these outliers from the data set. Thus we kept all data within eight SDs of zero bias. With this criterion, exactly five trials were discarded, and the SD of the remaining 4315 fell to 9.3°.

Each point in Fig. 2 shows the average response bias of our five naïve observers, collapsed across display duration and orientation variance. Error bars contain two standard errors (SEs), i.e. $2\sqrt{\sum_{i=1}^{5}[\mathrm{var}(i_\mu)/N_{i,\mu}]/5}$, where i_μ denotes observer i's response bias when the Gabor orientations were selected from a distribution with mean μ, and $N_{i,\mu}$ represents the number of trials observer i performed in that condition.

As a rule, these data points fall in the shaded regions of this figure, indicating a tendency to give the comparison dots an alignment that was *more oblique* than the mean orientation in the stimulus array. Exceptions to this rule, which occur at mean physical tilts of ±55° with respect to vertical, suggest that biases toward (or away from) the vertical and horizontal axes may not be equal.

The smooth curve in Fig. 2 satisfies the equation

$$r(s;a,y) = a\,\mathrm{sgn}(s)(\sin[4|s| - \sin^{-1}(y)] + y), \tag{1}$$

where s is the mean physical tilt of the stimulus and r is the response bias. The parameter a determines the maximum bias, and the parameter y determines how much stronger biases away from the vertical axis are than biases away from the horizontal axis. (NB: $-1 \leqslant y \leqslant 1$) When $y = 0$, these two biases are equal, and the

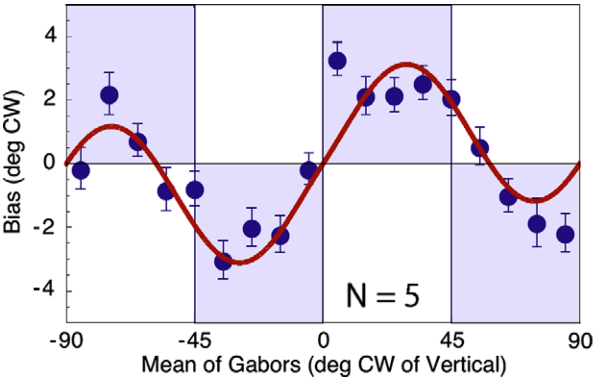

Fig. 2. Response bias versus tilt of the Gabor array. Results from the main experiment have been collapsed across observer, display duration and orientation variance to illustrate the general trend, which is that most data fall in the shaded regions, indicating response biases away from the closest cardinal axis. In all figures, each error bar contains two standard errors of its respective mean. In this figure, the smooth curve adheres to Eq. (1), with parameter values $\alpha = 2.1^\circ$ and $y = 0.45$.