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Integration biases in the Ouchi and other visual illusions

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Abstract. A texture pattern devised by the Japanese artist H Ouchi has attracted wide attention because of the striking appearance of relative motion it evokes. The illusion has been the subject of several recent empirical studies. A new account is presented, along with a simple experimental test, that attributes the illusion to a bias in the way that local motion signals generated at different locations on each element are combined to code element motion. The account is generalised to two spatial illusions, the Judd illusion and the Zöllner illusion (previously considered unrelated to the Ouchi illusion). The notion of integration bias is consistent with recent Bayesian approaches to visual coding, according to which the weight attached to each signal reflects its reliability and likelihood.

1 Introduction

The Ouchi illusion (figure 1) is thought to arise from retinal motion signals, generated either by moving the image (eg waving the page to and fro), or by small involuntary eye movements while viewing a static pattern (Spillmann et al 1993).

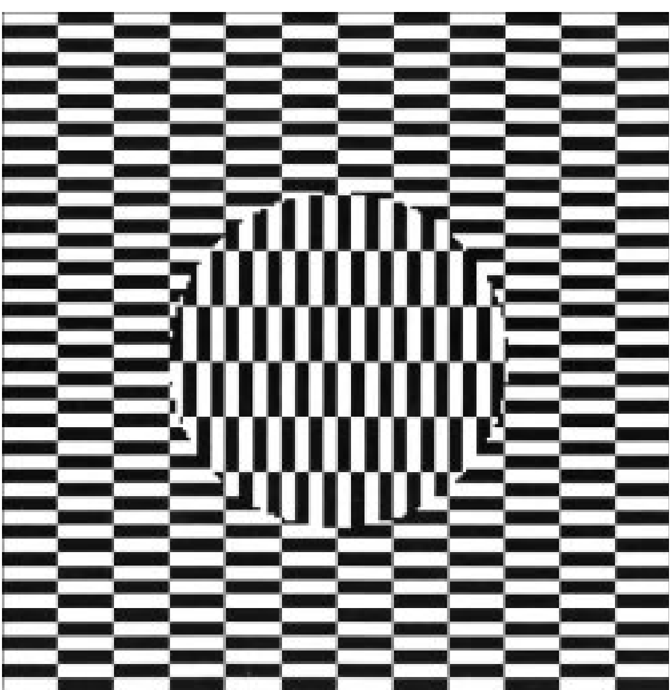


Figure 1. A variant of the Ouchi illusion, in which relative apparent movement is seen between the central region and the surround. Free viewing of a static pattern leads to small 'shimmering' movements (presumably due to retinal motion signals during eye movement). More pronounced relative apparent motion can be seen when the page is gently rocked to and fro.

Khang and Essock (1997) speculated that the illusion arises from interactions between visual cells with concentrically organised receptive fields that differ in their polarity (ON or OFF). They argue that:

> "... the central test region and the surround may become dissociated, or segmented, owing to the occurrence of local contrast reversals from pattern element movement occurring at different times (ie. rates) in the two parts of the pattern, owing to the differing sizes/orientations of the elements in the two patterns" (page 596)

Hine et al (1997) suggested an explanation in terms of anomalous integration of motion signals. They offer the conjecture that the anomaly "is related to activity in grating cells" (page 453), and present data to show that the spatial-frequency dependence of the effect agrees with the spatial-frequency tuning of cells in primate visual cortex.

The present explanation offers a specific proposal concerning the source of the anomaly. An apparently unrelated motion illusion seen in tilted lines was the starting point for the explanation. The Ouchi figure contains line segments at two different orientations (usually vertical and horizontal), and the illusion can be elicited by rapid oscillation to-and-fro (Spillmann et al 1993; Hine et al 1997). Castet et al (1993) found that drifting oblique lines appear to move more slowly than lines oriented at right angles to their direction of motion. They offered an explanation in terms of the integration of motion signals arising from different locations on moving tilted lines. Integration of local motion signals is widely regarded as a necessary step in motion analysis to overcome the so-called aperture problem—motion detecting cells in the brain with relatively small receptive fields can only signal the motion component at right angles to the local contour orientation. Nakayama and Silverman (1988) had earlier suggested that during motion integration the visual system exhibits a bias in favour of motion orthogonal to the local contour. Castet et al took up this idea to argue that biases in favour of certain local signals can also explain their speed illusion. The notion of integration bias is used in the present paper to explain the Ouchi and other illusions.

The basic idea is illustrated in figure 2. A tilted bar is shown (figure 2, upper left) moving horizontally between two positions, t_1 and t_2. Local motion signals will be generated by movement detectors positioned along the edges of the bar (arrows). In order to recover the direction and velocity of the bar, the visual system must integrate these local signals or vectors to arrive at a single global motion vector. Consider a weighted linear combination of the two local vectors ($\boldsymbol{v}_\mathrm{P}$ and $\boldsymbol{v}_\mathrm{O}$ in figure 2).

$$\boldsymbol{v}_\mathrm{C} = a\boldsymbol{v}_\mathrm{P} + b\boldsymbol{v}_\mathrm{O}\,; \qquad a + b = 1\,.$$

The weight b attached to the orthogonal signal $\boldsymbol{v}_\mathrm{O}$ will be called the orthogonal bias. In the absence of bias (a and b both equal to 0.5), $\boldsymbol{v}_\mathrm{C}$ will give the true direction of the bar (horizontal). However, if the weights are unequal, then $\boldsymbol{v}_\mathrm{C}$ will be biased in one direction or the other. For example, the grey arrow in figure 2 (lower left) shows the combined vector assuming an orthogonal bias of 0.6. Note that the direction of the vector is slightly below horizontal, favouring the orthogonal signal. Thus if a second bar is added to the display, at a different orientation (90° away in figure 2, right)—it will appear to move in a different direction from the first. This difference in apparent direction, it is argued—may be responsible for the apparent relative movement seen in Ouchi figures between sets of bars at different orientations. When the motion of the Ouchi pattern is exactly parallel to the orientation of one of the two sets of bars, there is only one (orthogonal) motion vector generated by each bar, so there should be no illusion at all. Illusion magnitude as a function of pattern direction can be predicted from the scheme in figure 2.

Figure 3 shows predicted magnitude (ie the angular difference in direction between the two sets of bars) as a function of the direction of the pattern, on assuming an

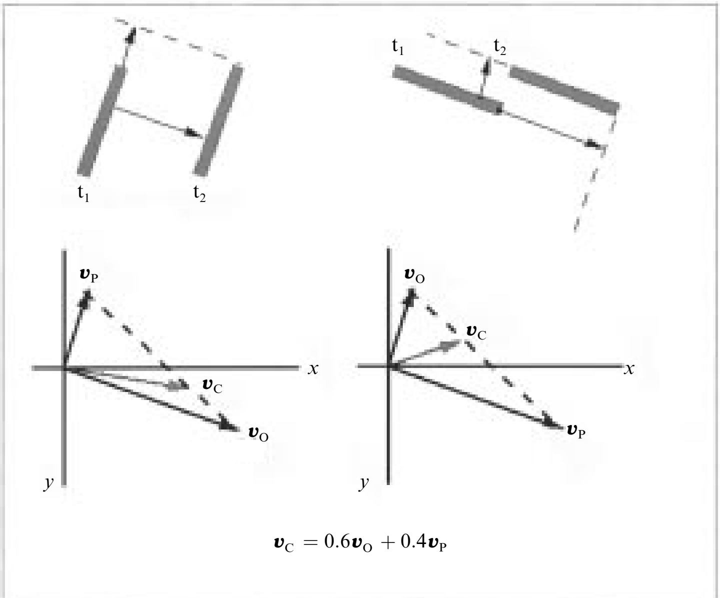


Figure 2. Proposed explanation for the Ouchi illusion. The top of the figure shows two tilted bars, differing in orientation by 90°, moving in the same direction (horizontally) at two time-frames (t_1, t_2). Arrows depict local orthogonal motion vectors generated along two sides of each bar. These vectors are plotted in vector space in the lower half of the figure as $\boldsymbol{v}_O$ (vector orthogonal to the orientation of each bar) and $\boldsymbol{v}_P$ (vector parallel to the orientation of each bar). The grey vector shows the weighted linear combination of each pair of vectors ($\boldsymbol{v}_C$), as given by the equation. Since the weights are biased in favour of the orthogonal component, the combined vector is nearer to the direction of the orthogonal component than the direction of the parallel component. Since the two bars differ in orientation, if their apparent direction is governed by weighted combination of local vectors, they should appear to move in different directions and at different speeds.

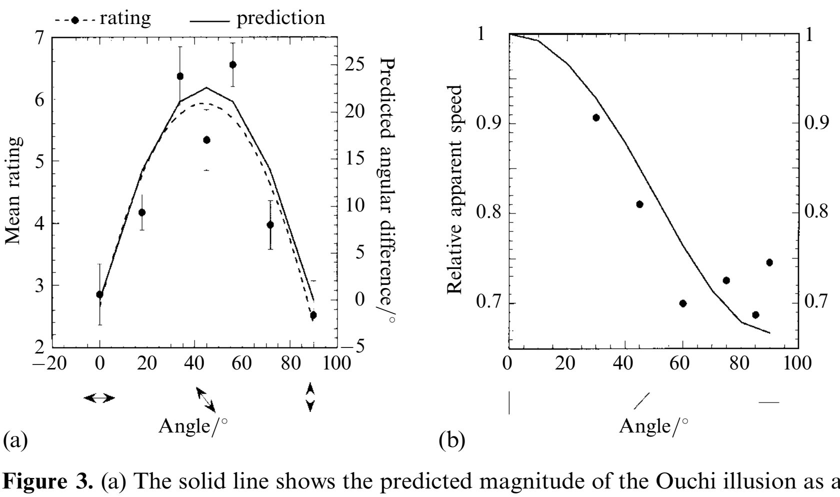


Figure 3. (a) The solid line shows the predicted magnitude of the Ouchi illusion as a function of the pattern's direction of motion relative to bar orientation (with bars assumed to be oriented vertically and horizontally, as in figure 1). Predictions were derived from the scheme shown in figure 2, for an orthogonal bias of 0.6. Predicted magnitude is greatest for patterns moving along an oblique axis. The data points show mean rating of illusion strength (± 1 SE) obtained in the experiment, and the broken line shows the line of best fit through the data. (b) Predictions (solid line) and data (circles) for the perceived velocity of tilted lines moving horizontally, as a function of line tilt. Predictions were derived from the scheme in figure 2; data are re-plotted from Castet et al (1993), figure 7.

orthogonal bias of 0.6. If integration bias is responsible for the Ouchi effect, then illusion magnitude should show a corresponding dependence on bar angle relative to pattern direction. The illusion should be strongest when the pattern moves in an oblique direction, at an angle intermediate between the orientations of the two sets of bars in the pattern.

No data are available in the literature regarding the effect of pattern direction [Hine et al (1995, 1997) varied the angular difference in orientation between the two sets of bars]. The predicted effect of pattern direction was tested here in an experiment in which naïve observers were shown moving Ouchi patterns similar to that in figure 1. In each presentation, the pattern oscillated along one of seven possible trajectories between horizontal and vertical, after which the observer rated the apparent magnitude of the illusory motion of the centre relative to the surround on a nine-point scale (1 = little or no illusory motion; 9 = marked illusory motion).

2 Methods

2.1 *Subjects*

Ten naïve undergraduate students at the University of Sussex acted as unpaid observers.

2.2 *Apparatus and stimuli*

Images were generated by a PC-compatible computer and displayed on a Hitachi 14MVX monitor (P22 phosphor, 60 Hz refresh rate). An Ouchi pattern identical to that shown in figure 1 was employed. The outer border of the pattern subtended 14 deg at the 57 cm viewing distance. Each bar in the checkerboard pattern (contrast 0.95) subtended 1.14 deg by 0.29 deg. The pattern could be made to oscillate through a distance of 1.1 deg along one of seven possible trajectories: 0°, 18°, 34°, 45°, 56°, 72°, and 90° relative to horizontal, at a velocity of 7.3 deg s^{-1}.

2.3 *Procedure*

A single presentation lasting 2 s involved four cycles of oscillation at one of the seven possible trajectories (reversal in direction every 250 ms, combined with the relatively high velocity, made pursuit eye movements extremely difficult, though eye movements were not recorded). After each presentation the pattern was replaced by a uniform mean-luminance background (63 cd m^{-2}), and the observer pressed one of nine numerical keys on the computer keyboard to report the amount of relative apparent movement seen between the central and surrounding regions of the pattern (1 = little or no relative motion; 9 = marked relative motion). A central fixation point was visible continuously, and observers were instructed to maintain fixation on it. Successive trials were separated by an interval of 2 s. Each observer made six judgments of each trajectory angle, in random order.

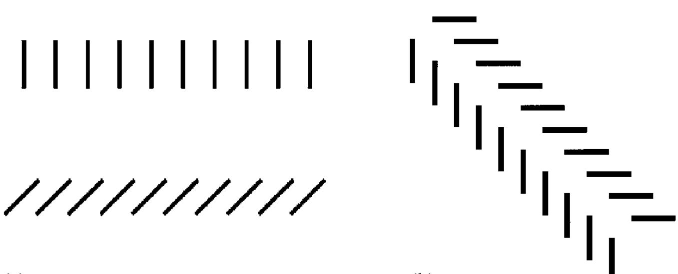
3 Results and discussion

Data points in figure 3a show the mean rating of ten observers as a function of trajectory angle. The broken line shows the best-fitting quadratic function, obtained by least-squares regression. There is close agreement between prediction and data, consistent with the idea that the illusion is related to deviation of the apparent direction of each bar from its true trajectory due to integration bias. The relation between the two vertical scales in figure 3a is arbitrary. Predictions are shown for an orthogonal bias of 0.6; other bias values would simply alter the height of the predicted curve. Note that subjects' rating of illusion strength do not fall to zero at angles of 0° and 90°. This may reflect the fact that integration bias produces a difference in perceived velocity between the lines, as well as a difference in apparent direction (see the lengths of the grey vectors in figure 2). Castet et al (1993) reported such a speed effect using isolated line segments, and in figure 3b their data are re-plotted, along with predicted vector length (velocity) for an orthogonal bias of 0.6. The relation between the vertical scales is not arbitrary: in Castet's experiment observers judged the speed of tilted lines relative to the speed of orthogonally oriented lines. Predicted vector lengths are similarly expressed as a proportion of the prediction for orthogonal lines. Weighted linear combination of motion vectors provides a good quantitative account of the data, on assuming an orthogonal basis of 0.6.

The present data are inconsistent with the explanation offered by Khang and Essock (1997). They argued that movements parallel to the long axis of one set of elements (and orthogonal to the other) would produce the greatest effect, since this maximises the difference in the rate of contrast reversals produced by the elements. Results are consistent with the general explanation offered by Hine et al (1997). Previous reports have detailed the dependence of the illusion on a range of stimulus parameters, including aspect ratio and spatial frequency. It remains to be seen whether the present explanation can accommodate these data.

4 Relation to other illusions

So far, integration bias has been shown to provide a good account of two apparently unrelated motion illusions. The hypothesis will now be applied to two well-known geometrical illusions. Returning to figure 2, we can consider the lines at two positions, t_1 and t_2, as two elements in an extended spatial pattern, such as those depicted in figure 4.



(a) (b)

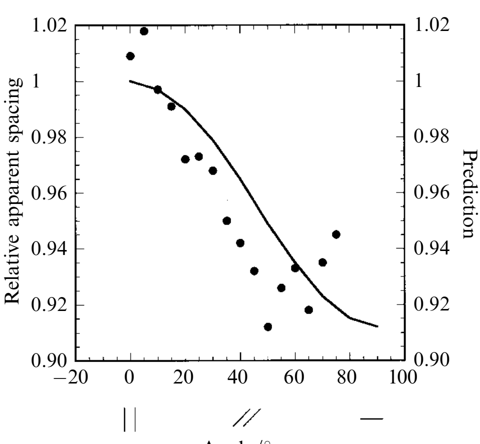
Figure 4. (a) The Judd effect. Horizontal line spacing is the same in the two rows, but the row of tilted lines appears more closely spaced than the row of vertical lines. (b) The Zöllner effect. The two rows of lines are parallel, but appear to diverge from bottom-right to top-left.

Figure 4a illustrates a variant of the Judd illusion (Judd 1899; Morgan and Casco 1990; Morgan et al 1990), the spacing illusion (Mather et al 1991), in which a horizontal row of tilted lines appears more closely spaced than a row of vertical lines. This illusion can be considered a relative of Castet's speed effect (if the lines in each row were presented one after the other in sequence, the tilted line would appear to move more slowly, ie undergo smaller frame-to-frame displacements). The pattern in figure 4b illustrates a variant of the Zöllner effect (Wallace 1964; Tyler and Nakayama 1984), in which rows of tilted lines appear tilted in the direction of line tilt. This illusion can be considered as related to the Ouchi illusion (if the lines in each row were presented in each sequence, they would follow the paths taken by two elements in an obliquely moving Ouchi pattern, and would appear to move in different directions). Previous research has already established possible links between illusions of the Judd and Zöllner type. Morgan and Casco (1990) noted a correlation between them, and attributed the two illusions to related 'orthogonal orientation' and 'orthogonal size' tendencies. Here it is shown that they can both be explained by the same kind of integration bias that accounts for the Ouchi and Castet illusions (though, of course, the actual neural mechanisms must differ, since one involves spatiotemporal coding, ie motion, and the other involves the encoding of spatial arrangement).

When encoding the spatial arrangement of a row of line elements, at least two signals are available. Orthogonal separation between adjacent lines may be signalled by spatial-frequency-tuned cells. End-point (parallel) separation may be signalled by end-stopped cells. If the process that integrates these signals applies a bias in favour of one of them, in an analogous manner to that depicted in figure 2, then Judd- and Zöllner-type effects will arise just as the Castet and Ouchi effects do. Can integration bias predict the known dependence of the Judd- and Zöllner-type effects on line orientation?

In a number of previous experiments the strength of Zöllner-type illusions has been measured as a function of the orientation of the lines in the pattern (Tyler and Nakayama 1984; Morgan and Casco 1990). Figure 5b shows re-plotted data from Tyler and Nakayama (1984), along with the best-fitting line according to least-squares regression (broken line). The solid line in figure 5b represents the prediction on the basis of the weighted linear combination of orthogonal and parallel signals, assuming a small orthogonal bias of 0.513 (the relation between the vertical axes is not arbitrary). The predicted curve captures the shape of the empirical function, but the latter is more sharply tuned to pattern orientation. Figure 5a shows re-plotted data on the spacing illusion from Mather et al (1991), along with the prediction from weighted linear combination, again on assuming an orthogonal bias of 0.513. Predictions follow the general trend of the data.

Deviation of predictions from the data in figure 5 may arise because the orthogonal bias itself changes slightly as a function of orientation. Bias may also be affected by stimulus configuration. Data on the Judd- and Zöllner-type displays reported by Morgan and Casco (1990), derived with the use of tilted 'H' configurations (eg comparison of H and *H*) showed much larger biases than those in figure 5, eg orientation shifts of up to 70°, and spacing underestimations of up to 50%. These effects can also be predicted by the present scheme, on assuming a very strong orthogonal bias of about 0.9.



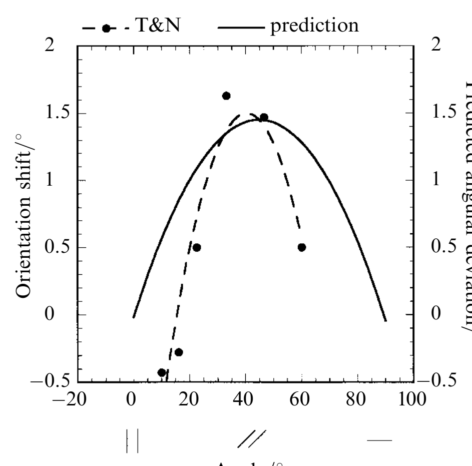


Figure 5. Predictions and data for the Judd effect (a), and the Zöllner effect (b). Predictions are based on the scheme in figure 2, on assuming that the displacement of each bar represents spatial separation rather than apparent motion, and on assuming an orthogonal bias of 0.513. Data on the Judd effect are re-plotted from Mather et al (1991), figure 2. Data on the Zöllner effect are re-plotted from Tyler and Nakayama (1984), figure 31.4.

5 General discussion

A simple scheme based on the weighted linear combination of local signal vectors, with just one free parameter (bias), can provide a good account of four visual illusions, two involving motion and two involving spatial arrangement. It is widely accepted that the encoding of motion and texture must involve processes that integrate local signals from different parts of the image. The account presented here requires that such processes exhibit a bias in favour of some signals over others, and that bias values differ in different stimulus arrangements. Integration bias seems an arbitrary notion, manipulated a posteriori to fit the data, though it is a recurring theme in explanations of illusions related to those described here. Previous authors have made a number of suggestions concerning the origins of bias. Nakayama and Silverman (1988) proposed that the bias favours motion orthogonal to the local contour. Morgan and Casco (1990) suggested that the perception of Judd- and Zöllner-type illusions is dominated by "the class of visual filter optimally tuned to the stimulus" (page 9). Castet et al (1993) argued that bias is based on "perceptual saliences" (page 1931), or on a preference for slow speed signals.

A more cogent theoretical framework for integration bias is emerging from recent Bayesian approaches to visual coding, in which weighted combination of multiple signals is governed by the uncertainty associated with each signal (eg Knill et al 1996). Weiss and Adelson (1998) have recently presented a Bayesian theoretical account of motion integration, which does predict biases of the kind proposed here. Their model can predict a range of motion phenomena, including Castet et al's speed effect, with biases assumed to reflect the uncertainty attached to different local signals, and preferences for smooth and slow velocity fields. A very recent computational paper also attributes the Ouchi illusion to biases in motion integration (Fermueller et al 2000).

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