Additive effects in a rod-and-frame illusion estimated by response classification

Melanie A. Lunsford
Department of Psychology, Rice University, Houston, TX, USA

James L. Dannemiller
Department of Psychology, Rice University, Houston, TX, USA

Previous research has shown that not all segments of a square frame are necessary to produce the illusory tilt of an enclosed vertical line. Indeed, the presence of a single tilted line is often sufficient to induce the illusory tilt of a nearby vertical line (Carpenter & Blakemore, 1973). How do the four segments of a quadrilateral frame contribute to the illusory tilt if any one of them is sufficient to induce the illusion? Response classification (RC) was used in two experiments to examine the independent contributions of the four segments of a quadrilateral frame to judgments of the direction of tilt of an enclosed vertical line. Orientation perturbations were added independently to the four frame segments. The orientation of the top segment contributed most systematically to these judgments, whereas the orientation of the bottom segment contributed very little. Individual differences were observed with two of the four observers showing the largest apparent tilt of the test line for shear configurations of the quadrilateral in which the top and bottom segments were rotated in a direction opposite to the right and left segments. Logistic regression was used with a double-pass technique to estimate the relative importance of the four segments. Interactions between the segments were not systematically related to the observers' judgments. The results are discussed in terms of the utility of RC and logistic regression for studying perceptual phenomena whose mechanisms are thought to lie at levels such as orientation that are different from those typically examined with RC and pixel noise.

Keywords: response classification, rod-and-frame illusion, logistic regression

Introduction

Response classification (RC) has been used to determine the features that an observer uses to discriminate two patterns (Beard & Ahumada, 1998). In the case of discriminating pictures of two different faces, for example, a classification image that estimates the relative weights given to different spatial regions such as the eyes, the mouth, and so forth can be computed. There are two important aspects of this methodology that are worth noting. First, to estimate weights, random noise is added to the original pictures to estimate areas of the image used by the observer in making the discrimination. Second, the method essentially correlates the observer's dichotomous responses (e.g., Face A vs. Face B) across trials with the random noise used to perturb the original pictures. The final classification image is usually estimated separately for each observer (Eckstein & Ahumada, 2002), although with proper combination weights, these images can be pooled across observers. This last point is important because real observers will differ from each other and from an ideal observer in making such discriminations. The methodology is particularly useful for revealing differences between observers in how they weight the information available for performing a given task.

These two aspects of the methodology led us to explore RC as a method for estimating the weighting of orientation information in a classical visual illusion: the rod-and-frame illusion (RFI; Asch & Witkin, 1948; Coren & Hoy, 1986). The RFI is similar, although not identical, to a large class of orientation illusions in which the presence of an inducing stimulus such as a tilted line influences the perceived orientation of a neighboring vertical test line (Wenderoth, Johnstone, & van der Zwan, 1989). In the RFI, a square frame is slightly rotated either clockwise (CW) or counterclockwise (CCW) from its canonical orientation (i.e., canonical = left and right sides vertical, top and bottom sides horizontal). A vertical rod enclosed within the frame appears to tilt in the direction opposite to the rotation of the frame for small frame rotations less than about 30 deg (e.g., see Coren & Hoy, 1986; Figure 1).

The RFI is a simple yet potentially powerful way of asking several fundamental questions about spatial perception. It is simple because it only involves five line segments: four segments comprising a frame and one segment comprising a test segment. The questions posed by the RFI are among the most fundamental in all of spatial perception. How does context affect perception? How do parts of a figure contribute to the perception of the whole? In this case, the context refers to the frame, and we are interested in how the frame affects the perceived orientation of the vertical test segment. Because the frame is composed of four segments, we are also interested in how each of these segments contributes to the overall context effect of the frame. This can be seen as an example of information...
integration (Kinchla, Chen, & Evert, 1995); how are the effects of the four frame segments integrated to produce the overall context effect of the frame on the perceived orientation of the vertical test segment?

Various theories have been proposed to explain the RFI. For example, Beh, Wenderoth, and Purcell (1971) proposed that the axis of symmetry nearest to vertical in the frame induces a perceived tilt of the rod in the opposite direction (repulsion). The axis of symmetry is simply a line that divides the inducing figure bilaterally into equal halves. As a square frame is rotated CW, initially, the axis of symmetry closest to vertical is the one that passes through the centers of the top and bottom sides of the frame. As the frame continues to rotate CW, another axis of symmetry through the upper left and lower right corners will now be closest to vertical. The frame will eventually be oriented at 45 deg with respect to its canonical orientation. Here, one of the axes of symmetry is perfectly vertical; hence, the illusory tilt of the rod should and does drop to zero; in other words, the orientation of the rod is veridically perceived when the frame is rotated to 45 deg. As the frame continues to rotate from 45 to 90 deg, the illusory tilt will reverse direction as the other axes of symmetry approach and pass through vertical. The RFI does not require a square frame; dot patterns with axes of symmetry also produce perceived tilt of a central rod (Joung & Latimer, 2003).

Although a square frame will have four axes of symmetry, only one of these axes—the one nearest to vertical—apparently produces the illusion as the frame rotates. This could imply that frames lacking one or more sides might still produce the illusion as long as they have an axis of symmetry. There are other reasons for supposing that only some parts of the frame might be involved in producing the illusion. A tilt illusion can result from a single neighboring inducing line (O’Toole, 1979; Wenderoth, O’Toole, & Curthoys, 1975). Deleting individual sides of the frame also shows that some of the configuration can be missing, yet the illusory rod tilt will persist (Wenderoth & Curthoys, 1974). Are observers simply insensitive to this apparently extraneous information? Are they ignoring it? Or is this information fundamentally unimportant to the mechanisms that produce such tilt illusions?

Deleting a frame segment to evaluate its importance in producing the illusory tilt of the rod has the drawback of changing the context within which the overall effect operates. In other words, a frame has four sides, but a frame with one side amputated has only three sides; hence, it provides a potentially very different context (e.g., open vs. closed) for assessing the impact of the individual frame segments. The RC method that we propose below preserves the four frame segments and allows an assessment of their independent contributions to the illusory tilt of the central test segment.

Another perspective on the RFI is provided by Carpenter and Blakemore (1973). Although not explicitly a theory of the RFI, Carpenter and Blakemore proposed that inhibition exists between nearby lines in the visual field at the level of orientation. Thus, adding a third line to a set of two lines can actually weaken the influence of one of the original two lines on the perceived tilt of the other. This kind of mutual interaction between the lines gives yet another suggestion for how the effects of the four frame segments might combine to produce the overall illusory tilt in the RFI.

Using the RC method allowed us to ask whether the different parts of an inducing frame were equally strongly correlated with the observer’s judgment of the perceived tilt of the test line. In the standard RFI, this question cannot be answered because all parts of the frame rigidly rotate. Alternatively, RC might be suited to answer this question provided that noise could be used to independently perturb the parts of the inducing figure. In the case of a nominally square-inducing frame, this means that orientation noise should be used to perturb the orientations of the four sides of the frame. In this case, the frame will appear on the majority of trials not with its four sides in their canonical orthogonal and parallel relations, rather with those sides randomly oriented with respect to each other. Just as contrast noise is added to the pictures in a face discrimination study to estimate the features contributing to the discrimination, orientation noise can be added to the standard orientations of the sides of an inducing frame to estimate the relative importance of these elements to the judgments of the perceived tilt of the test line.

What predictions would the approaches of Beh et al. (1971) and Carpenter and Blakemore (1973) make when the four frame segments can be independently rotated? First, the axis-of-symmetry approach of Beh et al. requires a rigidly rotating frame that maintains the angular relations between the sides as the whole frame rotates. In general, the configurations of the frame segments that we showed to observers did not have dominant axes of symmetry because each segment could take on its own orientation independent of the other three orientations. In this sense, then, the axis-of-symmetry approach does not make explicit predictions about the perceived direction of tilt for the stimuli that we used.

Carpenters and Blakemore’s (1973) approach requires something akin to solving a five-body problem. If all segments can mutually influence the perceived tilt of all other segments, and the task is to derive a prediction for the perceived tilt of the central vertical segment, then ultimately this would have to involve integrating the effects of the four frame segments on each other and on the central rod, as well as taking into account the effect of the central rod on the four frame segments. Needless to say, although certainly plausible, the construction of such a model requires a precise quantitative characterization of these mutual effects between the segments. Although Carpenters and Blakemore’s data provide some of this information, the construction of the full model would require additional pairwise measurements for each observer, which is beyond the scope of the present work. As a first approach to the question of how the individual segments
might separately or jointly contribute to the perceived orientation of the test segment, we tested a simple linear model using the RC methodology and logistic regression.

Because the RFI is an orientation illusion, we attempted to apply the RC methodology by adding orientation noise, rather than pixel contrast noise, to the line segments. Although most studies using the classification image methodology have used pixel noise, there have been several studies that have used nonpixel noise (Li, Levi, & Klein, 2004; Shimozaki, Eckstein, & Abbey, 2005). Because our question concerned the relative weights assigned to the four frame segments, we directly perturbed their orientations and derived the weights from a regression analysis much like Ahumada and Lovell (1971) did in estimating the contributions of various frequencies to a listener’s detection of a target frequency. We hope to show through this use of RC that noise at a level appropriate to the phenomenon under study can be used to answer general questions about the relative importance of different visual features in performing a given task.

It is also important to point out one other potentially important difference between our use of RC and most previous uses employing pixel noise. In many of the previous experiments, noise is directly added to the two images to be discriminated, and the observer is asked to guess which image was presented on each trial. In contrast, we are independently adding orientation noise to four frame segments and asking the observer for a judgment of the perceived tilt of a test line that was never perturbed by such orientation noise. Rather than asking for a direct judgment of which pattern was presented, we are asking for a more indirect judgment of the effect of a particular pattern or configuration of lines on a perceived characteristic of another perceptual object. We think that it is important to keep this distinction in mind in interpreting such data. In our use of RC, there is no correct answer. We did not ask observers to classify the frame configurations as either CW or CCW; rather, we asked for a judgment regarding the perceived effect of variations in those configurations on an unvaryingly vertical test line. We know of only one other study in which the noise being correlated with the observer’s responses was added not to the perceptual object being judged but to a surrounding region. Shimozaki et al. (2005) used annular ring noise surrounding a target to determine the perceptual filter in a contrast detection–discrimination task.

A standard classification image with pixel noise uses gray as a representation of no weight or no influence and gray scale variation as a representation of the correlation of a given pixel with the observer’s judgment. This kind of final representation of results is difficult to produce in the case of RC applied to the RFI because the mean orientation noise for a given frame segment would have to be displayed with respect to some reference orientation or translated into some other dimension such as luminance contrast. Alternatively, a plot of regression weights conveys the useful information from such a study; hence, we followed the lead of Ahumada and Lovell (1971) to represent our results.

In this original study, noise was added to an auditory stimulus to determine how different frequencies were related to a listener’s detection of a target frequency. Ahumada and Lovell then used standard multiple regression to estimate the contributions of the various noise frequencies to the listener’s judgments. In the original study, listeners rated their confidence in the presence of the signal on each trial on a 5-point scale. This dependent measure was then used with standard linear regression to estimate the contributions of the various frequencies to the listener’s detection judgments. In the experiments below, and in most RC studies to date, a dichotomous decision is made on each trial. In this case, the dependent variable is not continuous; hence, logistic regression is more appropriate for estimating the coefficients. The principle, however, is the same: The weights from logistic regressions applied to our data can be interpreted as the relative importance of orientation variation in the four frame segments to the decision of whether the test rod appears tilted CW or CCW.

These regressions estimate the additive effects of the orientations of these frame segments on observers’ judgments of perceived tilt. Previous research has indicated nonadditive effects of multiple inducing lines on illusory tilt (Carpenter & Blakemore, 1973; O’Toole, 1979; Wenderoth & Curthoys, 1974). For example, the addition of a second inducing line can weaken the effect of the primary inducing line on the magnitude of illusory tilt. Using our method, it was also possible to estimate interactions between the frame segments by entering interaction terms in the multiple regression. We did not observe such interactions in these experiments at levels above those expected by chance.

We conducted two experiments using RC to study the RFI. The same observers, stimuli, and procedures were used in both experiments. The observer’s task was to judge the orientation of a central rod surrounded by a quadrilateral frame of independent line segments. In both experiments, the orientation of the central rod was always perfectly vertical, and the orientation of each of the frame segments was perturbed in 5-deg increments from –25 to +25 deg of its mean orientation. In the second experiment, another factor was included to shift the mean orientation of the frame segments by ±10 deg.

### Experiment 1

#### Methods

One of the authors, M.L., along with three naive observers, A.A., A.R., and K.G., participated in this experiment. All had normal or corrected-to-normal acuity. In the first experiment, each observer participated in 10 sessions, each consisting of 200 trials, for a total of 2,000 trials.
Stimuli

The stimulus consisted of a vertical test line (rod) surrounded by four frame segments, generated using the Psychophysics toolbox (Brainard, 1997; Pelli, 1997) for Matlab. The frame and rod segments were white on a gray background. The Michelson contrast for the segments was 75% (background luminance: 26.45 cd/m², segment luminance: 183.6 cd/m²). Two of the frame sides, the top and bottom, had canonical orientations of horizontal at 0 deg, and the right and left sides had canonical orientations of vertical at 90 deg. The rod and frame segments were 0.08 deg wide × 1.1 deg long. Unlike in standard RFI studies, the frame segments did not intersect. The frame segments were separated from the central rod by a center-to-center distance of 0.75 × segment length or 0.825 deg. The central rod was always presented vertically. For each trial, the frame segments were allowed to deviate in 5-deg increments from 0 deg (canonical orientation) to 25 deg deviation in either direction. The classification image methodology requires Gaussian noise distributions. Because of discreteness issues regarding variation in the orientations of small line segments, we used noise values that were chosen instead of a discrete, uniform distribution that ranged from −25 to +25 deg in 5-deg steps. Although this violates one of the assumptions of the classification image methodology, we would not expect this difference to have a critical impact on the results reported below. Additionally, we primarily relied on binary logistic regression to estimate decision weights rather than using the standard method of differencing response-sorted noise vectors. CCW rotations were assigned negative values, and CW rotations were assigned positive values. The deviation for each frame segment was independent of the deviation for the other segments across trials. Frame segments were rotated about their center points that remained fixed in position.

Stimuli were displayed on a CRT monitor in noninterlaced mode at 75 Hz. The display measured 40 deg horizontally × 30 deg vertically when viewed from the 57-cm observation distance. The only room light during testing was provided by the gray background of the display monitor.

Design and procedure

Although the rod presented in the center of the frame was always vertical, the observer’s task was to indicate whether the center rod appeared to be tilted CW or CCW. The observer was not informed that, in fact, the rod never deviated from vertical. The timeline for events in a trial and an example of the stimulus are shown in Figure 1.

A thin ring (diameter: 3.1 deg) that encompassed the frame segments was used as an implied fixation point. A beep was given to signal the upcoming stimulus presentation. The stimulus was displayed for 21.4 ms followed by a return to a uniform gray field while awaiting the observer’s response. The observer was asked to report on each trial the direction of tilt of the top of the central test line. The observer pressed the “z” key on a standard keyboard to indicate a CCW perceived tilt and the “m” key to indicate a CW perceived tilt. A new trial was started approximately 2 s after the observer’s response. The very brief duration of the stimulus display was chosen based on a report that short display durations (10–60 ms) produced a large RFI (Wenderoth & van der Zwan, 1989).

A double-pass technique was also employed to estimate the reliability of these perceived tilt judgments. In the first pass, five sessions of 200 trials each were presented to the observer. In the second pass, the same five sessions of 200 trials each were presented in the same order so that the observer was presented with each trial twice during the experiment. The agreement between the judgments in the two passes could then be used as an estimate of the reliability of the judgments. This double-pass feature also provides a model-free test of whether the stimulus noise affects the observers’ responses. That is, it is possible that the perturbations of the frame segments could have a systematic, reliable effect on the observers’ responses, even if this effect was not captured by a linear model. In this case, we would expect to see reliable correlations between the judgments across the two passes but nonsignificant linear weights when the orientation noise was used to model those judgments.

Results and discussion

Reliability data

Because the test line never deviated from vertical, the observers’ judgments were based solely on the illusory tilt of this line. It is imperative to ask whether such judgments are (a) reliable and (b) related systematically to the orientations of the frame segments. We address the reliability of these judgments in this section, and their relations to stimulus features in the next.
The two identical passes through the same stimulus sequence allowed us to assess the reliability of the judgments. If the frame segments exerted no systematic effects on the perceived tilt of the test line, then an observer’s judgment would be solely based on internal noise in the perceived orientation of this line. In this case, we would expect chance similarity between the observer’s responses across the two passes. Observers’ reliability estimates (percentage of agreement [PA] across passes and correlation of responses across passes) were as follows: M.L. 70.1%, r = .402; A.A. 59.9%, r = .198; A.R. 63.7%, r = .268; K.G. 75.8%, r = .537. Responses on the two passes were the same at least 60% of the time or more for these four observers.

By chance, one would expect 50% agreement between the two passes if the judgments were entirely influenced by the internal noise in the representation of the vertical test line and if the observer was unbiased. The PAs approximately ranged from 60% to 76%. The biases for individual observers ranged from 0.05% to 4.45%, but the rank order correlation between bias and PA was 0. This means that none of the variation in the PA across observers was attributable to variation in bias. It is perhaps not surprising that the agreements across the two passes were in this range because there was no physical tilt signal for the central line, rather these judgments were entirely based on any illusory tilt induced by the frame segments.

**Psychometric functions**

Figure 2 shows the percentage of CCW responses for each level of deviation from a frame segment’s mean orientation across all 2,000 trials for each observer. Recall that the mean orientations of the top and bottom segments were horizontal and the mean orientations of the right and left segments were vertical. For observer M.L., as the top segment is increasingly rotated CW, the proportion of CCW responses increases. All observers showed the same direction of effect for the top segment. For M.L., this effect was larger in magnitude (steeper slope) for the top segment as compared with other segments. Observers A.R. and K.G. showed a directional effect for the top segments that was opposite to those for the right and left segments. Observer A.A. directionally showed consistent effects that tended to be low in magnitude.

The direction of the effect for the top segment is consistent with what has been observed in the literature when single inducing lines are used. For example, Wenderoth and Curthoys (1974) showed that a single inducing line that intersected a test line at an angle of 60 deg produced a perceived tilt of the vertical test line toward the inducing angle as if the angle between the two appeared to be less than it actually was. Gibson and Radner (1937) showed that inducing lines intersecting the test line at angles approximately between 50 and 90 deg produced apparent tilts of the test line in the same direction, again as if the angle between the two lines perceptually contracted. In Experiment 1, the top (and bottom) segments varied in their orientations with respect to the vertical test line across the range from 65 deg (CW orientation noise) to 115 deg (CCW orientation noise). Based on the prior literature, the relations between 65 and 90 deg would be expected to induce perceived CCW tilts and vice versa for the relations between 90 and 115 deg. In our data, all four of the observers showed increasing percentages of CCW responses as the top test line was rotated CW from its mean horizontal orientation. This means that the test line appeared to tilt in a direction that made it appear to intersect the top frame segment at an angle less than it would actually have if it had been spatially extended. In other words, variations in the orientation of the top segment around horizontal produced independent effects that were in the same direction as those observed in prior studies when single inducing lines were used.

The same cannot be said for the direction of the effects of the right and left segments for observers A.R. and K.G. In this case, the prior literature would predict that single inducing lines slightly perturbed from the vertical should make the test line appear to tilt in the opposite direction as if the angle between the two appeared to be expanded from its physical value (Carpenter & Blakemore, 1973). In our experiment, this would have resulted in increases in the proportion of CCW responses as the right and left segments had positive values of orientation noise added to them. Examination of Figure 2 shows that observers A.R. and K.G. showed effects opposite to these predictions for their right and left segments, whereas observers M.L. and A.A. showed effects consistent with these predictions but with very weak effects.

Why might these differences from the prior literature have emerged in Experiment 1? First, consider the weak-to-zero effects of the right and left segments for observers M.L. and A.A. In Wenderoth and Curthoys (1974), a single inducing line oriented at 30 deg from the vertical actually
produced no effect on the perceived tilt of the test line (see Experiment 1, −30 deg condition; Wenderoth & Curthoys, 1974). Thus, the lack of large effects for the right and the left segments for observers M.L. and A.A. is at least similar to the weak effects of single, near-vertical inducing lines observed in at least one prior study.

However, the reversal of sign on these segments for observers A.R. and K.G. cannot be explained in this way. Rather, we note that consistently repulsive effects of small frame rotations on the apparent tilt of the test line have not always been observed. Rather, they appear to depend on the spatial and temporal parameters of the display. For example, Wenderoth et al. (1975) observed slightly attractive effects for an inducing line oriented 15 deg CW from vertical when the inducing line was smaller than the test line, and this effect changed sign to a repulsive effect when the lengths of the inducing and test lines were more nearly equal. Spinelli, Antonucci, Daini, and Zoccolotti (1995) showed that 30-deg rotations of a square inducing frame produced no tilt illusion for the central test line when the gap between the frame and the test line was small (20 arcmin), but this rotation actually produced perceived tilts in the direction of the frame rotation (attractive or indirect effects) when the gap was larger (2 deg of arc). Zoccolotti, Antonucci, and Spinelli (1993) showed that there was a tendency for typically repulsive effects of frame rotations of as little as 22.5 deg to switch to attractive effects as the size of the frame was reduced and as the gap between the test line and the frame was increased. Wenderoth (1974) noted that even with square frame rotations of 15–20 deg, whereas the majority of observers showed repulsive illusions, a small percentage of observers showed attractive illusions. In all of these studies, there is evidence then that stimulus factors can modulate the direction of the effect of rotations of either single lines or square frames and that there are individual differences in the sign of the illusion. Our frame segments were quite small relative to some of these prior studies (1.1 deg), with the implied square frame in Experiment 1 being 1.65 deg on a side. It is possible that the small size of our stimuli and the very brief duration produced atypical effects at least for two of our observers.

### Estimating segment weights

To estimate the contributions of the four frame segments to an observer’s tilt judgments, we used logistic regression. The observer’s response on each trial was coded as −1 (CCW) and +1 (CW). The random noise deviations for each segment were entered as predictors with CW deviations positively coded.

The logistic regressions correctly classified responses on 78.9%, 67.5%, 73.1%, and 81.1% of all trials for observers M.L., A.A., A.R., and K.G., respectively. This measure is analogous to an $r^2$ from a standard linear regression.

Figure 3 shows the coefficients obtained from the analysis for each observer. A weight of zero for a given segment indicates that noise deviation had no effect on the probability of a CCW response. A negative weight indicates a repulsive effect of the segment on the observer’s response; that is, perturbing a segment’s orientation in a CW direction results in more CCW responses. For example, both M.L. and A.A. show negative weights for all segments, indicating that their judgments of rod tilt run counter to the direction of changes in the segment tilts. In contrast, two of the observers, A.R. and K.G., show positive weights for their right and left segments. This means that, for A.R. and K.G., as the left and right segments tilt more CW, they respond with more CW judgments of rod tilt. The weighting profiles for A.R. and K.G. are remarkably similar. As an additional check on the stability of these coefficients, separate logistic regressions were conducted for the data from the two passes. As shown in Figure 4, the signs remain the same for the majority of segment weights across passes for each of the observers, although the magnitudes changed a small amount.

The magnitudes of these weights are informative as well. Observer A.A. approximately equally weights all of the segments. In contrast, observer M.L.’s top segment weight is approximately four times larger than the weights on any of the remaining segments. For observers A.A., A.R., and K.G., their judgments are approximately equally influenced by at least three of the four segments. In other words, the effects of three of the four frame segments on the apparent
tilt of the test line appear to be approximately equally integrated (although with different signs) in determining the observer’s final judgment of the direction of tilt. It is noteworthy that for all of the observers, the bottom segment is never weighted very heavily. Changes in the tilt of the base appear to be ignored.

It is important to keep in mind that the coefficients from a multiple regression are typically interpreted as indicating the slope between predictor and criterion with all other variables being held constant. In other words, a logistic regression coefficient of $0.05$ for the top segment means that with the other three segments held in fixed orientations, a 10-deg CW change in the orientation of the top segment leads to a 0.5 logit decrease in the probability of a CW response, $\logit(p) = \ln[p/(1-p)]$. For example, with the other segments set to produce a net proportion of CCW responses of 50%, rotating the top segment 10 deg CW by itself would increase the proportion of CCW responses to approximately 62% with a coefficient of $-0.05$ for the top segment.

For purposes of comparison, we used two other methods to estimate the influences of the four segments. For the first, we computed the simple correlation between the noise deviations and the responses. This is equivalent to a point-biserial correlation coefficient. When the predictors are independent as they are here to a first approximation, these simple correlations will mirror the regression coefficients from a multiple regression. We included these correlations here because most readers will have an intuitive grasp of the meaning of the correlation coefficient and be able to interpret these as measures of the relative influences of the frame segments. For the second, we followed traditional classification image methodology by computing the mean difference values for each segment from the response-sorted trials. The mean difference value for each segment was calculated by subtracting the mean noise deviation when the observer responded CW from the mean noise deviation when the observer responded CCW. For a segment that has no influence on the observer’s tilt judgments, both of these measures should be zero, and hence their difference should be zero as well. These measures are shown in Table 1. We included this index because it is the standard one computed from a classification image study, and we wanted to be able to show the correspondence between the logistic regression weights and these mean orientation noise values.

The segment weights discussed above reveal the additive effects of orientation noise on the observers’ judgments of rod tilt. It is possible, however, that these frame segments might interact to influence these judgments. We also conducted a logistic regression with all possible two-, three-, and four-way interactions between the segments, as well as their main effects for each observer. There were 11 possible interactions in each analysis, for a total of 44 possible interactions across the four observers. We observed 5 significant ($p < .05$) interactions out of the set of 44. If we

\[ \text{Observer} \quad \text{Segment} \quad r \quad \text{Mean difference (deg)}^a \]

<table>
<thead>
<tr>
<th>Observer</th>
<th>Segment</th>
<th>$r$</th>
<th>Mean difference (deg)$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>M.L.</td>
<td>Top</td>
<td>-.566*</td>
<td>17.20</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>-.022</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td>Bottom</td>
<td>-.141*</td>
<td>4.42</td>
</tr>
<tr>
<td></td>
<td>Left</td>
<td>-.081*</td>
<td>2.64</td>
</tr>
<tr>
<td>A.A.</td>
<td>Top</td>
<td>-.240*</td>
<td>7.41</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>-.165*</td>
<td>5.14</td>
</tr>
<tr>
<td></td>
<td>Bottom</td>
<td>-.177*</td>
<td>5.57</td>
</tr>
<tr>
<td></td>
<td>Left</td>
<td>-.207*</td>
<td>6.54</td>
</tr>
<tr>
<td>A.R.</td>
<td>Top</td>
<td>-.351*</td>
<td>10.87</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>.291*</td>
<td>-9.09</td>
</tr>
<tr>
<td></td>
<td>Bottom</td>
<td>-.082*</td>
<td>2.58</td>
</tr>
<tr>
<td></td>
<td>Left</td>
<td>.220*</td>
<td>-6.98</td>
</tr>
<tr>
<td>K.G.</td>
<td>Top</td>
<td>-.358*</td>
<td>11.05</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>.348*</td>
<td>-10.85</td>
</tr>
<tr>
<td></td>
<td>Bottom</td>
<td>-.027</td>
<td>0.85</td>
</tr>
<tr>
<td></td>
<td>Left</td>
<td>.414*</td>
<td>-13.13</td>
</tr>
</tbody>
</table>

Table 1. Correlations and mean difference values for all observers in Experiment 1. $^a$CCW − CW. $^p < .003$ (Bonferroni corrected for 16 tests).
correct for multiple tests \((0.05 / 11 = 0.004)\), only one of these interactions will remain significant. The observed number of significant interactions does not exceed what would be expected by chance. We conclude that to a first approximation, the segments independently behaved in influencing the observer’s tilt judgments.

Why did we mostly observe additive, independent effects of these frame segments when other studies have decidedly observed nonadditive interactions between multiple segments? We return to this question in the General discussion section.

**Experiment 2**

**Methods**

Experiment 1 showed (a) clear individual differences between observers in their weighting of the four frame segments, (b) mostly additive effects of the frame segments on the perceived tilt of the central test segment, and (c) consistently weak influence of the bottom segment on the perceived tilt of the central test segment. These effects were observed with the mean configuration of the frame vertical and horizontal with respect to gravity. The strongest illusory tilt in the RFI occurs with the frame rotated approximately 10–15° in either direction from vertical (Beh et al., 1971). In Experiment 2, we examined the generality of the effects noted above when the mean frame configuration was rotated away from vertical and horizontal.

In this experiment, we used two frame configurations offset from the canonical horizontal and vertical configuration used in Experiment 1. In one frame configuration, each segment was rotated CCW by 10° from its canonical orientation in Experiment 1, and in the other, each segment was rotated CW by 10° (for examples of the stimulus configuration, see Figure 5). We used the same range of orientation noise \((\pm 25°)\) that we used in Experiment 1. Because of the addition of another variable, the number of trials was doubled and each observer participated in 20 sessions, each consisting of 200 trials, for a total of 4,000 trials.

The same methodology as that in Experiment 1 was applied. That is, noise deviation was independently added to each frame segment in the same manner as that in Experiment 1. The same observers reported whether the central rod appeared to be tilted CW or CCW. The observers did not know again that the test rod was always vertical, nor did they know that two mean frame offsets served as the base configurations across trials.

**Results and discussion**

**Reliability data**

We estimated reliability from the double pass through each sequence of trials as we did in Experiment 1. Observers’ reliability estimates \((PA across passes and correlation of responses across passes)\) were as follows: M.L. 74.7%, \(r = 0.495\); A.A. 60.2%, \(r = 0.201\); A.R. 74.5%, \(r = 0.483\); K.G. 72.2%, \(r = 0.448\). These reliability estimates are similar to, and slightly higher than, those in Experiment 1. Once again, they show that despite the constant vertical orientation of the central test line, identical perturbations of the orientations of the four line segments produced reasonably similar responses for the perceived tilt of the test line.

**Psychometric functions**

Figure 6 shows the percentage of CCW responses for each level of noise deviation from a segment’s mean orientation. The two frame configurations (+10° CW, −10° CCW) are separately plotted. We plotted the data from Experiment 1 again in Figure 6 for purposes of comparison.

![Figure 5. Example of CCW and CW configurations in Experiment 2. These two figures show the mean orientations of the frame segments in the two configurations.](https://jov.arvojournals.org/pdfaccess.ashx?url=/data/journals/jov/933516/)

![Figure 6. Percentage of CCW responses as a function of deviation from the mean orientation (in degrees) for each segment and frame configuration, for each observer. The data from the CW configuration are plotted in green, and the CCW configuration data are plotted in blue. The data from Experiment 1 are plotted in black. Positive values indicate CW, and negative values indicate CCW.](https://jov.arvojournals.org/pdfaccess.ashx?url=/data/journals/jov/933516/)
exception of the top segment for observer A.A., we observed similar effects of noise deviation on the observers’ responses as had been observed in Experiment 1. The top segment generally exerted the strongest effect (had the steepest slope). Again, A.R. and K.G. showed effects for the right and left segments that were directionally opposite of that for the top segment.

Observer M.L. shows large shifts of psychometric functions with changes in the frame configuration (−10, 0, and +10 deg). These shifts appear for all segments. For example, the proportion of CCW responses substantially increases as the frame configuration is oriented more CW. The same is apparently true for the other three segments when the three frame configurations are compared (i.e., there are large changes in the vertical levels of the psychometric functions across the three frame configurations). These shifts, however, actually reflect the high weighting M.L. gives to changes in the orientation of the top segment. From the logistic regression in Experiment 1, we can estimate the proportion of CCW responses that M.L. gives when the top segment is rotated −10 and +10 deg while the other segments are held constant in their canonical orientations. The values of these two proportions are 0.272 and 0.737, respectively. Inspection of Figure 6 shows that the mean proportions of CCW responses for the two frame configurations are approximately equal to these two predicted proportions for the right, bottom, and left segments regardless of the level of orientation noise added to these segments (the psychometric functions are flat). In other words, as in Experiment 1, all of M.L.’s responses in Experiment 2 can be entirely explained by the fact that only the orientation of the top segment influences the reported tilt of the rod. Essentially, there is no independent effect of the frame configuration on observer M.L.’s responses; those responses are entirely determined by the absolute orientation of one segment.

A.R. and K.G. show a pattern of results different from M.L. Regardless of frame configuration, noise deviations for all segments affected responses in the same way as they had in Experiment 1. That is, although the mean orientation of the frame is tilted 10 deg CCW (mean orientation = −10 deg), a segment’s noise deviations continue to approximately produce the same proportions of CCW responses as when the mean orientation of the frame is 10 deg CW (mean orientation = +10 deg). The fact that the psychometric functions for a given segment for these two observers substantially overlap despite as much as a 20-deg difference in the segment’s mean orientation implies that these two configurations lead to nearly identical responses. Indeed, the proportions of CCW responses for the two mean configurations (above a value of 0 on the X-axis in Figure 6) are both near 50%. Other configurations produce proportions of CCW responses that substantially deviate from 50%; hence, this is not simply insensitivity to the added noise deviations. It is interesting to note that the two mean stimulus configurations used in this experiment had neighboring segments orthogonally oriented to each other, as shown in Figure 4. It is as if these two observers are immune to the illusion when the segments are configured to resemble a square frame regardless of its orientation.

This result is at first puzzling because it appears to contradict the significant weights observed for these observers on at least three of the four segments in Experiment 1. We think that this result can be explained in a manner similar to that used for M.L. above. Recall that the differences in the psychometric functions in Experiment 2 shown by M.L. across the CW and CCW configurations could be explained by the large and dominant weight given to the top segment. Changing this segment from −10 deg CCW to +10 deg CW produced a large change in the proportion of CCW responses in Experiment 1, and it produced the same effect in Experiment 2 when the mean orientation of the top segment was changed from −10 deg in the CCW configuration to +10 deg in the CW configuration. The coefficients on the top and bottom segments for A.R. and K.G. in Experiment 1 were opposite in sign to those for the right and left segments. Thus, when all of the segments were rotated by −10 deg to produce the CCW configuration in Experiment 2, the additive effects of the orientations of these segments would approximately cancel, leaving no net effect of either configuration on the perceived tilt of the test line. This is essentially what we saw from these two observers in Experiment 2; the psychometric functions for each segment for all mean frame configurations overlapped and centered at approximately 50%. Square configurations produced very little illusory tilt regardless of the orientation at which they were presented to these two observers.

For observer A.A., the trends show that the percentage of CCW responses for any noise deviation, regardless of frame orientation, is approximately the same as in Experiment 1 for the right and bottom segments. For the left segment, the slope of the function for the CW frame configuration is steeper than that of the CCW frame configuration. Although most of the trends we see for observer A.A. were similar to those from Experiment 1 with respect to magnitude (slope) and direction, the direction of the top segment unexpectedly changes in Experiment 2. We have no explanation for this reversal.

These observations, based on examinations of the psychometric functions, lead to the hypothesis that changes in the mean orientations of the frame segments should produce effects that could be simply explained by the additive effects that we observed in Experiment 1. The following analysis of segment weights confirms this hypothesis.

**Estimating segment weights**

The logistic regressions correctly classified responses on 73.3%, 67.7%, 80.2%, and 76.6% of all trials for observers M.L., A.A., A.R., and K.G., respectively.

Figure 7 shows the weights obtained from the logistic regression analysis from Experiments 1 and 2. With the exception of observer A.A., the directions and magnitudes
of the weights between experiments were similar. The logistic regressions in Experiment 2 were conducted without the use of frame configuration (CCW vs. CW) as a predictor in the regression. Several things are evident from these classification plots. With the exception of observer A.A., the directions and magnitudes of the weights are quite similar across the different frame configurations. We interpret this as showing that the additive effects of perturbations in the orientations of the frame segments on the perceived tilt of the vertical test line are largely independent of the overall configuration of the frame. Second, as in Experiment 1, changes in the orientation of the bottom segment are largely ineffective in influencing the perceived tilt of the test line. In contrast, for all observers, changes in the orientation of the top segment most substantially contribute to the decision about the direction in which the test line appears to tilt. Finally, for observers A.R. and K.G., the directions of the weights for the top versus right–left segments were opposed, as was evident in Experiment 1. For these two observers, square configurations produce very little illusory tilt regardless of the orientation at which they are presented. In contrast, shear configurations in which the top and bottom segments are rotated in directions opposite to those applied to the right and left segments produce substantial illusory tilts of the test line. Such configurations are not generally tested when the RFI is used to assess field independence versus field dependence (Asch & Witkin, 1948); hence, observers A.R. and K.G. would be probably classified as being field independent despite the fact that changes in the orientations of inducing lines are reliably correlated with their judgments of the perceived tilt of an unvarying vertical test line.

In the logistic regression, with all possible segment interactions, we observed 6 significant (p < .05) interactions out of the set of 44 possible interactions across the four observers. After correcting for multiple tests, only two of these remained significant. Once again, the observed number of significant interactions did not exceed what would be expected by chance. As in Experiment 1, we conclude that to a first approximation, changes in the orientations of the frame segments for the most part additively contribute to judgments of the perceived tilt of the test line.

For purposes of comparison with Experiment 1, Table 2 shows the alternative estimates of the importance of the four segments for the four observers. A mean difference of zero in the rightmost column of this table would indicate no differential contribution from that segment toward the tilt judgments.

**General discussion**

These experiments showed that when the four sides of a quadrilateral frame are independently rotated about their...
respectively. Observers’ judgments of the perceived direction of tilt of an enclosed vertical test line reflected differential weightings of this variation in segment orientation. Observers were asked to make a forced choice on the perceived direction of tilt of a vertical line (CW or CCW) surrounded by this frame. Their dichotomous responses were used to estimate the weights assigned to the four frame segments in judgments of the perceived tilt of the test line. There were very few significant interactions between the four frame segments, implying that for the most part, the segments mostly exerted additive effects on the perceived tilt of the test line.

Double passes through the same set of trials showed that with the possible exception of one of the observers, observers responded similarly to the same orientation configuration of segments when it appeared twice across the course of either 2,000 trials (Experiment 1) or 4,000 trials (Experiment 2). The PAs in these judgments across the two passes were in the range approximately from 60% to 75%. It should be noted that this level of agreement exists despite the fact that the object being judged never deviated from its vertical orientation. Had the frame segments not exerted systematic effects on these tilt judgments, then one would have expected 50% agreement because only internal observer noise would determine the response on each trial. Additionally, weights representing the influences of the four segments were also similar across the two passes, showing that the RC methodology yielded reliable estimates of these weighting profiles for different observers.

There were both similarities and differences across observers in the segment weighting profiles. All four observers tended to weight variations in the orientation of the top segment most or more highly than variations in the other three segments. The direction of this weighting was consistent with previous research using single inducing lines (Gibson & Radner, 1937; Wenderoth & Curthoys, 1974). As the top segment was rotated CW, observers’ CCW judgments tended to increase. Conversely, all four observers also tended to give very little weight to variations in the orientation of the bottom segment. It is as if the bottom segment either exerted very little differential effect on these tilt judgments or was itself influenced by the orientations of the other segments in such a way that its differential influence was diminished. There is no direct evidence for this latter hypothesis in our data, although previous research has clearly demonstrated inhibitory effects of additional lines on the tilt-inducing power of a primary line (Carpenter & Blakemore, 1973; O’Toole, 1979; Wenderoth & Curthoys, 1974); hence, this could be one potential explanation for the weak-to-zero weighting consistently observed for the bottom segment. It is also possible that the higher weights given to the top segment and the lower weights given to the bottom segment could have resulted from our instructions to observers to report the direction of tilt of the top of the central test line on each trial. This could have drawn attention to the top of the pattern.

In contrast to these similarities across observers, we also found reliable individual differences in their weighting profiles. For example, observer M.L.’s judgments were almost exclusively dominated by changes in the orientation of the top segment. This was most evident in Experiment 2, where M.L.’s psychometric functions relating the proportion of CCW judgments to orientation deviations added to the left, right, and bottom segments were largely flat. Observers A.R. and K.G., on the other hand, showed consistent non-zero weights for the top, right, and left segments, with those for the right and left segments being opposite in sign to the weighting of the top segment. This pattern was repeatable across the two experiments for observers A.R. and K.G. Observer A.A. showed the lowest reliability in judgments, and A.A.’s regression weights were low and approximately equal in magnitude for the four segments. The data of A.A. were perhaps the least interpretable because of their low reliability.

It is worth noting that the weighting profile exhibited by observers A.R. and K.G. would most likely lead to a classification of field independence, whereas that shown by M.L. would most likely lead to a classification of field dependence, if we could generalize from these results standard measures of this characteristic assessed with the rod-and-frame test (Asch & Witkin, 1948). However, all three observers actually showed reliable effects of surrounding frame context on the perceived tilt of the center test rod. For observer M.L., small CW rotations of a square frame would induce CCW illusory tilt of an enclosed test line because of the correlated rotation of the top side of the square frame. For observers A.R. and K.G., on the other hand, even large rotations of a square frame would yield very little perceived tilt of the test line because rotations of the square frame would produce effects that would cancel for the left-right versus the top sides of the frame. The weighting profiles of these two observers favored sheared configurations like those shown in Figure 8 for maximum tilt induction, in which the top and bottom segments were rotated in directions opposite to those of the right and left segments. To our knowledge, this is the first that a systematic individual difference of this particular type has been reported for the RFI. This illustrates the

Figure 8. Shear configurations that produced stronger CCW (left) and CW (right) responses for observers A.R. and K.G. than the rectilinear configurations shown in Figure 4. The top and bottom segments in each figure have been rotated 15 deg in a direction opposite to the same 15-deg rotation of the right and left segments.
utility of this method, as well as the complexity of the individual differences observed in such illusions.

The signs on the right and left weights for observers A.R. and K.G. deserve comment. These observers showed positive weights for these segments. Because of the directions in which the orientation deviations and the responses were coded, these weights indicate attractive effects. That is, as the right and left segments had their mean orientations perturbed with CW orientation noise, these observers proportionately responded with more CW responses. The direction of these effects is opposite to that typically observed in the RFI. As noted above, although most studies have revealed repulsive effects for single inducing lines slightly rotated away from vertical, there have also been both stimulus conditions and individual differences associated with attractive effects under these conditions (Spinelli et al., 1995; Wenderoth, 1974; Wenderoth et al., 1975; Zoccolotti et al., 1993).

Finally, one of the limitations of RC in studying the RFI is that it could be best suited for revealing the additive effects of angular noise on judgments of illusory tilt. Several studies have clearly revealed nonadditive effects of multiple inducing lines on illusory tilt (Carpenter & Blakemore, 1973; O’Toole, 1979; Wenderoth & Curthoys, 1974). Although we were able to test for interactions between the segments, we did not observe what appeared to be any systematicity across observers, nor did we find them at a rate above what would have been expected by chance. Was this because interactions did not exist in this task under these stimulus conditions or because the RC method was insensitive to these interactions? We cannot definitively answer this question at this point, although the issue of sensitivity must be acknowledged. With four segments and 11 possible noise values for each segment, there would be 4.2 million possible combinations of these noise levels in a complete four-way interaction. We only presented 2,000–4,000 trials; hence, estimating a four-way interaction using this method is obviously inefficient. One alternative approach to answer this question would be to use a Monte Carlo method with simulated additive and nonadditive effects to estimate the sensitivity of the technique at detecting artificial observers with known, nonadditive weighting profiles.

Acknowledgments

This research was supported by the Autry Chair Research Fund from Rice University to James L. Dannemiller. Equipment support was provided by the Social Sciences School at Rice University.

Commercial relationships: none.
Corresponding author: Melanie A. Lunsford.
Email: melanie@rice.edu.
Address: Department of Psychology, Rice University, Houston, TX, USA.

References


