

Exploration of vertical bias in perceptual completion of illusory contours: Threshold measures and response classification

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We investigated whether the perceptual completion of illusory contours exhibits a vertical bias (J. Pillow & N. Rubin, 2002). Experiments 1–3 measured completion with Pillow and Rubin’s shape discrimination procedure, while including novel control conditions to determine if the results were related to perceptual completion per se. These experiments found no evidence for perceptual completion with stimuli used by Pillow and Rubin but did find completion with smaller stimuli that had larger support ratios. However, even when perceptual completion occurred, there was no evidence for a vertical bias in perceptual completion. Experiments 4–5 used the response classification method (B. L. Beard & A. Ahumada, 1998) to determine which local areas were related to illusory contour discrimination in central and peripheral vision. For central stimuli, there was a slight bias favoring completion of vertical contours, although the extent of the bias varied across participants. There was no vertical bias for peripheral stimuli. Overall, although subject to several important caveats, the results obtained with classification images (but not threshold measures) were consistent with the Pillow and Rubin’s idea that perceptual completion is more difficult when it requires integrating visual features that are on different sides of the vertical meridian.

Keywords: perceptual organization, illusory contour, response classification, vertical and horizontal completion

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Introduction

One of the first steps of visual processing is segmenting the retinal image into surfaces attributed to an object and background. This segmentation process can be based on differences in factors such as luminance, color, or texture at the border between objects or between an object and its background (e.g., Beck, 1966a, 1966b, 1967; Nagai, Bennett, & Sekuler, 2007; Nothdurft, 1985, 1992, 1993). However, in the case of illusory contours, humans perceive surface boundaries even in the absence of a physical difference at the border (e.g., Kanizsa, 1976, 1979). Examples of illusory contours are shown in Figures 1A (far-left and middle-left), 1B, and 1C. Luminance-defined edges of square-like figures are present only at the positions of the four pacman-shaped inducers. Despite the absence of luminance edges, we perceive a bright, square-like figure in front of four discs.

Traditionally, studies of the perception of illusory contours (and the related phenomenon of amodal completion) used subjective methods for estimating the clarity or sharpness of the perceived contour (e.g., Kanizsa, 1979; Petry & Meyer, 1987), but more recent research has made use of objective, performance-based measures (e.g., de Wit, Bauer, Oostenveld, Fries, & van Lier, 2006; de Wit, de Weert, & van Lier, 2005; Gold, Murray, Bennett, & Sekuler, 2000; Gold & Shubel, 2006; Guttman, Sekuler, & Kellman, 2003; Halgren, Mendola, Chong, & Dale, 2003; Imber, Shapley, & Rubin, 2005; Lee & Nguyen, 2001; Murray, Sekuler, & Bennett, 2001; Pillow & Rubin, 2002; Ringach & Shapley, 1996; Sekuler, 1994; Sekuler & Palmer, 1992; Sekuler, Palmer, & Flynn, 1994). For example, Ringach and Shapley (1996) presented subjects with stimuli consisting of four pacman-like inducers rotated to make a thin figure or rotated in the opposite directions to make a fat figure (Figure 1A, far left and middle left). The angle of rotation was manipulated to

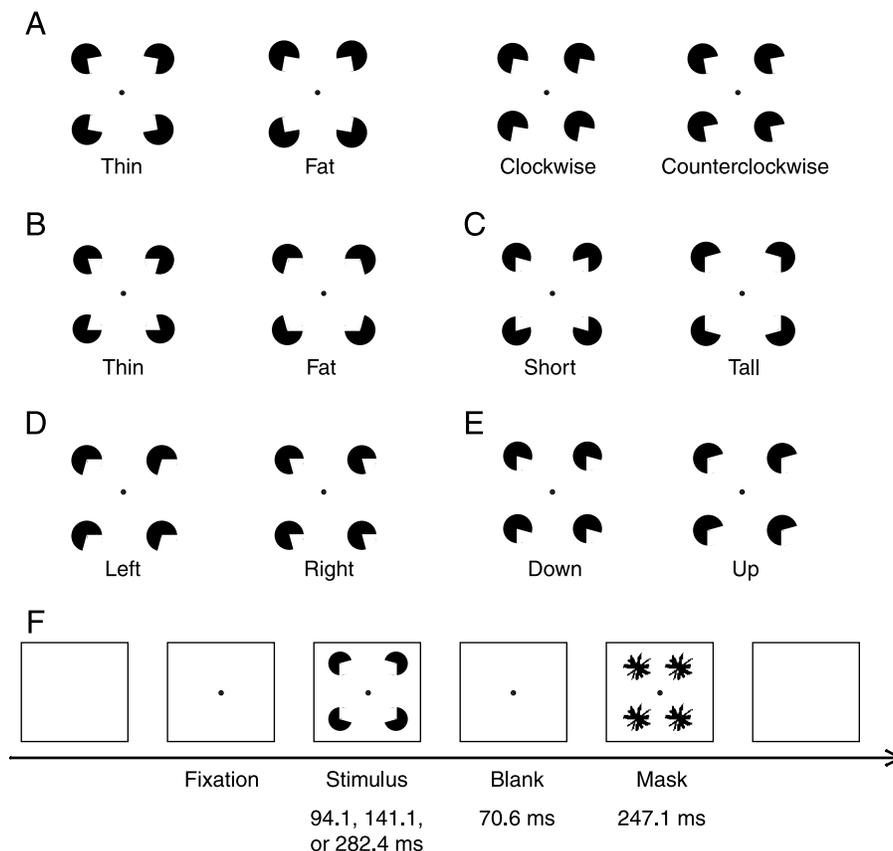


Figure 1. (A) Example of illusory contour stimuli and their control stimuli. (B–E) The stimuli used in the present experiments. (B) The stimuli used in the vertical completion (i.e., Thin/Fat) condition. (C) The stimuli used in the horizontal completion (i.e., Tall/Short) condition. (D) The stimuli used in the vertical control condition. (E) The stimuli used in the vertical control condition. Note that the support ratio of these figures is about 0.40, whereas it was between 0.25 and 0.65 in the actual experiments. (F) Time course of presentation on each trial.

determine the threshold for rotation of the inducers to discriminate fat from thin figures. Ringach and Shapley compared thresholds obtained for illusory contours to thresholds obtained with real, luminance-based contours and with a stimulus in which no completion was perceived (referred to as “fragmented” in our experiments; Figure 1A, far right and middle right). The basic result was that, when presented for enough time, discrimination thresholds for illusory contours were lower than those for the control (fragmented) condition but similar to that for real contours. These results were consistent with the idea that subjects perceived illusory contours similarly to real contours, but that perceptual completion takes some measurable time (e.g., Murray et al., 2001; Sekuler & Palmer, 1992).

Using the response classification technique (Ahumada & Lovell, 1971; Beard & Ahumada, 1998), Gold and colleagues provided more direct evidence for the perceptual completion of modal and amodal contours (Gold et al., 2000; Gold & Shubel, 2006). In this type of experiment, subjects are asked to identify a target stimulus on each trial (e.g., A or B), and a unique external luminance noise is added to the stimulus image on each

trial. On some trials, the noise may strengthen the correct perception of the stimulus, and a subject’s responses will be correct. However, on other trials, the noise may make stimulus A look more like stimulus B, or vice-versa, leading to incorrect responses. After many trials, the noise fields presented on each trial are sorted into four stimulus-response classes: N_{AA} , N_{AB} , N_{BA} , and N_{BB} . Here, N_{AB} represents all samples of noise fields where stimulus A was presented and the subject identified it as stimulus B. The classification image (CI) is calculated as follows:

$$CI = [\text{mean}(N_{AA}) + \text{mean}(N_{BA})] - [\text{mean}(N_{BB}) + \text{mean}(N_{AB})]. \quad (1)$$

The classification image is effectively a map that shows the locations where there was a correlation between the noise contrast at each location in the stimulus and the subject’s response. Consequently, this map is sometimes referred to as a “behavioral receptive field” (Gold et al., 2000).

In Gold et al. (2000), subjects discriminated thin and fat illusory contours (far left and middle left of Figure 1A,

respectively) in the context of a response classification experiment. The resulting classification images showed that subjects were influenced by noise located in-between the inducers to discriminate thin and fat figures, even though there was no physically present information in those regions. Classification images for real contours showed a similar pattern of results, whereas classification images for fragmented stimuli (Figure 1A, far right and middle right), showed that subjects used only regions in the mouth of the inducers to perform the task. In addition, consistent with the indirect measure of Ringach and Shapley (1996), Gold et al. found that threshold contrast levels were similar for real and illusory contours, and significantly lower in both cases than for the fragmented condition.

Interestingly, although the percept of completion for illusory contours is seen in both horizontal and vertical contours, classification images for all subjects in Gold et al. (2000) revealed the influence of vertical contours but not horizontal contours. This vertical contour bias was also found recently by Gold and Shubel (2006), who examined spatiotemporal processing of the perceptual completion with dynamic classification images.

Pillow and Rubin (2002) suggested that this vertical contour bias might be the result of the relative ease of completion for contours falling within a single hemifield, compared to completion of contours crossing the vertical meridian. Pillow and Rubin tested this idea by separately manipulating the curvature of the top/bottom and left/right sides of the inducers. In one condition, when subjects discriminated fat from thin, the critical cue was the illusory curvature of vertical contours (Figure 1B); in a second condition, when subjects discriminated short from tall (Figure 1C), the critical cue was the illusory curvature of horizontal contours. In both cases, Pillow and Rubin estimated angular rotation thresholds for discrimination and showed that thresholds were lower for rotations about the vertical axes than for rotation about the horizontal axes, leading to their conclusion that illusory contours can be completed more easily when they fall within a single hemifield.

Pillow and Rubin (2002) conducted control experiments to determine whether performance was generally better for tasks that used stimuli that were aligned vertically instead of horizontally. For example, one control experiment compared vernier acuity thresholds along the vertical and horizontal dimensions. Another control experiment compared curvature discrimination thresholds for real vertical and horizontal contours. No advantage for performance along the vertical axis was found in either of these control tasks, and therefore Pillow and Rubin argued that the effect of contour orientation found in the main experiment was related specifically to perceptual completion. However, the control experiments used stimuli and tasks that differed considerably from those used in the primary experiment. A better control condition would have been to measure angular rotation thresholds for

inducers arrange in a way that did not produce illusory contours (i.e., the fragmented stimuli shown Figures 1D and 1E). Thresholds measured with such stimuli could also be used to determine if perceptual completion occurred for the illusory contour stimuli. Specifically, if perceptual completion did occur, then one would expect thresholds to be lower in the illusory contour condition than in the fragmented control condition. If thresholds in those two condition do not differ, then one does not have strong evidence for perceptual completion (e.g., Gold et al., 2000; Ringach & Shapley, 1996; Sekuler & Palmer, 1992). Given the lack of appropriate control conditions in Pillow and Rubin's original study, it is not clear whether their results tell us about the completion of illusory contours, or the ability of subjects to perceive rotation of local vertical versus local horizontal contours.

Thus, the purpose of the present study was to determine whether there was, in fact, an advantage for detecting angular deviations in vertical contours related to perceptual completion. Experiments 1–3 attempted to replicate Pillow and Rubin's basic effect, while including control conditions (Figures 1D and 1E) to ensure that results were related to perceptual completion per se rather than to the effects of local horizontal versus vertical contours. Experiments 4 and 5 used the response classification technique to further investigate the extent to which subjects might be biased toward using vertical contours, compared to horizontal contours, in the perceptual completion of illusory figures, and whether any bias that exists related to vertical contour processing per se versus processing contours that cross the vertical meridian.

Experiment 1a

In Experiment 1a, we attempted to replicate Pillow and Rubin's (2002) basic effect. Our procedure mirrored theirs, with several modifications intended to improve the psychophysical methods. Stimulus size and support ratio (i.e., the ratio of the size of the illusory contour to that of the inducers) were similar to those used by Pillow and Rubin (2002) in their main experiment; however, we increased stimulus duration to maximize the visibility of illusory contours. Previous research (e.g., Guttmann et al., 2003; Murray et al., 2001; Ringach & Shapley, 1996; Sekuler & Palmer, 1992) has shown that the visual completion of modal and amodal contours requires some measurable time, and, in fact, pilot experiments suggested that subjects sometimes had difficulty perceiving illusory contours at the short stimulus duration used in Pillow and Rubin's original experiment. Indeed, Pillow and Rubin reported that, in their own experiment, four out of fifteen subjects could not perform shape discrimination based on such briefly presented illusory contours "at an adequate level," and these subjects were not allowed to participate

in their actual experiments. A second methodological change was based on the fact that Pillow and Rubin's estimates of threshold sometimes fell outside the range of stimulus values presented to a subject. For example, in their main experiment, they used the method of constant stimuli with ten levels of contour rotation ranging from about -4 to $+4$ deg, but threshold in the vertical completion condition was approximately 7.4 deg (see Figure 2A in Pillow & Rubin, 2002). We were concerned that this amount of extrapolation might introduce significant error in threshold estimation, so our experiments used interleaved staircases to ensure that thresholds were within the range of stimuli presented. Finally, as described before, we included control conditions to obtain an objective measure of visual completion.

Methods

Participants

Ten undergraduate students at McMaster University participated in the experiment for partial course credit or a small stipend (\$10). All subjects had normal or corrected-to-normal Snellen acuity, and all were naive as to the experimental hypotheses.

Apparatus

Stimuli were presented on a 21-in. monitor that displayed 1600×1200 pixels (38×28.5 cm) at a frame rate of 85 Hz. The stimuli were generated and presented with a Macintosh G3/350 Apple computer using Matlab (v 5.2) and the Psychophysics and Video Toolboxes (Brainard, 1997; Pelli, 1997).

Subjects viewed the stimulus binocularly through natural pupils from a distance of 60 cm. Head position and viewing distance were stabilized with a chin/forehead rest. The monitor was the only source of illumination in the room during testing.

Stimuli and procedure

Inducers were dark gray Pacman-shaped patterns presented on a light gray background (see Figure 1). Each inducer had a Weber contrast of 55%, a diameter of 3.6 deg, and was centered approximately 10.2 deg from a central fixation point. Each subject completed four different shape discrimination tasks: Thin/Fat, Short/Tall, Left/Right, and Down/Up (Figures 1B–1E). In the Thin/Fat and Short/Tall conditions, the open quadrants of the inducers faced towards the central dots, so that it was possible to perceive an illusory square that subtended 14.4×14.4 deg. The support ratio, defined as the inducer's radius divided by the length of one side of the square formed by inducers, was 0.25. In the Left/Right and Down/Up conditions, the open quadrants of the inducers all faced the same direction, and no illusory square was perceived.

Each subject completed four different shape discrimination tasks: Thin/Fat, Short/Tall, Left/Right, and Down/Up (Figures 1B–1E). Discrimination thresholds were obtained by varying the orientations of the vertical or horizontal edges within the inducers, as in Pillow and Rubin (2002). For example, in the Thin/Fat condition, as well as the corresponding control condition, the difference between stimuli was varied by adjusting the orientation of each inducer's vertical edge while leaving the horizontal edge unchanged (see Figures 1B and 1D). On the other hand, in the Tall/Short condition (and the corresponding control condition), the inducers were altered by varying the orientation of the horizontal edge while leaving the vertical edge unchanged (see Figures 1C and 1E). Edge orientation was manipulated with two interleaved staircases (2-down/1-up and 4-down/1-up) that used starting values that were above each subject's thresholds. Each staircase ended after ten reversals, and the threshold for each staircase was computed from averaging the orientation values at the last four reversals. The two separate thresholds for each staircase were averaged to produce a single estimate of threshold, which is similar to the difference in inducer edge orientation needed to produce 77% correct responses.

The discrimination tasks were performed in separate blocks of trials, and the order of the tasks was randomized for each subject. Each subject was tested twice in each condition, yielding a total of eight blocks. Each block of trials was preceded by four practice trials that used stimuli that were discriminated easily and which were not altered by either staircase. A trial began with the presentation of a fixation dot at the center of display. Subjects fixated the dot and then pressed the space bar on the computer keyboard. Immediately after the space bar was pressed, four inducers were presented simultaneously for 141 ms, followed by a blank screen for 71 ms, and then a masking display for 247 ms. The masking display consisted of four masks centered on the locations of the inducers. Each mask contained 20 randomly oriented lines (thickness = 0.25 deg; length = 1.9 deg) that radiated from a point that coincided with the location of the inducer's. At the end of each trial, subject's identified the stimulus (e.g., Thin/Fat, Short/Tall) by pressing one of two buttons on the computer keyboard. Subjects were instructed to maintain fixation on the central dot throughout each trial. Auditory feedback was given only in practice trials and in the first four trials in each experimental block.

Results and discussion

Average discrimination thresholds in each condition are listed in Table 1. To test the effects of perceptual completion and orientation, thresholds were analyzed with a 2 (illusory contours vs. control) \times 2 (vertical vs. horizontal axis) within-subjects analysis of variance

Experiment	Completion		Control	
	Vertical	Horizontal	Vertical	Horizontal
1a	6.90	6.61	6.29	5.86
1b	4.21	3.68	5.91	4.94
2	20.91	15.84		

Table 1. The result in Experiments 1–2. The averaged discrimination threshold in the deviation of angular opening from 90 deg in each condition (deg).

(ANOVA). Neither the main effects of completion and orientation nor their interaction were significant (all p values >0.18).

In the present experiment we did not replicate the biased processing of vertical perceptual completion reported by Pillow and Rubin (2002). Such a result may not be surprising, however, because we did not find evidence for perceptual completion in the stimulus configuration tested in the current experiment. The inclusion of the fragmented control condition enabled us to show that, contrary to what one would expect if illusory contours were perceptually completed, thresholds were not lower in the completion conditions than in the control conditions.

Experiment 1b

Pillow and Rubin (2002) did not include details about their initial instructions to participants, and it was possible that the language they used primed subjects to see illusory contours. In Experiment 1a, we did not advise participants of the presence of illusory contours in the stimuli, and we wondered if alerting them to this fact could influence our results, promoting the visual completion of illusory contours, and thus leading to biased processing of vertical perceptual completion. In Experiment 1b, therefore, participants were informed of the existence of illusory contours before testing.

Methods

Participants

Sixteen undergraduate students at McMaster University participated in the experiment for partial course credit or a small stipend (\$10). All participants had normal or corrected-to-normal Snellen acuity, and all were naive as to the hypothesis. None of them participated in Experiment 1a.

Apparatus

The apparatus was the same as that used in Experiment 1.

Stimuli and procedure

Stimuli and procedure were the same as in Experiment 1a except that the instructions were altered to highlight the presence of illusory contours. At the beginning of the experiment, subjects were shown a piece of paper depicting an illusory square. The experimenter explained that although most people perceive a white square in front of four disks, the four sides of the square were illusory and did not correspond to changes in the lightness of the paper. If they did not understand or perceive the illusory contours, we showed them four black circles on a sheet and placed a small yellow square in front of the black circles to ensure that subjects understood the concept and correctly localized the illusory contours.

Results and discussion

Average discrimination thresholds for each condition are presented in Table 1. Thresholds were analyzed with a 2 (illusory vs. control) \times 2 (vertical vs. horizontal axis) within-subjects ANOVA. As in the Experiment 1a, neither the main effects of completion and orientation nor their interaction were significant (all p values $>.15$). Although the instructions were changed to ensure that participants were aware of the presence of illusory contours, we did not find evidence for perceptual completion, and we did not replicate the biased processing of the vertical perceptual completion.

Experiment 2

As noted earlier, the procedure for Experiments 1a and 1b varied slightly from that of the original Pillow and Rubin (2002) study, most notably altering the presentation duration in an effort to enhance perceptual completion, and including fragmented controls to enable us to test for the presence or absence of perceptual completion. Here, we attempted to more closely mirror the conditions in which Pillow and Rubin found their largest vertical contour completion bias. To that end, the control conditions were eliminated and stimulus duration was reduced to 94 ms (compared to 97 ms in Pillow and Rubin). Additionally, in the present experiment, the two different completion judgments were mixed rather than blocked because, although Pillow and Rubin found vertical completion biases in both blocked and mixed design, the effect was somewhat stronger in their mixed design conditions.

Methods

Participants

Fourteen undergraduate students at McMaster University participated in the present experiment for partial

course credit or a small stipend (\$10). All participants had normal or corrected-to-normal Snellen acuity, and all were naive as to the hypothesis. None of them participated in [Experiments 1a](#) or [1b](#).

Apparatus

The apparatus was the same as that used in [Experiment 1](#).

Stimuli and procedure

Stimuli in this experiment were the same as those used in the completion condition in [Experiment 1](#), but the stimulus duration was reduced to 94 ms. On each trial, one of four figures (Thin, Tall, Fat, or Short) was presented. Participants were asked to discriminate between [Thin and Tall] and [Fat and Short] as in Pillow and Rubin (2002). In other words, participants were required to press one key when Thin or Tall figures were presented and to press another key when Fat or Short figures were presented. The rotation of inducer edges was adjusted with four interleaved staircases (2-down/1-up for [Thin or Fat] and [Short or Tall], and 4-down/1-up for [Thin or Fat] and [Short or Tall]). The staircases were stopped after 10 reversals, and threshold was defined as the average of the last four reversals. We analyzed only thresholds derived from the 4-down/1-up staircases, which converge on the 84% correct point on the psychometric function, to more closely approximate the threshold level in Pillow and Rubin (82%).

Each subject completed 8 blocks of trials. A pilot experiment indicated that some subjects could not reliably discriminate the stimuli in the current conditions. We therefore altered the experimental procedure to start with a block of 32 practice trials which used Thin/Fat and Tall/Short stimuli that were constructed with inducers that had edges that differed by 50 deg. Subjects were required to respond correctly on at least 75% of the practice trials before proceeding to the experimental trials. Several participants required more than one block of practice trials, but all subjects eventually reached the criterion level of performance.

Results and discussion

Average discrimination thresholds for the vertical and horizontal completion conditions are listed in [Table 1](#). A *t*-test revealed a significant difference between the conditions ($t(13) = 4.38, p < .001$). However, the difference between conditions was opposite to that reported by Pillow and Rubin (2002): thresholds were lower in the horizontal completion condition than in the vertical condition. Thus, although we closely matched the stimulus conditions of Pillow and Rubin, we were unable to replicate their finding of biased processing of vertical lines

of illusory contours. Discrimination thresholds in the current experiment were much higher than thresholds obtained in the first two experiments, even taking into account the fact that thresholds converged to 84% in the current experiment but to 77% in the previous experiment, which suggests that the short duration, the mixed-block design, and/or the complexity of the response-key assignments made the task more difficult. Indeed, thresholds in the present experiment were larger than those estimated by Pillow and Rubin.

Experiment 3a

In [Experiment 1](#), we found no evidence for perceptual completion of illusory contours. In [Experiment 2](#), we were unable to test for perceptual completion because, following Pillow and Rubin (2002), we did not include control conditions. The goal of [Experiment 3](#) was to ensure that our method was sensitive to perceptual completion and to determine whether the bias toward completion of vertical contours would be present when participants perceived illusory contours. One issue with the stimuli used by Pillow and Rubin and in our [Experiments 1](#) and [2](#) is that the illusory contours were long, and the support ratio was low. Previous research has found that, when the support ratio is held constant, both modal and amodal completion become more difficult and/or require more time as the length of the to-be-completed contours increase, and that contour completion is easier with high support ratios (e.g., Banton & Levi, 1992; Dresch & Bonnet, 1993; Guttman et al., 2003; Kojo, Liinasua, & Rovamo, 1993; Shipley & Kellman, 1992; but see Ringach & Shapley, 1996, for an example of modal completion over large distances). Therefore, our stimuli may not have been optimal for evoking the perception of illusory contours. To facilitate perception of illusory contours, we reduced the size of our stimuli, used a longer stimulus duration, and increased the support ratio.

Methods

Participants

Ten undergraduate students at McMaster University participated in the present experiment for partial course credit or a small stipend (\$10). All participants had normal or corrected-to-normal Snellen acuity, and all were naive as to the hypothesis. None of them participated in [Experiments 1](#) or [2](#).

Apparatus

The apparatus was the same as that used in [Experiment 1](#). However, viewing distance was increased to 80 cm.

Experiment	Completion				Control			
	Vertical		Horizontal		Vertical		Horizontal	
	Short	Long	Short	Long	Short	Long	Short	Long
3a	1.83	1.62	1.98	1.81	4.08	3.00	3.69	2.84
3b	2.92		3.05		4.64		4.37	

Table 2. The result in [Experiment 3](#). The averaged discrimination threshold in the deviation of angular opening from 90 deg in each condition (deg). Note that the short duration was different between [Experiments 3a](#) and [3b](#). See details on text.

Stimuli and procedure

The inducers had diameters of 2.69 deg and were centered on points that were 4.25 deg away from the central fixation point. Thus, the size of illusory square was 6.01 deg \times 6.01 deg and the support ratio was 0.45. Note that although Pillow and Rubin (2002) found that the size of the vertical bias decreased with increasing support ratio, a support ratio of 0.45 is still in the range in which they found a significant vertical contour processing bias. Two longer stimulus durations (141 and 282 ms) were used in the present experiment. Each participant completed 16 blocks (4 discrimination tasks [Thin/Fat, Short/Tall, Left/Right, and Down/Up] \times 2 durations \times 2 replications). The order of blocks was randomized for each subject. Other aspects of the procedure were the same as in [Experiment 1](#).

Results and discussion

Average discrimination thresholds for each condition are shown in [Table 2](#). Thresholds were analyzed in 2 (illusory vs. control) \times 2 (vertical vs. horizontal axis) \times 2 (shorter vs. longer duration) within-subjects ANOVA. The main effect of completion was significant ($F(1, 9) = 16.1$, $MSE = 3.2$, $p < .01$), but the other main effects and interactions were not significant (all other p values $>.12$).

By decreasing stimulus size and increasing support ratios, we found evidence for perceptual completion: thresholds for completion conditions were lower than those for control conditions at both stimulus durations. Therefore, we confirmed that our paradigm was sensitive to perceptual completion. However, we still did not find evidence for biased processing of vertical contours in perceptual completion.

Experiment 3b

In [Experiment 3a](#) we found evidence for perceptual completion, but not for biased processing of vertical

perceptual completion. Here we used the same stimulus size and support ratio as in [Experiment 3a](#) but decreased stimulus duration to one comparable to that used by Pillow and Rubin (2002) to determine whether biased processing of the vertical perceptual completion would occur at this shorter duration.

Methods

Participants

Ten undergraduate students at McMaster University participated in the present experiment for partial course credit or a small stipend (\$10). All participants had normal or corrected-to-normal Snellen acuity, and all were naive as to the hypothesis. None of them participated in the previous Experiments.

Apparatus

The apparatus and viewing distance was the same as that used in [Experiment 3a](#).

Stimuli and procedure

Stimuli and procedures were as in [Experiment 3a](#), except that stimulus duration was 94 ms. Each subject was tested in 8 blocks of trials (4 different discrimination tasks \times 2 replications). The order of blocks was randomized for each subject.

Results and discussion

Average discrimination thresholds for each condition are shown in [Table 2](#). Thresholds were analyzed in a 2 (illusory vs. control) \times 2 (vertical vs. horizontal axis) within-subjects ANOVA. As in [Experiment 3a](#), the main effect of completion was significant ($F(1, 9) = 9.4$, $MSE = 2.5$, $p < .05$), but neither the main effect of orientation nor the interaction between completion condition and orientation were significant (all other p values $>.39$). As in [Experiment 3a](#), we found evidence for perceptual completion, here with a duration comparable to that used in

Pillow and Rubin's (2002) study. However, we still did not find evidence for biased processing of vertical contours in perceptual completion.

Experiment 4

Our previous three experiments did not show evidence of biased processing for the vertical lines of illusory contours that Pillow and Rubin (2002) reported. Although we did not find evidence for perceptual completion using stimuli with size and support ratios comparable to those used by Pillow and Rubin, we did find perceptual completion for smaller stimuli with larger support ratios. These results suggest that our method is sensitive to perceptual completion and highlight the importance of including control conditions to appropriately assess perceptual completion and the effects thereof.

Although we did not find evidence supporting the presence of a strong bias for completion of vertical contours, closer analysis of the data from Experiments 3a and 3b indicated that there was a great deal of individual variability with respect to the relative performance for vertical and horizontal tasks: roughly half of the subjects had results consistent with a vertical bias, and the other half had results consistent with a horizontal bias. Such a result suggests that there may be individual differences in the way in which subjects complete illusory contours, and it may be that the difference between our results and those of Pillow and Rubin (2002) simply reflected a biased random sample in their subject population. Unfortunately, the methods used in Experiments 1–3 were not designed explicitly with an individual difference approach in mind, and did not gather enough data on individual subjects trials to examine this hypothesis rigorously.

The next experiment used response classification (e.g., Ahumada & Lovell, 1971; Beard & Ahumada, 1998; Gold et al., 2000; Murray, Bennett, & Sekuler, 2002) to examine whether individuals have a vertical or horizontal bias for perceptual completion. One clear advantage of the response classification technique is that it can provide evidence for differential processing strategies across individuals, even when overall performance thresholds do not differ significantly across individuals (e.g., Gold, Sekuler, & Bennett, 2004; Nagai et al., 2007). Thus, response classification can be quite useful in illuminating individual differences in perceptual tasks.

Previously, Gold et al. (2000) used response classification to determine the parts of a stimulus, real and illusory, that influence a subject's decision about shape. They found evidence for the use of vertical contours, but not horizontal contours, in perceptual completion. However, although the perceived shape of the illusory figures in Gold et al. varied in both the horizontal and

vertical illusory contours, the instructions to participants to discriminate fat and thin figures may have specifically directed subjects' attention to vertical contours. Here we attempted to direct attention either to the horizontal or the vertical contours by using different instructions, and we more carefully controlled the location of perceived shape differences in illusory contours relative to Gold et al. By using the same stimuli and tasks as in Experiments 1 and 3, subjects could use only the horizontal contours in the horizontal completion condition (i.e., the Short/Tall discrimination condition) and only the vertical contours in the vertical completion condition (i.e., the Thin/Fat discrimination condition). If subjects are more efficient at completing vertical contours (within-hemisphere) than horizontal contours (across-hemispheres), we should see evidence for strong biasing effects of vertical contours in the fat/thin task, but weak or no effects of horizontal contours in the tall/short task.

Methods

Participants

Three undergraduate students at McMaster University participated in the present experiment. They were paid \$10 for each of 32 one-hour sessions (8 sessions for each of 4 conditions). They participated in the experimental sessions on mostly consecutive days (ranging from 64 to 75 days for 32 sessions), excluding weekends and holidays. All participants had normal or corrected-to-normal Snellen acuity, and all were naive with respect to the specific experimental hypotheses. However, all participants had extensive experience participating in other psychophysical experiments. Subject JP participated in Experiment 1a, but the rest of the subjects had not participated in previous experiments.

Apparatus

Stimuli were presented on a 21-in. CRT monitor (Apple, Studio Display), which was controlled with a computer (Apple, Power Macintosh G4/733 MHz). The monitor was set to a spatial resolution of 1600×1200 pixels (38×28.5 cm) and a temporal resolution of 85 Hz. Viewing distance was 80 cm.

Stimuli and procedure

Stimulus size and support ratio were the same as in Experiment 3. As such, stimuli subtended 6.01×6.01 deg, which consisted of 552×552 pixels. In most studies using response classification, independent luminance noise is added to each pixel. Given the relatively large number of pixels (304,704) in each stimulus, it would be difficult to converge on a clear classification image solution using the standard approach (cf. Murray et al.,

2002). Therefore, we used noise that contained 92×92 independent elements, where each element consisted of a 6×6 pixel region. The luminance of each noise element was selected randomly from a Gaussian distribution that had a mean of zero and a contrast variance of 0.14. Stimulus duration was 282 ms.

As was done in the Gold et al. (2000) experiment, the rotation angle of the inducer edges was held constant, and a 2-down/1-up staircase was used to adjust inducer contrast to maintain response accuracy at approximately 71% for the duration of a testing session. Pilot experiments indicated that a rotation angle of ± 8.0 deg yielded stable performance, and so that value was selected for the main experiment. Each session consisted of 1250 trials, but only the last 1200 trials of each session were used to estimate the classification images. Subjects completed eight sessions for each condition, and all sessions for a given condition were completed before moving on to the next condition. The order of conditions was randomized across participants. The order for subject AP was the vertical completion, horizontal completion, horizontal control, and vertical control conditions; that for subject JP was the horizontal completion, vertical completion, vertical control, and horizontal control conditions; and that for subject MB was the horizontal control, vertical control, horizontal completion, and vertical completion conditions.

Results

Figure 2 shows thresholds, which were estimated by determining the 71% correct point on a psychometric

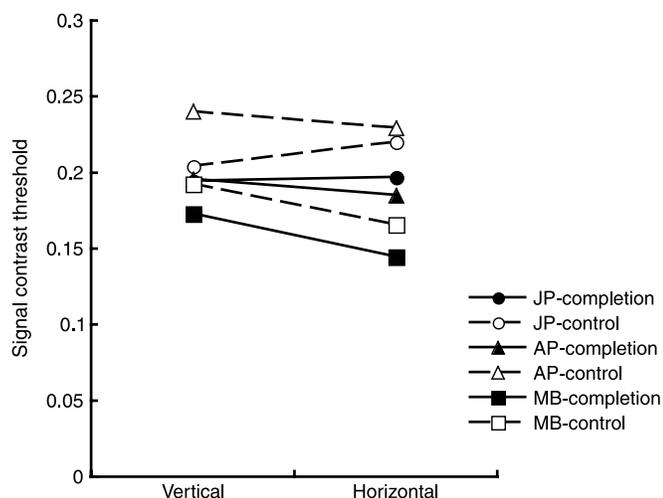


Figure 2. Discrimination thresholds, expressed as signal contrast, measured in Experiment 4. Solid symbols represent thresholds in the completion conditions, and open symbols represent thresholds in the control conditions. Different shapes of symbols represent the data for different subjects. Error bars indicate standard errors of the mean (SEMs).

function fitted to the data for each individual subject in each condition. All subjects showed evidence of perceptual completion. In other words, contrast thresholds for the vertical and horizontal completion conditions were lower than contrast thresholds for control conditions. Moreover, as in Experiments 1–3, threshold differences showed no evidence for biased processing of vertical (within-hemisphere) illusory contours.

Figure 3 shows raw (Figure 3A) and smoothed (Figure 3B) classification images for each subject in each condition. The positions of inducers are shown in red pixels, although inducers shown here contain only horizontal and vertical edges: they have not been rotated to create the Thin/Fat or Tall/Short stimuli. The locations in the classification images exhibiting high contrast (bright or dark) correspond to positions where the value of the noise was correlated with subjects' decisions. For all three subjects, high-contrast elements in the classification images obtained in the vertical and horizontal control conditions were clustered around the physical edges of the inducers' mouths: no high-contrast elements were found in-between any of the inducers. In the classification images for subjects AP, JP, and MB, there are high-contrast elements at the left-bottom, the right-bottom, and left-top inducer's mouth in both control conditions, respectively. Moreover, in subject MB's classification images there were high-contrast elements at top-right inducer's mouth in the horizontal control condition. In the completion conditions, the classification images from all subjects also contained high-contrast elements clustered near the edges of the inducers. However, these classification images also contained high-contrast elements in-between the inducers (except for subject JP in the horizontal completion condition). For subject AP, there are high-contrast elements along both vertical completion lines in the vertical completion condition and along the upper horizontal completion line in the horizontal completion condition. For subject JP, there are high-contrast elements along the left vertical completion line in the vertical completion condition, but no high-contrast elements along any completion line in the horizontal completion condition. For subject MB, there are high-contrast elements along both vertical completion lines in the vertical completion condition and along both horizontal completion lines and both vertical lines in the horizontal completion condition. This latter result is particularly interesting because in the horizontal completion condition the vertical edges of the top and bottom inducers on the left and right sides were always aligned and therefore provided no information for the task.

We quantified the perceptual completion effect by determining the average values of different horizontal and vertical segments of the classification images. The horizontal and vertical segments varied in position, but only included elements that were in-between the innermost edges of the inducers. If subjects relied on the illusory contour, then values for horizontal or vertical

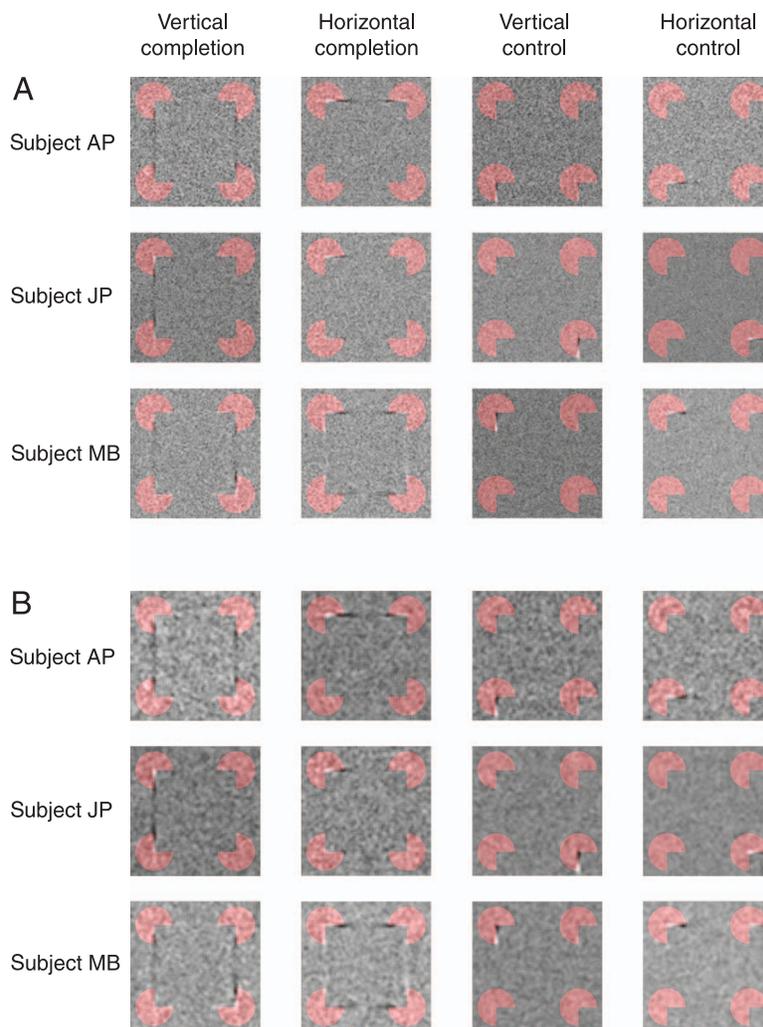


Figure 3. Raw and smoothed classification images in each condition for each subject in Experiment 4. The position of inducers are shown in red pixels. Note that the edges of the inducer mouths are horizontal or vertical and are not rotated as they were in the actual experiment.

segments that fell along the completed contour—i.e., along lines connecting the inducers—should be highly positive or negative.

There were 32 elements (6×6 pixels per element) in-between the two inducers in both the vertical and horizontal dimensions, and we calculated the average luminance for each of these 32 elements. Figure 4 shows results for each subject in each condition. The first and third columns show values obtained by averaging in the vertical direction, plotted as a function of horizontal position; columns two and four show the values obtained by averaging in the horizontal direction, plotted as a function of vertical position. Data from the completion and control conditions are indicated by solid and dotted lines, respectively. Two black horizontal lines in each plot indicate the boundaries of significance levels ($p < .05$) with Sidak–Bonferroni correction: values falling below the lower line or above the upper line are significant. None of the average values from the classification images collected in control conditions were statistically signifi-

cant. However, several between-inducer elements in classification images collected in completion conditions were significant. Furthermore, the significant values in the completion condition occurred at locations that coincided with the locations of illusory contours (indicated by arrows in Figure 4).

Results from this quantitative analysis support the qualitative interpretation from classification images: The values at some locations in-between the inducers reached statistical significance, but only in completion conditions, not control conditions. In the vertical completion condition, all three subjects were significantly influenced by noise that was located in-between two vertically aligned inducers. Subjects AP and MB were influenced by noise along both vertical sides of the illusory square, but subject JP was influenced by noise only along the left side of the illusory square (see column 1 in Figure 4). None of the subjects were influenced by noise along the horizontal sides of the illusory square in the vertical completion condition (see column 2 in Figure 4). In the horizontal

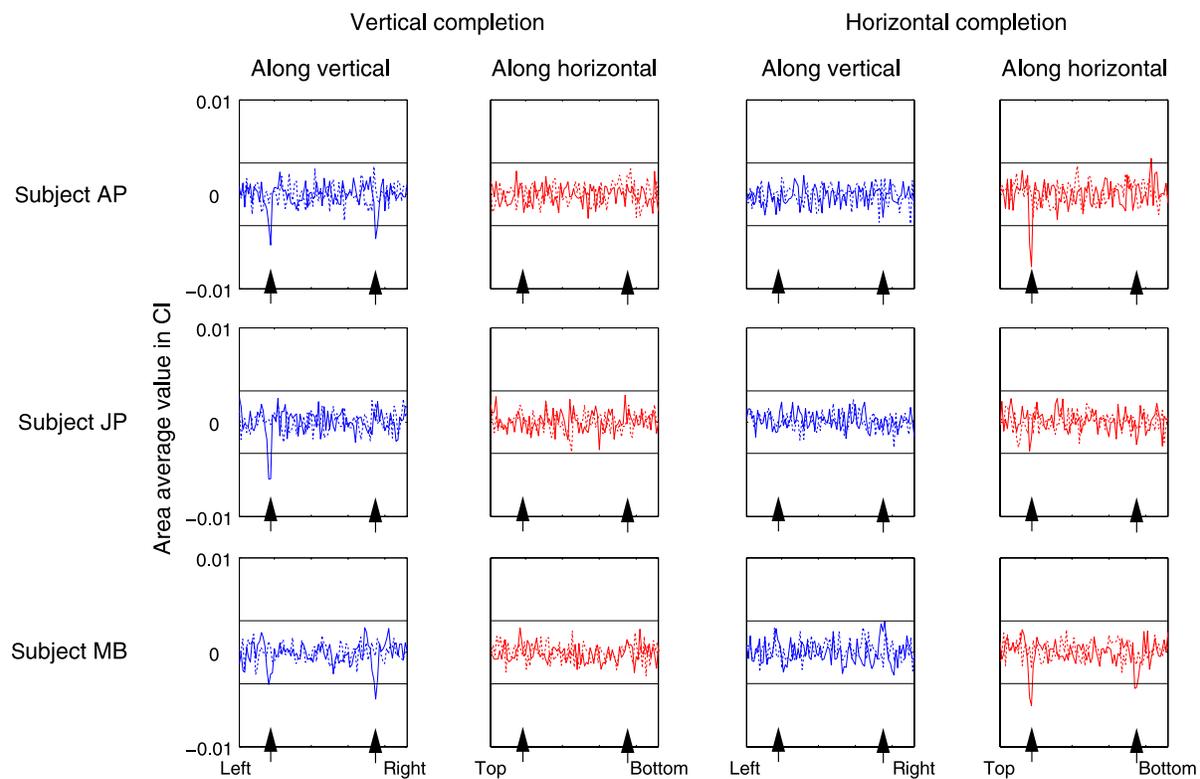


Figure 4. Area average values [32×1 element area] from the classification images measured in completion (solid lines) and control conditions (dotted lines) in Experiment 4. The first and third columns show values averaged along vertical lines in blue plots, and the second and fourth columns show values averaged along horizontal lines in red plots. In the first and third columns, the horizontal axis of each plot indicates the horizontal position of the averaged area. In the second and fourth columns, the horizontal axis indicates the vertical position of the averaged area.

completion conditions (see column 4 in Figure 4), subject AP was influenced by noise along the top horizontal side, and along a row near the bottom of the display. However, the lower row was located significantly below the inducers, and therefore we suspect that this latter finding is a spurious significant result. Subject JP was not influenced by noise along either the top or bottom sides (but was influenced by noise on the top-left inducer; see Figure 3). Subject MB was influenced by noise along both the top and bottom sides (just below significant level for the right vertical side in the horizontal completion condition). No subject was influenced by noise along the vertical sides of the illusory square in the horizontal completion condition. Therefore, two subjects showed a stronger influence of noise in the vertical completion condition than in the horizontal condition (i.e., more side(s) of illusory contour were affected in the vertical completion condition).

Discussion

In this experiment we used two different measures for assessing perceptual completion and the potential bias

toward the perceptual completion of vertical (i.e., within-hemisphere) contours: the inducer contrast (needed to achieve 71% correct responses and the spatial distribution of significant elements within classification images). The contrast thresholds yielded similar results to those we obtained in Experiment 3 by varying the orientation of inducer edges: evidence for perceptual completion was observed in the both vertical and horizontal completion conditions, but there was no evidence for biased processing of the vertical lines in illusory contours.

Classification images showed that all subjects were influenced by noise distributed between vertically aligned inducers in the vertical completion condition. This result is consistent with the idea that subjects were discriminating stimuli at least partly on the basis of completed vertical contours. The influence of noise distributed between horizontally aligned inducers in the horizontal completion condition was less strong and is consistent with the hypothesis that completion of horizontal contours was weaker and/or more variable across trials and subjects. Hence, the classification image results could be interpreted as supporting the idea that modal completion is easier for vertical contours than for horizontal contours, although the effect is relatively weak.

Experiment 5

Although classification images in [Experiment 4](#) showed some evidence of biased processing for vertical contour completion in illusory contours, the previous experiment did not examine the source of biased vertical processing. Pillow and Rubin (2002) suggested that the vertical contour bias was related not to vertical contour processing per se, but to perceptual completion of contours being more efficient within a single hemifield compared to completion of a contour that crossed the vertical meridian. This hypothesis was supported by an experiment in which Pillow and Rubin presented the stimuli in the lower-right quadrant of the visual field, where both the vertical and horizontal illusory contours would fall within a single hemifield. As predicted by the within- vs. across-hemifield completion hypothesis, Pillow and Rubin found no vertical bias under this stimulus presentation condition, and they suggested that this bias might be due to the relative ease of completion of contours that are induced by features encoded by mechanisms within the same cortical hemisphere rather than mechanisms that are in different hemispheres. In [Experiment 5](#), we replicated the single quadrant presentation experiment with the response classification method to examine the source of the small vertical bias found in [Experiment 4](#).

Methods

Participants

The first author and a graduate student at Tohoku University participated in the present experiment. They each completed 12 experimental sessions on mostly consecutive days (one or two sessions per day). Both participants had extensive experience participating in other psychophysical experiments and had normal or corrected-to-normal Snellen acuity, and the graduate student was naive with respect to the specific experimental hypotheses. None of them participated in [Experiments 1–4](#).

Apparatus

Stimuli were presented on a 21-in. CRT monitor (Eizo, T961 for subject MN and Sony, GDM-FW900 for subject SH), which was controlled with a computer (Apple, Power Macintosh G4/400 MHz for subject MN and 500 MHz for subject SH). The monitor was set to a spatial resolution of 1600×1200 pixels (38×28.5 cm) and a temporal resolution of 85 Hz. Viewing distance was 80 cm.

Stimuli and procedure

Pilot experiments showed that it was difficult to perceive illusory contours when stimuli were presented

in the peripheral visual field. So, to facilitate the perception of illusory contours, similar to Pillow and Rubin (2002), stimulus size was reduced relative to that used in [Experiment 4](#). The illusory contour subtended 3.0×3.0 deg, which consisted of 310×310 pixels. As in the previous experiment, we used coarse noise that contained 62×62 elements (i.e., total 3,844, elements) where each element consisted of a 5×5 pixel region. The luminance of each noise element was selected randomly from a Gaussian distribution that had a mean of zero and a contrast variance of 0.14. The stimulus was presented in the lower right quadrant: the upper-left inducer was located along the oblique axis, centered on an eccentricity of 1.14 deg from the fixation point. As in Pillow and Rubin, the size of each inducer was scaled based on the cortical magnification factor: the diameter of the upper-left inducer was 1.0 deg, that of upper-right and lower-left inducers was 1.72 deg, and that of the lower-right inducer was 2.18. Thus, the support ratio of top and left sides of illusory contour was 0.453 and that of right and bottom sides of it was 0.650. This range of support ratios is similar to that used in Pillow and Rubin's peripheral stimuli, and our smallest support ratio was similar to that of [Experiments 3](#) and [5](#). Stimulus duration was 282 ms.

Each session consisted of 1550 trials, but only the last 1500 trials of each session were used to estimate the classification images. Subjects completed three sessions for each condition and the order of conditions was randomized block to block and counterbalanced across subjects. The rest of procedure was the same as in the previous experiment.

Results

[Figure 5](#) shows thresholds, which were estimated by determining the 71% correct point on a psychometric function fitted to the data for each subject in each condition. Both subjects showed evidence of perceptual completion: contrast thresholds for the vertical and horizontal completion conditions were lower than contrast thresholds for control conditions. Moreover, as in [Experiments 1–4](#), there was no evidence for biased processing of vertical illusory contours.

Raw and smoothed classification images are shown in [Figures 6A](#) and [6B](#), respectively. In the control conditions, high contrast elements in the classification images were clustered around the physical edges of the inducers' mouths in the vertical and horizontal control conditions for subject MN. For subject SH, this was true only in the horizontal control condition, and high-contrast elements were found along the outside edge of the inducer in the vertical control condition. No high-contrast elements were found in-between any of the inducers for either subject. The classification images from subject MN exhibited high-contrast elements at the top-left inducer in both

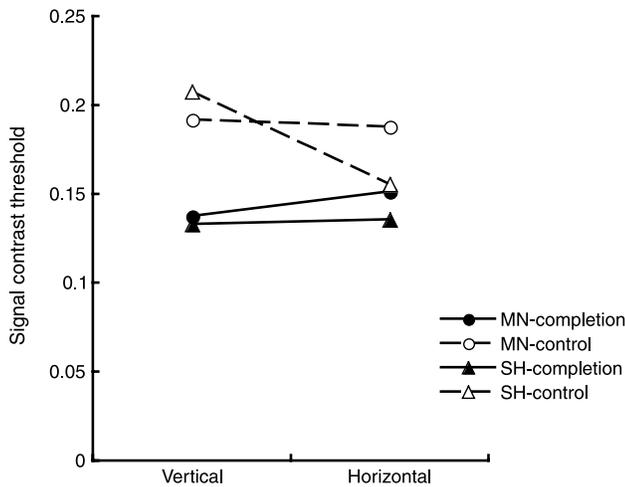


Figure 5. Discrimination threshold, expressed as signal contrast, measured in Experiment 5. Solid symbols represent the data for completion conditions, and open symbols represent the data for the control conditions. Different shapes of symbols represent the data for different subjects. Error bars indicate standard errors of the mean (SEMs).

control conditions, whereas those from subject SH there are high-contrast elements at the bottom-left inducer in the vertical condition and at the bottom-left and top-right inducers in the horizontal control condition.

In the completion conditions, the classification images from both subjects contained high-contrast elements in-

between the inducers as well as near the edges of the inducers' mouths. For subject MN, there are high-contrast elements along the left-vertical and upper-horizontal completion lines in the vertical and horizontal completion conditions, respectively. For subject SH, there are high-contrast elements along the right-vertical and lower-horizontal completion lines in the vertical and horizontal conditions, respectively.

As in Experiment 4, we quantified the perceptual completion effect by averaging values along horizontal and vertical segments in the classification images. However, the fact that the inducers were in different sizes (to compensate for cortical magnification) meant that different numbers of noise elements were included in between different pairs of inducers: the top and left sides consisted of 15 elements and the right and bottom sides consisted of 21 elements. Figure 7 shows results for each subject in each condition. The two black horizontal lines representing statistical significance ($p < .05$ with Sidak–Bonferroni correction) were not straight, reflecting the fact that there were different numbers of elements between inducers. In control conditions, just one of the average values was statistically significant at a location that coincided with the location of an illusory contour (i.e., upper-horizontal contour in the horizontal control condition for subject MN in column 4 of top row in Figure 7). In the completion conditions, several average values that coincided with the locations of illusory contours (indicated by arrows in Figure 7) were significant, although there were some exceptions to this general rule. Specifically, subject SH

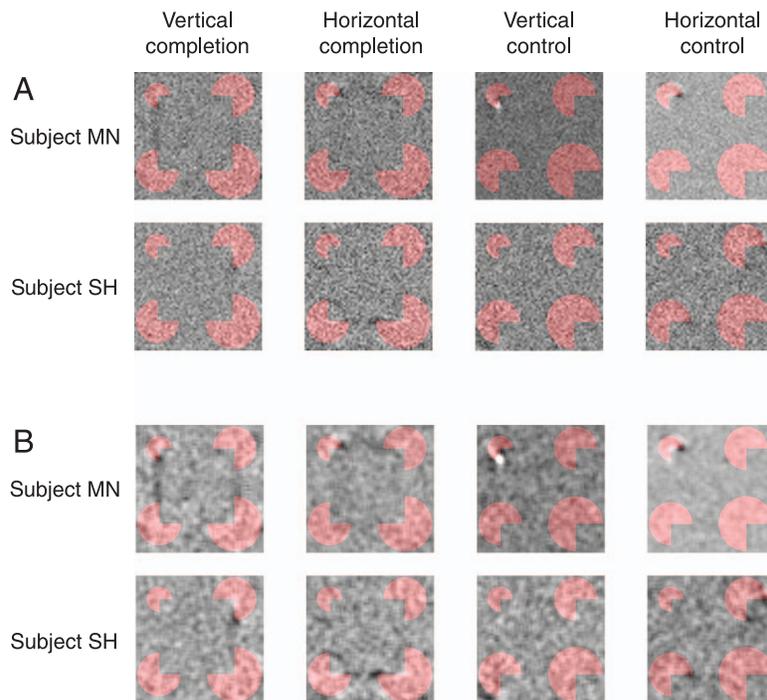


Figure 6. Raw and smoothed classification images in each condition for each subject in Experiment 5. The position of inducers is shown in red pixels. Note that the edges of the inducer mouths are horizontal or vertical and are not rotated as they were in the actual experiment.

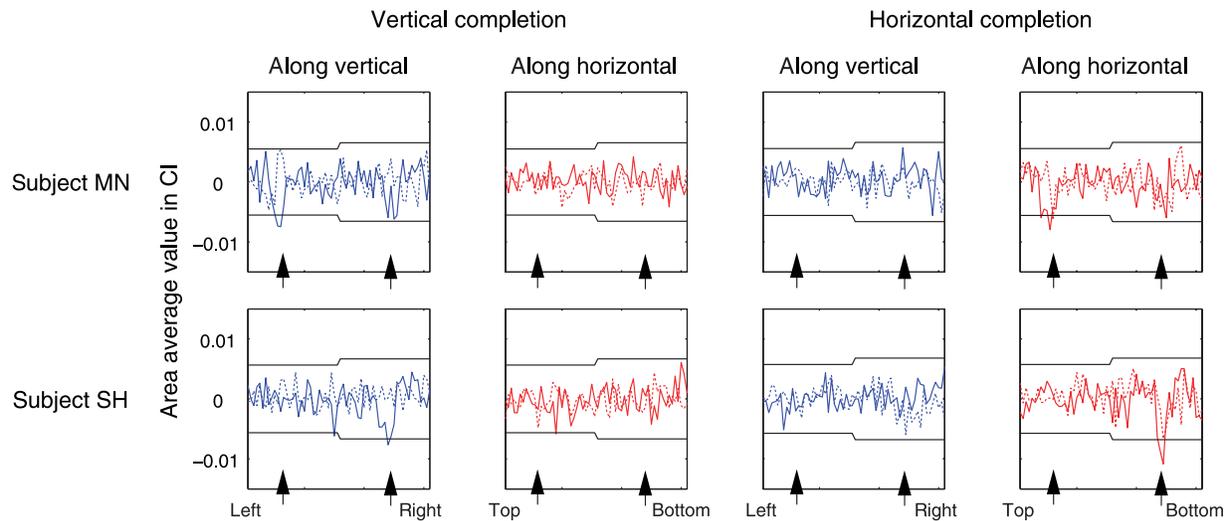


Figure 7. Area average values [15 or 21×1 element area] from the classification images measured in completion (solid lines) and control conditions (dotted lines) in Experiment 5. The first and third columns show area values averaged along vertical lines in blue plots, and the second and fourth columns show values averaged along horizontal lines in red plots. In the first and third columns, the horizontal axis of each plot indicates the horizontal position of the averaged area. In the second and fourth columns, the horizontal axis indicates the vertical position of the averaged area.

exhibited significant average values along a vertical segment that was not aligned with inducers in the vertical completion condition (column 1 of bottom row in Figure 7) and along a horizontal segment in the vertical completion condition (column 2 of bottom row in Figure 7). In general, however, the results from this quantitative analysis support the qualitative interpretation of the classification images: Both observers were influenced by noise elements that fell in-between inducers and along the approximate locations of illusory contours. In the vertical completion condition, both subjects were influenced significantly by noise that fell along a single vertical side of the illusory square, but neither subject was influenced by noise that fell along the horizontal sides (columns 1 and 2, Figure 7). In the horizontal completion condition, both subjects were influenced significantly by noise that fell along a single horizontal side of the illusory square, but neither subject was influenced by noise that fell along the vertical sides (columns 3 and 4, Figure 7).

Discussion

The classification images demonstrated that both subjects were influenced by noise falling along one illusory contour in both the vertical and horizontal completion conditions. This result differs from the results obtained in Experiment 4, which found that two of three subjects were influenced by noise falling along two vertical illusory contours but only one horizontal illusory contour. A main difference between the two experiments concerns the placement of the stimuli. In Experiment 4, the stimuli

were centered on the fixation point, and therefore horizontal, but not vertical, illusory contours crossed the vertical meridian. In the current experiment, the stimuli were presented in the lower-right quadrant of the peripheral visual field, and therefore neither horizontal nor vertical illusory contours crossed the vertical meridian. Hence, the current results are consistent with the Pillow and Rubin's hypothesis that the vertical bias found in Experiment 4 was caused by the horizontal inducers being placed in different hemifields.

An alternative explanation, not considered by Pillow and Rubin (2002), is that the differences between results obtained with centrally viewed and peripherally viewed stimuli reflect the effects of the stimulus support ratio on vertical completion bias. With centrally viewed stimuli, Pillow and Rubin found significant vertical completion bias when the support ratio was less than or equal to 0.5, but little or no bias when the support ratio was 0.8. In the current experiment, the support ratio was 0.453 for the top and left sides and 0.650 for the right and bottom sides. These values were selected so that our stimuli were similar to the ones used by Pillow and Rubin. Furthermore, the value of 0.453 was essentially identical to the support ratio used in Experiments 3 and 4. Based on the findings of Pillow and Rubin, we would expect a support ratio of 0.453 to be low enough to produce a completion bias that favored the left side of our stimulus over the top side. However, the support ratio of 0.65 may have been too high to elicit a bias for the right side over the bottom side. Hence, the support ratios used in the current experiment may have reduced the sensitivity of our experiment to vertical completion bias for peripherally viewed stimuli.

General discussion

Based on shape discrimination thresholds in completion and control conditions, we could not find any objective evidence of perceptual completion using stimuli that were virtually identical in size and support ratio to the stimuli used by Pillow and Rubin (2002). We did obtain objective evidence of perceptual completion when the stimuli were smaller and had higher support ratios. Nevertheless, even in these conditions, shape discrimination thresholds did not yield evidence that vertical contours were consistently easier to complete than horizontal contours. Indeed, [Experiment 2](#) found that shape discrimination thresholds were different between the horizontal and vertical completion conditions, but it was opposite to the trend reported by Pillow and Rubin. In [Experiments 3a](#) and [3b](#), which found no overall effect of contour orientation, roughly half of the subjects had thresholds that were consistent with a vertical bias and the remaining subjects had results consistent with a horizontal bias. Hence, discrimination thresholds did not reveal evidence of a strong and/or consistent bias for completing vertical contours more easily than horizontal ones. Classification images, on the other hand, revealed differences in processing strategies among subjects and were consistent with the idea that perceptual completion of vertical contours might be slightly easier than completion of horizontal contours, at least in the two of three subjects who participated in [Experiment 4](#) (which used centrally viewed stimuli). In that experiment, subjects were influenced by noise distributed along horizontal illusory contours, but there was a tendency for a slightly greater influence of noise that was distributed along vertical illusory contours. In this respect, our results are consistent with the classification images obtained by Gold et al. (2000), who found that shape discrimination judgments were influenced by noise distributed along only the vertical contours of illusory squares. The slight tendency toward a vertical bias was not apparent in [Experiment 5](#), when the stimulus was presented in the lower-right quadrant of the visual field. These different results may reflect differences in the way that modal completion operates on inducers that do or do not fall within the same visual hemifield. However, we cannot rule out the possibility that differences between [Experiments 4](#) and [5](#) (or between the corresponding conditions in Pillow and Rubin, 2002) are due to differences in the support ratios used to generate the peripheral and central stimuli. Together, our results with classification images in [Experiments 4](#) and [5](#) were weakly consistent with Pillow and Rubin's idea that the perceptual completion is more difficult when it requires integrating information across two hemispheres than when information can be integrated within a single hemisphere.

Nevertheless, unlike Pillow and Rubin (2002), we failed to find any evidence of vertical completion bias when measuring angular rotation thresholds in [Experiments 1–3](#).

What might explain this inconsistency between the current results and those reported previously? In [Experiments 1–3](#), we did not provide subjects with trial-by-trial feedback. Although the issue of feedback is not addressed in Pillow and Rubin, personal communication with one of the authors confirmed that feedback was not used in those studies. Therefore, the different results cannot be explained by differences in the feedback provided to subjects. One difference between the studies is that Pillow and Rubin excluded four subjects (out of 15) who, in a test conducted prior to the actual experiment, failed to demonstrate that they could use illusory contours to perform shape discrimination tasks, whereas our experiments did not exclude any subjects. Unfortunately, Pillow and Rubin did not describe the procedure they used to screen subjects, and so it is not clear if it was a more stringent test of sensitivity to illusory contours than the practice trials in our experiments, or whether it may have induced a vertical completion bias. Another difference is that we used a staircase method to determine thresholds, whereas Pillow and Rubin used the method of constant stimuli. In their main experiment, levels of contour rotation ranged from about -4 to $+4$ deg, but estimated thresholds sometimes exceeded this range. As such, the validity of some of the threshold estimates is difficult to gauge, and the staircase method may provide a more accurate measure of thresholds. Finally, as noted in [Experiment 3](#), although we did not find an overall vertical completion bias, there were large individual differences among subjects. In fact, some individuals exhibited a vertical bias, whereas others exhibited a horizontal bias. It may be that Pillow and Rubin's sample was skewed toward including the former type of subjects.

Such an explanation does not, however, account for the differences between threshold measures of performance and classification images. For example, in [Experiment 4](#), the classification images of two of three subjects exhibited a slight vertical bias, but none of the subjects exhibited a bias in their thresholds. A potential explanation of the apparent discrepancy is that our measure of vertical completion bias in a classification image—i.e., a difference in the number of sides in which significant structure was found in-between inducers—is not a good index of sensitivity in the discrimination task. It is important to realize that good performance in the discrimination task does not require subjects to use the contrast of noise elements that are in-between the inducers. Indeed, an optimal strategy would be to accurately encode the orientations of the four vertical or horizontal edges (in the vertical and horizontal completion conditions, respectively) and to ignore the noise in-between inducers where there is no stimulus information (Murray, Bennett, & Sekuler, 2005). Therefore, the fact that subjects were influenced by noise elements in-between inducers can be thought of as a source of inefficiency that constrains performance in the completion conditions but not the fragmented condition. Why then are thresholds lower in

the completion conditions? The reason is that subjects' use a more efficient strategy in completion conditions. Using stimuli that were similar to the ones used in [Experiment 4](#), Murray et al. demonstrated that, in completion conditions, subjects' decisions were based on the orientations of more inducer edges than in the fragmented condition. Furthermore, Murray et al. found that the increased reliance on multiple inducer edges meant that classification images measured in completion conditions were more similar to an ideal observer's template than were classification images in the fragmented condition, and that differences between thresholds were well-predicted from the differences between classification images measured in those conditions. In the current [Experiment 4](#), subjects exhibited a greater tendency to be influenced by noise elements in-between inducers in the vertical completion condition, but that does not necessarily imply that they encoded the orientation of the inducer edges more accurately in that condition. Indeed, a close examination of [Figures 3](#) and [6](#) suggests that local contrast in the classification images near the edges of the transducers was greater in the horizontal completion condition than in the vertical completion condition.

Recently, several studies used classification images to explore spatiotemporal processing (e.g., Gold & Shubel, 2006; Nagai et al., 2007; Neri & Heeger, 2002; Neri & Levi, 2007). For example, Gold and Shubel (2006) examined the spatiotemporal properties of perceptual completion using response classification. The results showed a gradual increase over time, over the course of the initial 200 ms, in the influence of noise in the vertical regions between the inducers for illusory contours. As in Gold et al. (2000), however, Gold and Shubel (2006) did not independently control whether information for completion was contained in vertical or horizontal contours. As such, it would be interesting in future studies to determine whether the microgenesis of visual completion differ for contours completed across-hemispheres and within-hemispheres.

Lastly, the present study suggested an advantage of the response classification method over traditional threshold measures. The vertical bias in perceptual completion might be too weak to be consistently shown with threshold measures. However, the response classification method is much more sensitive to perceptual strategies and individual differences than global threshold measures and thus may reveal even the relatively weak vertical bias identified in the current study.

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