Perception of 3D slant from textures with and without aligned spectral components

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The image of a textured surface provides multiple potential cues that could be used to perceive its 3D structure. When a surface texture has oriented structure, perspective convergence of the oriented components provides a texture cue, in addition to texture scaling and compression. Some findings suggest that oriented spectral components aligned with the direction of slant are important for 3D perception from texture, but this has only been demonstrated in restricted situations. In this study, we tested the contribution of oriented spectral components for planar surface patches with varied slant (0°–80°) and field of view (16° and 6°). Observers viewed simulated textured surfaces and estimated slant to the perceived surfaces. The simulated textures were octotropic plaids with a full range of orientations, or with either the aligned or perpendicular plaid components removed. We measured perceptual bias in monocular conditions and also the relative weighting of texture and stereo information in binocular conditions. We found that the presence of aligned spectral components did produce some improvement in slant estimates, but the effects were small and only observed in some conditions. There were no detectable differences in texture cue weights. Our results demonstrate that aligned spectral components contribute to perception of slant from texture, but suggest that the contribution is limited when other texture cues are available and informative. Our findings are consistent with the notion that the visual system utilizes multiple sources of texture information for 3D perception.

Introduction

When a textured surface is viewed in perspective, deformations of the texture in the projected image provide information about the 3D structure of the surface. Previous studies have shown the visual system can utilize texture information from a monocular image to perceive the 3D slant of planar surfaces (e.g., Rosenholtz & Malik, 1997; Knill, 1998a; Tibau, Willems, van den Bergh, & Wagemans, 2001; Saunders, 2003; Rosas, Wichmann, & Wagemans, 2004; Norman, Crabtree, Bartholomew, & Ferrell, 2009; Todd, Christensen, & Guckes, 2010; Saunders & Chen, 2015), and to perceive the 3D shape of curved surfaces (e.g., Todd & Akerstrom, 1987; Li & Zaidi, 2000; Todd, Thaler, & Dijkstra, 2005; Thaler, Todd, & Dijkstra, 2007; Todd, Thaler, Dijkstra, Koenderink, & Kappers, 2007; Todd & Thaler, 2010). Texture information also contributes to 3D perception in binocular viewing conditions that provide stereo depth information, as demonstrated by studies using a cue conflict paradigm (Gillam, 1968; Buckley & Frisby, 1993; Knill & Saunders, 2003; Hillis, Watt, Landy, & Banks, 2004; Watt, Akeley, Ernst, & Banks, 2005; Rosas, Wagemans, Ernst, & Wichmann, 2005; Girshick & Banks, 2009; Saunders & Chen, 2015).

The image of a textured surface typically contains multiple potential cues that could convey 3D slant or shape from texture. Potential cues include foreshortening of texture due to local surface slant, variations in texture size or spatial frequency along an image due to variations in viewing distance, and perspective convergence of oriented structure along a surface in a projected image. As illustrated in Figure 1, these texture cues can be defined in terms of the local spatial frequency spectra. Surface orientation could potentially be estimated from the asymmetry in spectra due to foreshortening, the changes in spatial frequency across the image, or the changes in orientation across the image.

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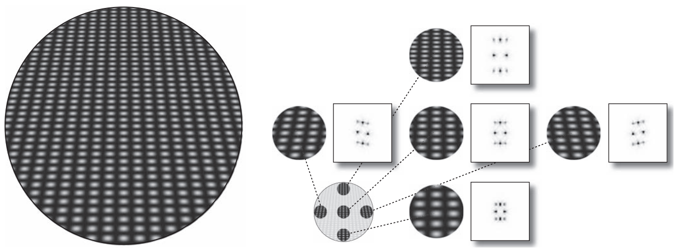

Figure 1. Illustration of texture cues for 3D slant. The left image shows a simulated view of a slanted planar surface with rectangular grid texture. The right figures show different regions of the image and their spatial frequency spectra. Foreshortening causes regions to have higher spatial frequency in the tilt direction (vertical) than in the horizontal direction, which provides a cue for local surface orientation (texture compression). There is also an increase in spatial frequencies across the image in the tilt direction (bottom vs. top regions), which provides another potential cue to surface orientation (texture scaling). Because the grid texture has parallel components, the projected image also provides a perspective convergence cue. The projected orientations of the vertical components vary along the direction perpendicular to the tilt direction (left vs. right regions), with the rate of change depending on the distance to the horizon of the surface.

All of these texture cues have been shown to contribute to 3D perception, but their relative contributions in various situations are not fully understood. A number of studies have investigated the roles of texture compression and texture scaling in 3D slant perception using stimuli with cue conflicts. Some have observed a contribution from both texture compression and scaling, with texture compression having larger influence (e.g., Rosenholtz & Malik, 1997; Knill, 1998a, 1998b). Other studies by Todd and colleagues (Todd et al., 2005; Todd et al., 2007; Todd et al., 2010) observed that slant judgments across a range of conditions were well predicted by a single variable based on texture scaling, which they term *scaling contrast*. In addition to texture scaling and compression, there is also evidence that perspective convergence of oriented texture components can be used for 3D perception. Textures with oriented structure have been found to be more effective at conveying 3D slant than isotropic textures (Braunstein & Payne, 1969; Rosas et al., 2004; Todd et al., 2005; Saunders & Backus, 2006), and oriented components have been found to improve perception of 3D curvature in some conditions (Li & Zaidi, 2000, 2001a, 2001b, 2004; Zaidi & Li, 2002). In the conditions tested by Li & Zaidi, perceived shape was highly dependent on the presence of oriented texture components aligned with the direction of curvature, suggesting an important role for perspective convergence. However, Todd & Oomes (2002) have argued that this finding is limited to specific situations, and many other studies have found that isotropic textures without oriented structure can be effective for perception of 3D shape from texture (e.g., Todd & Akerstrom, 1987; Todd et al., 2007; Todd & Thaler, 2010). The visual system is clearly capable of using all three of these texture cues, but their relative contribution may vary depending on factors like field of view (FOV), the magnitude of surface slant, and the specific type of texture.

In this study, we investigated the role of perspective convergence for 3D slant perception. Specifically, we tested the role of oriented spectral components that are aligned with the direction of slant. There is some evidence that aligned spectral components contribute, but this has only been demonstrated in conditions that provide degraded information from one of the other textures. We tested the effect of removing aligned spectral components on perceived 3D slant for surfaces with a range of slants, and manipulated the information of other texture cues by using either a small or medium FOV.

Role of oriented spectral components

The information provided by perspective convergence of oriented components depends on the alignment of the oriented components relative to the 3D structure of the surface. In Figure 1, the parallel lines in the vertical direction have a large change in orientation across the projected images, while the parallel lines in the horizontal direction do not change orientation. Oriented structure in other directions would also create perspective convergence when a surface is viewed from a slant, but there would be less change in orientation across the projected image than when oriented structure is aligned. Similarly, for a curved surface, parallel structure that is aligned with the direction of maximum curvature would show the most angular variations in the projected image. To the extent that perspective convergence is used for 3D perception, an oriented structure that is aligned with the direction of surface tilt would therefore be most informative.

Some studies have demonstrated that aligned spectral components can have a large influence on perception of slant from texture in the case of surfaces that are close to the frontal plane. Tam, Shin, and Li (2013) used cue conflict conditions to test the relative contributions of texture orientation and scaling for slant discrimination. Figure 2a shows examples of their cue conflict stimuli. Tam et al. (2013) found that aligned components was the primary determinant of slant judgments for surfaces near the frontal plane, which they interpret as evidence that observers relied on the orientation modulation. However, this result would also be consistent with the scaling contrast model of Todd et al. (2007), which uses the change in scaling across an image as measured in a perpendicular

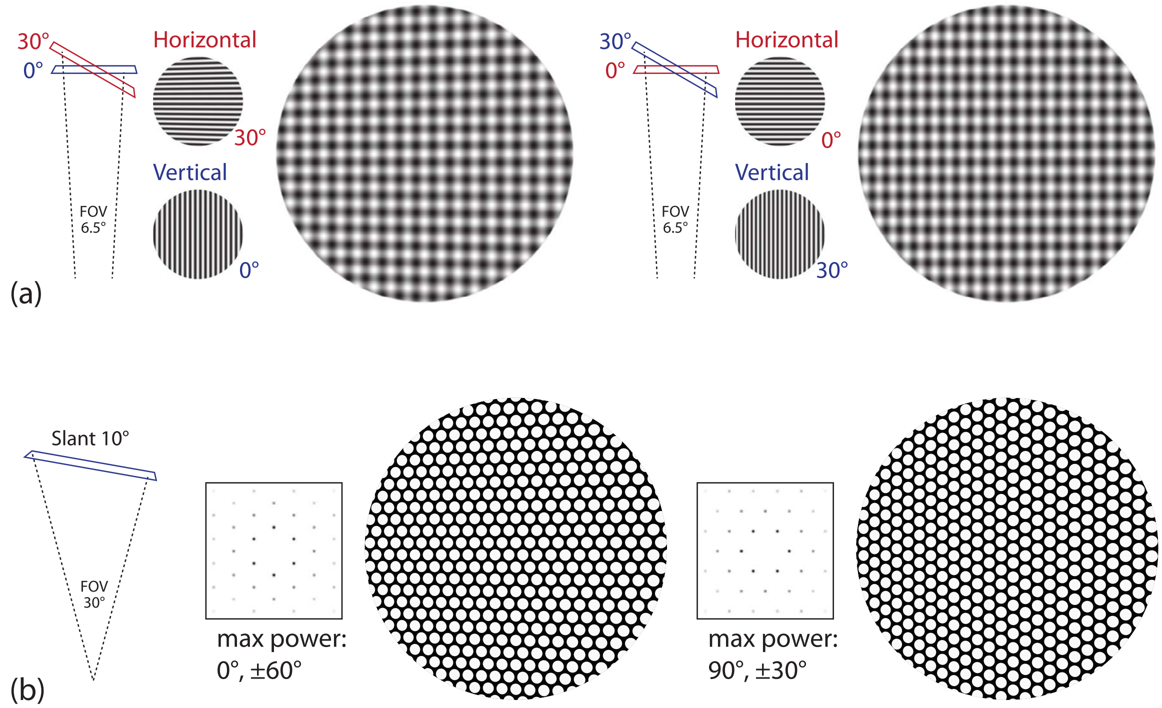

Figure 2. (a) Examples of cue conflict stimuli from Tam et al. (2013) that independently varied orientation and frequency cues. The left image combines the projected images of a horizontal grating slanted to the left by 30° and a vertical grating with zero slant, while the right image combines a vertical grating with 30° slant and a frontal horizontal with zero slant. The left image with orientation modulation appears slanted, while the right image with only frequency modulation does not. (b) Examples of stimuli from Saunders and Backus (2006). Both images simulate a planar surface slanted by 10° with texture composed of circles arranged in a hexagon grid, but with different alignment. The primary spectral components have orientations of 0° and ±60° relative to the direction of slant (left), or orientations of ±30° and 90° (right). Slant is easier to perceive in the case when aligned spectral components are given (left), resulting in lower slant discrimination thresholds.

direction (i.e., change in vertical size from left to right in the image, or vice versa). Another study by Saunders and Backus (2006) tested slant discrimination relative to frontal plane for hexagon grid textures with different orientations, and observed better discrimination when one of the primary components of the spatial frequency spectra was aligned with the direction of slant. Figure 2b shows examples of the two alignment conditions. The largest oriented components of the spectra for these textures correspond to the main rows of the grid pattern. Although these textures are regular arrangements of circles in both cases, with the same directions of translational symmetry, slant is easier to perceive when one of these oriented components is aligned with the direction of slant. Saunders and Backus (2006) attribute this difference to the perspective convergence cue provided by the aligned spectral components, and argue that it would be difficult to explain in terms of other texture cues.

Although these results show that perspective convergence of aligned spectral components can contribute to perception of 3D slant from texture, a strong influence has only been demonstrated in conditions that provide limited information from other texture cues. In both Tam et al. (2013) and Saunders and Backus (2006), observers judged slant relative to the frontal plane. When slant is low, texture compression is not a reliable cue to slant (Knill, 1998c), and slant discrimination from isotropic textures is poor (e.g., Knill & Saunders, 2003; Hillis et al., 2004; Saunders & Backus, 2006). At higher slants, when texture compression provides better information, aligned components would likely have less influence. The stimuli in Tam et al. (2013) also had a small field view (6.5°), which limits the information from changes in texture scaling. This could have further exaggerated the influence of aligned spectral components. In conditions of Tam et al. (2013) that tested discrimination around 30° slant rather than around frontal, perspective convergence was no longer the dominant factor in slant judgments. Other studies have tested slant judgments in conditions with higher slant and observed differences between textures with and without oriented structure (Braunstein & Payne, 1969; Rosas et al., 2004; Todd et al., 2005). However, these studies did not attempt to isolate the information from perspective convergence, so the differences could be due to other factors, such as texture regularity. The results of Tam et al. (2013) and Saunders and Backus

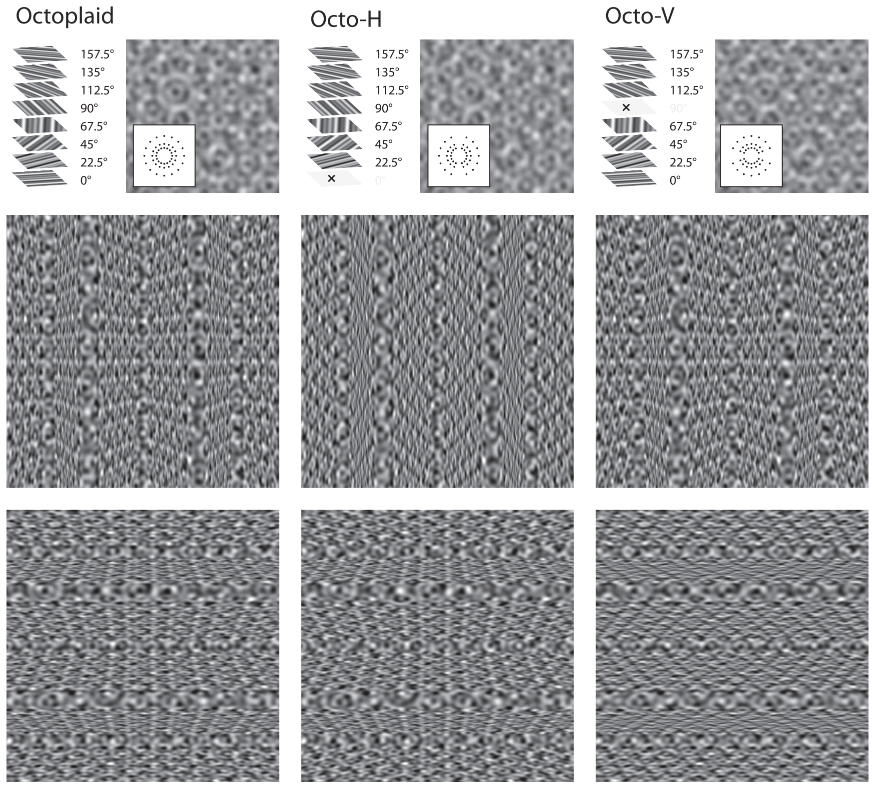

Figure 3. Illustration of a plaid texture created by superimposing oriented components with eight different directions (Octotropic, left), and plaids without the horizontal component (Octo-H, middle) or the vertical components (Octo-V, right). The top panels show frontal views of the three plaid textures and their corresponding spectra (inserts). The middle panels show perspective views of a corrugated surface with horizontal direction of curvature covered with each of the plaid textures, constructed to match conditions tested by Li and Zaidi (2000). For the two plaids that contain horizontal components, Octoplaid and Octo-V, one can readily see the qualitative shape. For the plaid without this component, Octo-H, there is less of a 3D percept and it is hard to distinguish peaks and valleys. When the direction of surface curvature is vertical (bottom panels), removing the vertical plaid component (Octo-V) interferes with shape perception while removing the horizontal component (Octo-H) does not.

(2006) demonstrate that the presence of aligned spectral components can greatly facilitate slant perception when surfaces are near frontal or when FOV is small, but it is not yet known how much this information contributes when other texture cues provide more reliable information.

Some findings of Li and Zaidi provide another source of evidence that oriented spectral components are important for 3D perception (Li & Zaidi, 2000, 2001a, 2001b, 2004; Zaidi & Li, 2002). Figure 3 shows examples of conditions tested by Li and Zaidi (2000) that demonstrate an influence of oriented spectral components on perceived curvature. These plaid textures are the same except for the presence of either horizontal or vertical components. Li and Zaidi (2000) found that observers had difficulty perceiving the shape of the corrugated surface from the plaid texture when the oriented components aligned with the direction of curvature is removed, and observed similar effects for other textures composed of spectral components. Unlike the slant perception studies by Saunders and Backus (2006) and Tam et al. (2013), these corrugated surfaces include regions with high slant, which could provide a reliable texture compression cue. This suggests that aligned spectral components may be important in a wider range of conditions, and not just in the case of surfaces oriented near the frontal plane.

However, Todd and Oomes (2002) have argued that conditions tested by Li and Zaidi (2000, 2001a) are atypical situations that provide degenerate information, and that the apparent importance of oriented spectral components is not representative of more generic conditions. They note that the simulated corrugated surfaces used in these studies had large variations in depth over a small visual angle, which would require nongeneric combinations of shape and viewing condition. The rapid change in depth could make it difficult to measure and compare texture properties across the image, such as variations in texture scaling. While aligned oriented components appear necessary to perceive the shape of these deep corrugated surfaces, isotropic textures without aligned components can effectively convey 3D shape in other situations (e.g., Todd & Akerstrom, 1987; Todd &

Oomes, 2002; Todd et al., 2007; Thaler & Todd, 2010). Whatever texture information is used to perceive, 3D shape from isotropic textures appears to be absent or degraded in the corrugated surface stimuli used by Li and Zaidi (2000, 2001a).

The present study

In this study, we used the octotropic plaid textures introduced by Li and Zaidi (2000, 2001a, 2001b, 2004) and Zaidi and Li (2002) to test the contribution of aligned spectral components to 3D slant perception. These plaid textures provide texture compression and scaling cues with or without the aligned spectral components, so any observed differences could be attributed to the orientation information provided by these components. Observers viewed planar surface patches with different slants and performed a manual slant estimation task (Saunders & Chen, 2015). In Experiment 1, we used a medium size FOV (16°), and in Experiment 2 we used a smaller FOV (6°) that is closer to the size of the stimuli used by Tam et al. (2013).

We assessed the effectiveness of texture in two ways: perceptual bias in perception of slant from texture only, and the relative weighting of texture information in the presence of conflicting binocular information. Both of these measures would be expected to depend on the informativeness of texture information.

Previous studies have found that slant from texture is underestimated with monocular viewing (Saunders, 2003; Todd et al., 2005; Watt et al., 2005; Norman et al., 2009; Durgin, Li & Hajnal, 2010; Todd et al., 2010; Saunders & Chen, 2015), and the underestimation is greater when texture information is degraded (Saunders, 2003; Rosas et al., 2004; Todd et al., 2005; Saunders & Chen, 2015). One possible explanation is that texture information is integrated with prior knowledge or frontal cues (e.g., accommodation), resulting in biases toward frontal when texture information is unreliable (Saunders & Chen, 2015). This Bayesian model predicts that reducing texture information would increase underestimation of slant. If perspective convergence of aligned spectral components is utilized as slant information, then one would expect more bias toward frontal when this information is removed. For surfaces rotated around a horizontal axis (i.e., vertical slant), this would correspond to removing the vertical component (Figure 4). If perceptual underestimation is not due to a frontal prior or frontal cues, a difference in perceptual bias might still be expected. A number of studies have found that degrading texture information or reducing texture cues leads to greater underestimation of slant (Saunders, 2003; Rosas et al., 2004; Todd et al., 2005; Saunders & Chen, 2015). To the extent that the visual system relies on perspective convergence of oriented spectral components to perceive slant from texture, removing the aligned components would be expected to increase perceptual biases toward frontal.

Another way to evaluate the effectiveness of texture information is to measure relative weighting in the presence of other conflicting cues. Previous studies have found that observers spontaneously integrate texture and stereo cues to 3D slant according to their reliability (Knill & Saunders, 2003; Hillis et al., 2004; Saunders & Backus, 2006). In addition to testing perceived slant from texture in monocular conditions, we also tested perceived slant in binocular conditions with small conflicts ($\pm 5°$) between the slants specified by texture and stereo cues. If aligned spectral components improves slant information from texture, then removing these components would be expected to reduce the influence of texture relative to stereo information in cue conflict conditions.

Experiment 1

Method

Subjects

Ten right-handed adults (three men, seven women; mean age: 23.3 years) at the University of Hong Kong were recruited for the experiment. All the subjects had normal or corrected-to-normal visual acuity, and passed a stereo acuity screening test. All subjects were naïve as to the purpose of the study. Each subject finished two 1-hr sessions on two separate days and were paid 100 HKD. The procedures were approved by and conform to the standards of the Human Research Ethics Committee for Non-Clinical Faculties.

Apparatus and stimuli

The stimuli were computer-generated perspective images of the slanted planar surfaces covered with a regular texture pattern, viewed through a 16° diameter circular window. The images were presented on a LCD monitor (ASUS VG278H; Asus Computers, Fremont, CA) with a resolution of 1920×1080 pixels and a refresh rate of 120 Hz (60 Hz for each eye, respectively). The display was viewed from a chin rest at a viewing distance of 100 cm. A black board with a circular aperture with a diameter of 16.8 cm was placed 60 cm from the observer to mask the screen outside of a 16° circular region. Shutter glasses (NVIDIA 3D Vision 2; NVIDIA, Santa Clara, CA) were used to present left and right stereo images to the two eyes. Interocular distance was measured for each individual subject and used to render accurate stereo images. For monocular viewing conditions, the nondominant eye of each

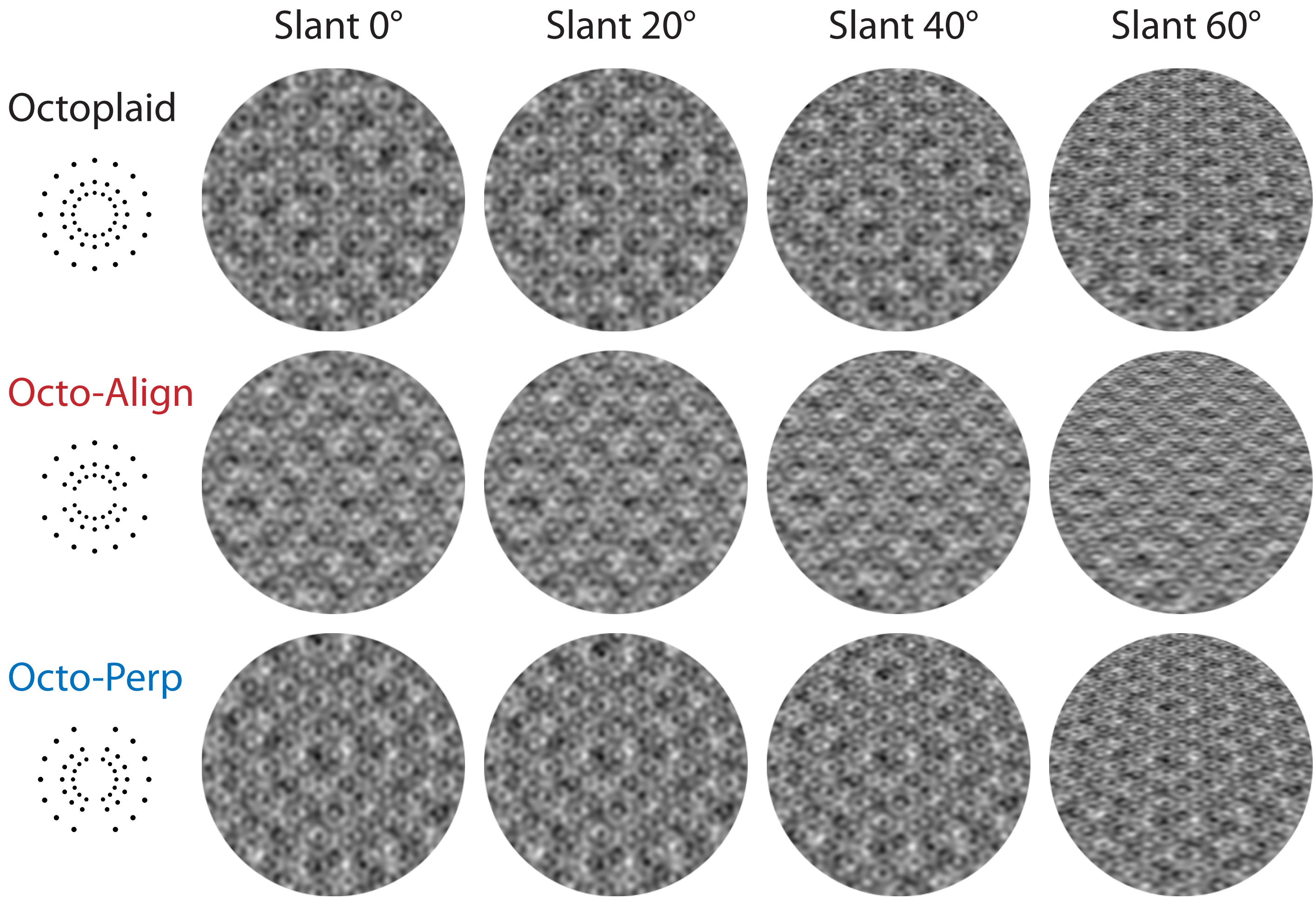

Figure 4. Illustration of the simulated surfaces with octotropic plaid textures either with all oriented spectral components (top), or missing the vertical (middle), or missing the horizontal components (bottom). In each row, we present the perspective views of surfaces with simulated slants of 0°, 20°, 40°, and 60°. The simulated FOV is 16°, as used in Experiment 1. For the surfaces are slanted along a horizontal axis, the vertical components are aligned with tilt direction while the horizontal components are perpendicular to tilt direction. Therefore, we will refer to the texture without vertical components as Octo-Align, and the texture without horizontal as Octo-Perp.

subject was covered with an eye patch. Images were rendered with OpenGL using a NVIDIA Quadro 600 graphics card, and were antialiased with sub-pixel resolution.

Observers indicated the perceived slant of a virtual surface by aligning the palm of their hand with the perceived surface (Figure 5). To record the hand orientation, we used a 3D Guidance trakSTAR system (Northern Digital, Waterloo, ON, Canada). A flat board with three trakSTAR sensors was attached to the palm of the observer's hand. The orientation of the palm was computed from the tracked locations of the three sensors.

Surfaces were slanted around a horizontal axis (i.e., receding in the vertical direction). For the monocular conditions and the binocular conditions with consistent cues, simulated surface slant varied from 10° to 70° in 10° steps. For the cue conflict conditions, the stereo slant was either 20°, 40°, or 60°, and the slant specified by texture differed by ±5°.

Three variants of the octotropic plaids were used for surface textures. Figure 4 shows examples of the three textures at four different surface orientations. The plaids were constructed in a similar way as in Li and Zaidi (2000). For the full octotropic plaid patterns (Octo), we superposed eight oriented components with angles sampled in 22.5° steps from 0° to 168.5°. The component at each orientation was composed of three sinusoids with spatial frequencies of 1.6, 3.1, and 6.2 cpd and approximately 10% contrast. The phases of the patterns were random. Two additional textures were created by removing either the components aligned with the tilt direction (Octo-Align) or the components perpendicular to the tilt direction (Octo-Perp). We also added trial-to-trial variations in the size of the surface texture, from 90% to 110% of the base size, to decouple

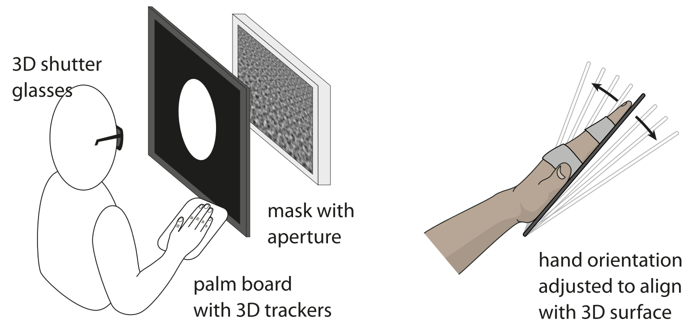

Figure 5. Illustration of the manual slant estimation task. Observers viewed displays that simulated a slanted planar surface, and adjusted their hand to be aligned with the perceived surface. A palm board with 3D trackers was attached to the observer's right hand, which they could otherwise move freely. The display was viewed though a round aperture that constrained the FOV to be 16° (Experiment 1) or 6° (Experiment 2). Stereo shutter glasses were used to present different images to the left and right eyes in binocular conditions.

surface slant and the scale of the projected texture at the top or bottom of the images.

Cue conflict stimuli were constructed as previous studies (Knill & Saunders, 2003; Hillis et al., 2004; Saunders & Chen, 2015). The images simulated the result of first computing a cyclopean projected image of a textured surface viewed from the desired slant from texture, then back-projecting the cyclopean image onto a 3D surface with the desired slant from stereo, and then computing stereo perspective views of 3D surface with back-projected texture. When the texture slant does not match the stereo slant, the back-project results in a distorted texture on the 3D surface that projects conflicting texture cues.

Procedure

Subjects performed a manual slant estimation task in which they aligned the palm of their right hand to the perceived slant of a simulated surface. Subjects began trials with their right hand at a starting position on a table. A small fixation cross was then presented for 2 s, followed by the presentation of simulated surface. When the surface appeared, the observer lifted his or her hand from the table and oriented it to match the perceived orientation of the surface, and then pushed a button to indicate completion. Trials were self-paced, and response times were typically 1-2 s. Subjects were asked to keep their hands in a general region in front and to the right of their body in order to be near the tracking apparatus; otherwise, the position of the hand and arm were not constrained. Subjects were took breaks every 5 min to avoid fatigue.

The experiment was conducted over two sessions on separate days. Each session consisted of a block of binocular trials and a block of monocular trials, with orders reversed across sessions, and initial order counterbalanced across subjects. Before the first session, subjects performed a practice block to become familiar with the task. Binocular blocks consisted of 312 trials (168 for cue consistent conditions and 144 for cue conflict conditions) and monocular blocks had 168 trials. All conditions were randomly intermixed within blocks.

Results and discussion

Perceptual bias

We first compare perceptual biases across different texture types. Figure 6 shows the mean slant estimates as a function of simulated slant, averaged across subjects, in the monocular viewing conditions (left) and the binocular viewing conditions (right). The top graphs show results for textures that were missing the vertical spatial frequency components (Octo-Align, red), and the bottom graphs show results for texture that were missing the horizontal components (Octo-Perp, blue). The results for the full octotropic plaid are also plotted on both figures (black). Judged slant varied systematically as a function of simulated slant in all conditions. In the binocular viewing conditions, the slant estimates appeared to be a linear function of simulated slants. With monocular viewing, the function was nonlinear with estimates highly compressed at low slants, as has been observed previously (Todd et al., 2010; Saunders & Chen, 2015).

We performed a 7×3 ANOVA on slant estimates from monocular viewing across texture type and slant conditions. There was a significant main effect of texture type on overall bias, $F(2, 18) = 4.12$, $p = 0.034$, partial $\eta^2 = 0.314$. Slant estimates were higher in the Octo-Align condition than in the Octo-Perp condition, $F(1, 9) = 6.46$, $p = 0.032$, partial $\eta^2 = 0.418$, though this difference was small (1.29° ± 0.51° *SE*). There was no significant difference between the bias in these conditions and the Octotropic conditions with full spectral content: Octo vs. Octo-Align, $F(1, 9) = 1.09$, $p = 0.324$, partial $\eta^2 = 0.108$; Octo vs. Octo-Perp, $F(1, 9) = 3.47$, $p = 0.095$, partial $\eta^2 = 0.278$.

Slant estimates in the monocular conditions were significantly modulated by simulated slant, $F(6, 54) = 110.66$, $p < 0.001$, partial $\eta^2 = 0.919$. We further tested polynomial contrasts to evaluate the nonlinearity of the psychometric functions. We found that there was a significant quadratic trend, $F(1, 9) = 34.44$, $p < 0.001$, partial $\eta^2 = 0.793$, and cubic trend, $F(1, 9) = 11.55$, $p = 0.008$, partial $\eta^2 = 0.562$, in addition to a significant linear trend, $F(1, 9) = 141.94$, $p < 0.001$, partial $\eta^2 = 0.940$. There was no significant interaction between slant and texture types, $F(12, 108) = 1.19$, $p = 0.297$, partial $\eta^2 = 0.117$, indicating that the shape of

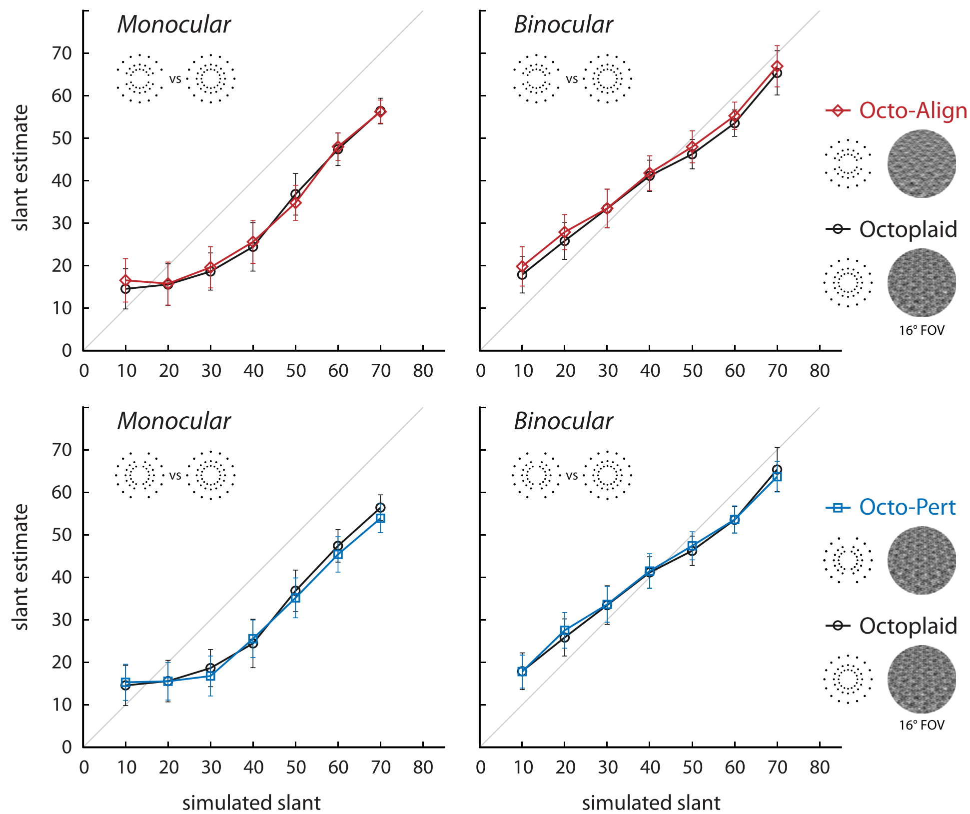

Figure 6. Mean slant estimates as a function of simulated slants in the monocular (left) and binocular (right) viewing conditions of Experiment 1. The upper panel shows the comparison between the slant estimates in the Octotropic and Octo-Align conditions. The lower panel compares the estimates in the Octotropic and Octo-Perp conditions.

psychometric functions were comparable across texture types.

For the slant estimates with binocular viewing, there was a significant main effect of texture type, $F(2, 18) = 4.91$, $p = 0.020$, partial $\eta^2 = 0.353$. Pairwise tests found that slant estimate was higher in the Octo-Align condition than in the Octo condition, $F(1, 9) = 19.89$, $p = 0.002$, partial $\eta^2 = 0.689$, but the difference was limited ($1.39° \pm 0.31°$ *SE*). For the other comparisons, no significant difference was found: Octo versus Octo-Perp, $F(1, 9) = 0.23$, $p = 0.646$, partial $\eta^2 = 0.024$; Octo-Align versus Octo-Perp, $F(1, 9) = 3.96$, $p = 0.078$, partial $\eta^2 = 0.308$. There was also a main effect of simulated slant, $F(2, 18) = 84.46$, $p < 0.001$, partial $\eta^2 = 0.904$, confirming that slant estimates were modulated by simulated slant. The psychometric functions were approximately linear in the binocular conditions, so we used the slopes of the functions for further comparisons across the texture type conditions. We computed slopes for each subject and texture type by performing robust linear regression fits. There was no significant differences in the slopes across the three texture conditions, $F(2, 18) = 0.308$, $p = 0.739$, partial $\eta^2 = 0.033$, and no significant interaction between slant and texture was observed, $F(12, 108) = 0.90$, $p = 0.549$, partial $\eta^2 = 0.091$.

Our results indicate that removal of specific spectral components had little or no effect on perception of slant from texture for our task and conditions. If spectral components in the tilt direction were crucial for perception of slant, then one would expect slant estimates from Octo-Align textures to be more biased than estimates with other textures. This was not observed in either monocular or binocular viewing conditions. The only detectable differences across texture types were small and opposite to this prediction. The similarity of the psychometric functions suggest that the three textures are equally effective at conveying 3D slant from texture for these viewing conditions.

Cue weight in the conflict conditions

We also tested whether removing spectral components affected the weighting of texture information relative to stereo information in cue conflict conditions. Figure 7 plots mean slant estimates as a function of slant conflict for the three texture types and three base slants. Each set of points shows results from conditions where stereo information specifies the same slant but monocular texture information specifies different slants. If texture information was ignored by the visual system, the slope across these sets of points would be

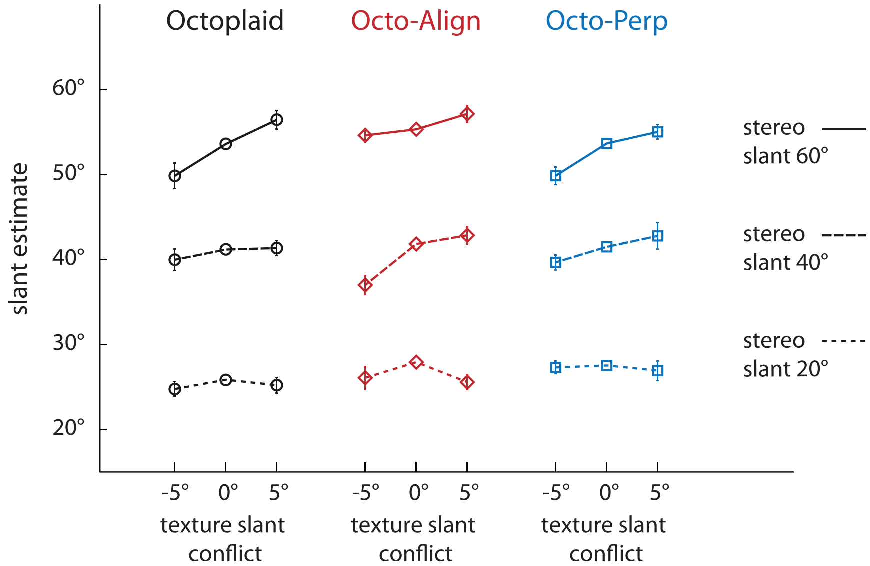

Figure 7. Mean slant estimates in the cue-conflict conditions of Experiment 1 for the Octoptropic, Octo-Align, and Octo-Perp textures. Each set of points shows results from conditions with the same stereo slant but different slant from texture. A non-zero slope indicates an influence of the conflicting texture information.

zero, while a positive slope would indicate an influence of texture information.

We computed the best-fitting slopes to these functions as a measure of the influence of texture for each condition and subject, and tested whether the mean slopes were significantly greater than zero for different base slants and textures types. For the base slant of 60°, non-zero slopes indicating an influence of texture were observed in all the texture conditions, $t(9) > 2.46$, $p < 0.036$, Cohen's $d > 0.77$. At lower slants, the influence was less clear. When the base slant was 40°, the mean slope was significantly larger than zero with the Octo-Align texture, $t(9) = 4.73$, $p = 0.001$, Cohen's $d = 1.50$, but not with the Octo texture, $t(9) = 1.24$, $p = 0.246$, Cohen's $d = 0.39$, or the Octo-Perp texture, $t(9) = 2.09$, $p = 0.066$, Cohen's $d = 0.66$. For base slant of 20°, the mean slope was not significantly larger than zero for any of the texture conditions, $t < 0.90$, $p > 0.392$, Cohen's $d < 0.29$. Less influence of texture at lower slants would be expected because texture cues are known to be less informative (Knill, 1998c). At higher slants, when texture was more informative, our results show a clear influence of texture information even in presence of conflicting stereo information.

For analysis across conditions, we computed cue weights representing the influence of texture relative to stereo information for each texture type and base slant. The texture cue weight was computed as the ratio of two slopes, b_{tex}/b_{full}, where b_{tex} is the change in slant estimated caused by modulation of texture only (i.e., slopes from Figure 7) and b_{full} is the slope in the consistent cue conditions when both texture and stereo slant are varied (i.e., slopes from binocular conditions in Figure 6).

We performed an ANOVA on cue weights across base slant and texture type conditions. There was a significant a main effect of base slant, $F(2, 18) = 10.45$, $p = 0.001$, partial $\eta^2 = 0.532$, corresponding to larger texture weighting at higher slants. This increase in texture weighting as a function of slant is expected theoretically (Knill, 1998b), and has been observed previously (Knill & Saunders, 2003; Hillis et al., 2004). Comparing across texture types, we found no main effect of texture, $F(2, 18) = 0.02$, $p = 0.980$, partial $\eta^2 = 0.002$, indicating that the overall texture weights were similar across texture types. However, there was a significant interaction between texture type and slant, $F(4, 36) = 3.59$, $p = 0.015$, partial $\eta^2 = 0.285$. Pairwise tests found that the texture weights was higher for Octo-Align texture than for Octo texture at the base slant of 40°, $t(9) = 3.11$, $p = 0.013$, Cohen's $d = 0.983$, while the trend reversed at a base slant of 60° (Octo-Align < Octo), $t(9) = 2.86$, $p = 0.019$, Cohen's $d = 0.905$. However, we suspect that these differences may be spurious. There is no theoretical reason to expect that removing a texture component would have opposite effects at 40° and 60° slant, nor a reason to expect a nonlinear effect of simulated slant on texture weights as observed in the Octo-Align condition.

As with perceptual biases, the cue weights showed no indication that removing an aligned spectral component reduces the effectiveness of texture information. If an aligned component were crucial for conveying slant from texture, then the Octo-Align texture would be the least informative in our conditions, and therefore would be expected to have the least influence relative to stereo information. We did not observe a specific impairment in the Octo-Align condition. The overall pattern of cue weights is similar across texture types, and the apparent differences between the Octo and Octo-Align texture conditions were not in a consistent direction.

In summary, we found no evidence from either perceptual biases or cue weights to support Li and Zaidi's (2000, 2001a, 2001b, 2004) claim that aligned spectral components are crucial to perceive 3D structure from texture. Our results suggested that these octotropic plaid textures provided comparable 3D information in these viewing conditions, with or without a horizontal or vertical component.

Experiment 2

In Experiment 1, removing oriented spectral components did not appear to affect slant estimates with monocular viewing or the weighting of texture information with binocular viewing. This appears to conflict with the findings of Li and Zaidi's studies (2000, 2001a, 2001b, 2004), which found that removing spectral components along the maximum curvature had a large effect on shape perception. However, such effects were not observed in Experiment 1.

Experiment 2 used conditions that more closely match those of Li and Zaidi's previous studies (2000, 2001a, 2001b, 2004). One factor is FOV. The stimuli used by Li and Zaidi (2000) were sinusoidal corrugated surfaces with three periods over 8.8°, leaving each local slanted region very narrow. In contrast, the stimuli in our Experiment 1 had a FOV of 16°. The larger FOV might have enhanced other sources of texture information, thereby reducing the influence of oriented spectral energy. In Experiment 2, we reduced the FOV to 6° by using a smaller viewing aperture and increasing the viewing distance. Experiment 2 also increased the maximum simulated slant to 80°, and matched the spatial frequencies of the plaid patterns to those used in Li and Zaidi (2000; 2001a).

Method

Subjects

Eleven right-handed adults (two men, nine women) at the University of Hong Kong were recruited for the experiment. One female subject was excluded because the experimenter used the wrong interocular distance for the program. The other 10 subjects had a mean age of 25.4 years and normal or corrected-to-normal visual acuity. They all passed a stereo acuity screening test as in Experiment 1. All subjects were naïve to the purpose of the study and were paid 100 HKD for participating. The procedures were approved by and conform to the standards of the Human Research Ethics Committee for Non-Clinical Faculties of the University of Hong Kong.

Apparatus and stimuli

The apparatus was the same as in Experiment 1 except that the FOV was decreased to 6° and the viewing distance was increased to 135 cm. The stimuli were the same except that we increased the range of simulated slants and the base slants of the conflict conditions, and adjusted the spatial frequencies of the plaid components to match the conditions of Li and Zaidi (2000). For cue consistent conditions and monocular conditions, surface slants adopted were 20°, 30°, 40°, 50°, 60°, 70°, and 80°. For cue conflict conditions, stereo specified slant varied by 30°, 50°, and 70° and texture specified slant differed by ±5° from stereo specified slant. The plaids were composed of sinusoidal gratings with frequencies 1.4, 2.1, and 3.5 cpd. Figure 8 shows examples of stimuli for the three texture types and various slants.

Procedure

The task and the experiment design were the same as in Experiment 1.

Results

Perceptual bias

Figure 9 plots the mean slant estimates as a function of simulated slant in monocular (left) and binocular (right) viewing conditions, respectively. As in Experiment 1, the slant estimates were a nonlinear psychometric function of simulated slants with monocular viewing. For binocular viewing conditions, the slant estimates again had an approximately linear relationship with simulated slant.

For monocular viewing conditions, the main effect of texture was not significant, $F(2, 18) = 0.46$, $p = 0.640$, partial $\eta^2 = 0.048$), indicating that slant estimates had similar overall magnitude across texture conditions. The slant estimates were significantly modulated by simulated slant, $F(6, 54) = 87.35$, $p < 0.001$, partial $\eta^2 = 0.907$), as in Experiment 1. In addition to a significant linear trend, $F(1, 9) = 127.17$, $p < 0.001$, partial $\eta^2 = 0.934$, there were significant quadratic and cubic trends: quadratic, $F(1, 9) = 54.30$, $p < 0.001$, partial $\eta^2 = 0.858$; cubic, $F(1, 9) = 5.98$, $p = 0.030$, partial $\eta^2 = 0.399$, confirming that the relationship between slant estimates and simulated slant was nonlinear.

Unlike in Experiment 1, we observed an interaction between texture type and simulated slant on slant estimates, $F(12, 108) = 5.44$, $p < 0.001$, partial $\eta^2 = 0.377$. The pairwise tests showed that the effect of

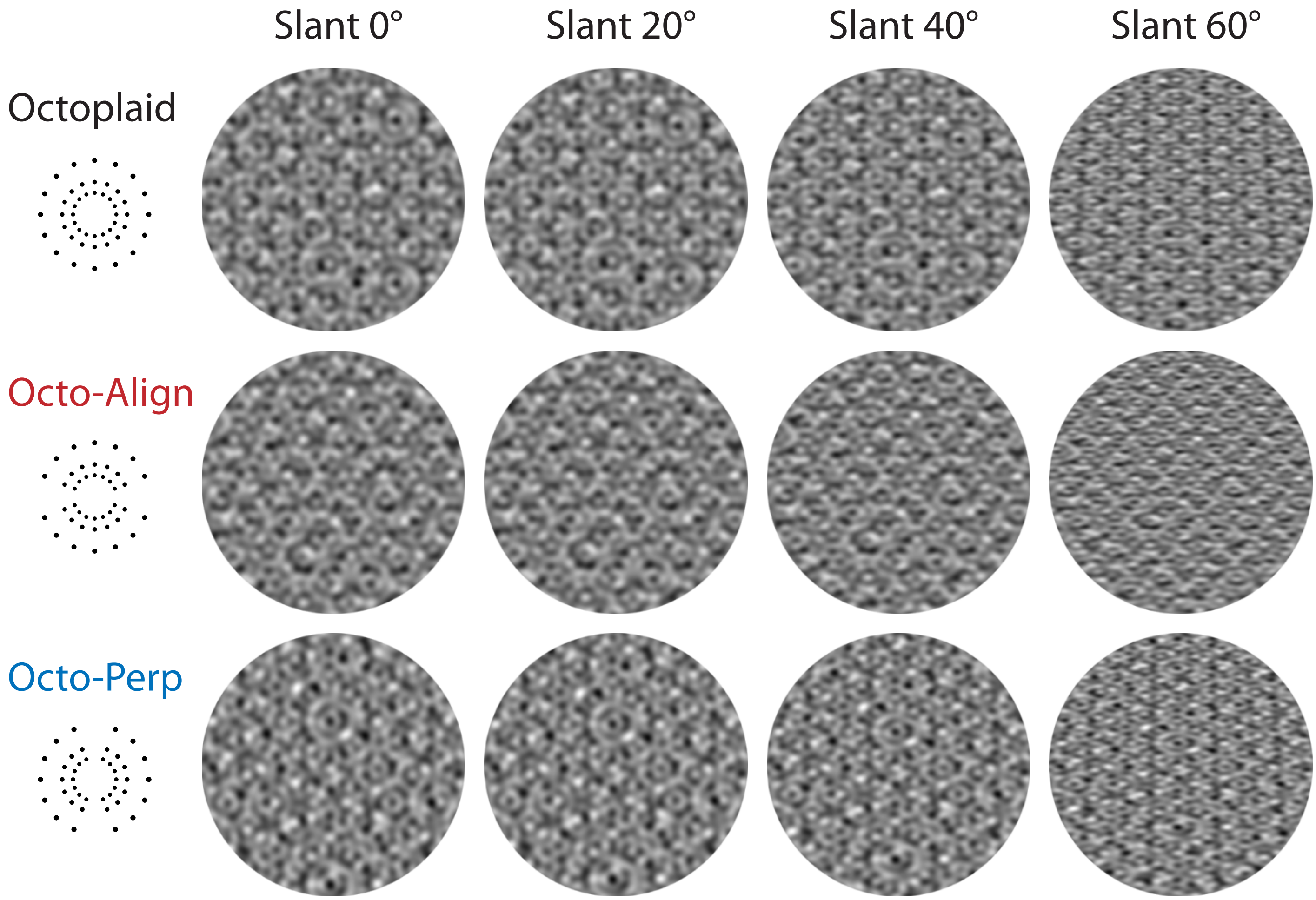

Figure 8. Illustration of the simulated surfaces with Octotropic, Octo-Align, and Octo-Perp textures for the smaller 6° FOV used in Experiment 2. Each row shows the perspective views of surfaces with simulated slants of 0°, 20°, 40°, and 60°.

simulated slant had similar trends in Octo and Octo-Perp conditions but differed between Octo-Align and the two other conditions (Texture × Slant, Octo vs. Octo-Perp: $F(6, 54) = 1.26$, $p = 0.293$, partial $\eta^2 = 0.122$; Octo-Align vs. Octo: $F(6, 54) = 6.49$, $p < 0.001$, partial $\eta^2 = 0.419$; Octo-Align vs. Octo-Perp: $F(6, 54) = 5.47$, $p < 0.001$, partial $\eta^2 = 0.378$. Further analyses found that the slant estimates in the Octo-Align condition were lower than in the other two conditions when the simulated slants were 60° and 70°, $F(2, 18) > 4.30$, $p < 0.030$, partial $\eta^2 > 0.324$, and higher when simulated slants were 80°, $F(2, 18) = 4.70$, $p = 0.023$, partial $\eta^2 = 0.343$. The lower slant estimates for the Octo-Align textures in the 60° and 70° slant conditions provides evidence that the absence of aligned spectral components did impair slant perception. At lower slants, there was no detectable differences across texture conditions, $F(2, 18) < 2.53$, $p > 0.108$, partial $\eta^2 < 0.219$, though this may be due to the fact that slant estimates showed little modulation by slant even for the full Octo texture.

In the binocular viewing conditions, there was no significant main effect of texture, $F(2, 18) = 0.17$, $p = 0.825$, partial $\eta^2 = 0.019$, nor an interaction between texture type and simulated slant, $F(12, 108) = 0.497$, $p = 0.916$, partial $\eta^2 = 0.052$. The slant estimates was significantly modulated by simulated slants, $F(6, 54) = 105.23$, $p < 0.001$, partial $\eta^2 = 0.921$. As in Experiment 1, we compared the linear slopes across the texture types and found no significant difference across the texture types, $F(2, 18) = 0.32$, $p = 0.729$, partial $\eta^2 = 0.034$.

Cue weight in the conflict conditions

Figure 10 plots the results from the cue conflict conditions in Experiment 2. We fit the slant estimates as a linear function of the slant specified by texture information for each condition and subject, and tested whether the fitted slopes were greater than zero. When the base slant was 70°, the slopes were significantly greater than zero for all texture types, $t(9) > 3.24$, $p < 0.010$, Cohen's $d > 1.025$). At slant of 50°, the trends suggest positive slopes as well, but these did not reach the level of statistical significance, $t(9) = 2.01$–2.25, $p =$

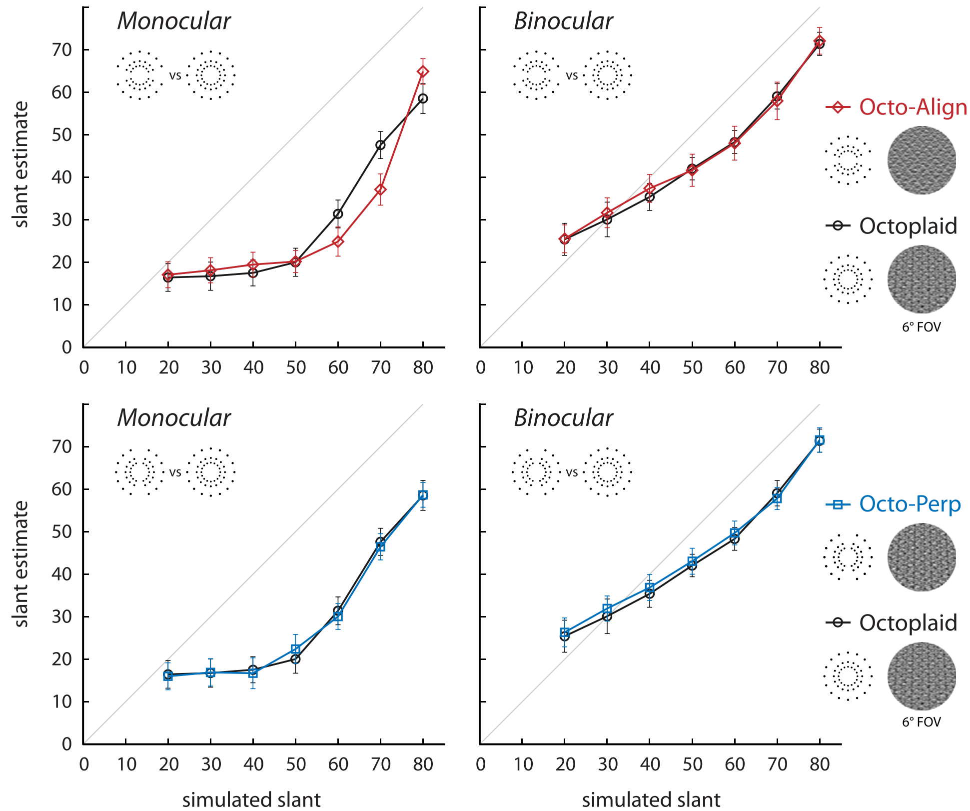

Figure 9. Mean slant estimates as a function of simulated slants in the monocular (left) and binocular (right) viewing conditions of Experiment 2. The upper panel shows the comparison between the slant estimates in the Octotropic and Octo-Align conditions. The lower panel compares the estimates in the Octotropic and Octo-Perp conditions.

0.051–0.075, Cohen's $d = 0.636$–0.712), At slant of 30°, the slopes were not significant in the Octo-Align condition, $t(9) = 0.43$, $p = 0.679$, Cohen's $d = 0.135$), and the Octo-Perp condition, $t(9) = 0.72$, $p = 0.491$, Cohen's $d = 0.227$, but significant in the full Octo texture condition, $t(9) = 2.70$, $p = 0.024$, Cohen's $d = 0.855$. Texture is expected to have less weighting at low slants (Knill, 1998b; Knill & Saunders, 2003; Hillis et al., 2004), so it is not surprising that we did not detect a clear influence of texture in the lower base slant conditions. An influence of conflicting texture information was clearly observed at 70° slant, and we suspect that there was probably an influence at 50° slant as well that we were not able to reliably detect.

We computed texture cue weights as in the previous experiment and performed an ANOVA across slant and texture conditions. We found that texture weights were significantly modulated by base slants from stereo information, $F(2, 18) = 4.28$, $p = 0.030$, partial $\eta^2 = 0.322$. Texture weights with a base slant of 70° were significantly higher than ones with a base slant of 30°, $F(1, 9) = 8.98$, $p = 0.015$, partial $\eta^2 = 0.499$. The observed increase of cue weights when the base slant is higher was consistent with both previous studies and the findings from Experiment 1. The main effect of texture type was not significant, $F(2, 18) = 0.96$, $p = 0.402$, partial $\eta^2 = 0.096$, nor the interaction between slant and texture type, $F(4, 36) = 1.38$, $p = 0.262$, partial $\eta^2 = 0.133$, indicating little influence of texture type on cue weighting.

Experiment 1 versus Experiment 2

While our main focus is the effectiveness of different textures, our results can also be used to assess how bias and cue weights vary as a function of slant and FOV. Figure 11 plots the mean results from Experiments 1 and 2 when averaged across texture types. The left panel shows slant estimates as a function of simulated slant in monocular conditions, and the right panel shows texture cue weights. The smaller field of view in Experiment 2 appears to affect bias and cue weights in consistent manner: slanted estimates were more underestimated, and texture had less influence relative to stereo information.

One complication in comparing across experiments is that the range of slants were different. For bias, we used the slant estimates over the shared range (20°–70°). For cue weights, we compared the average of the 40° and 60° conditions in Experiment 1 to the average of the 30°–70° conditions in Experiment 2, which range around the same center, 50°.

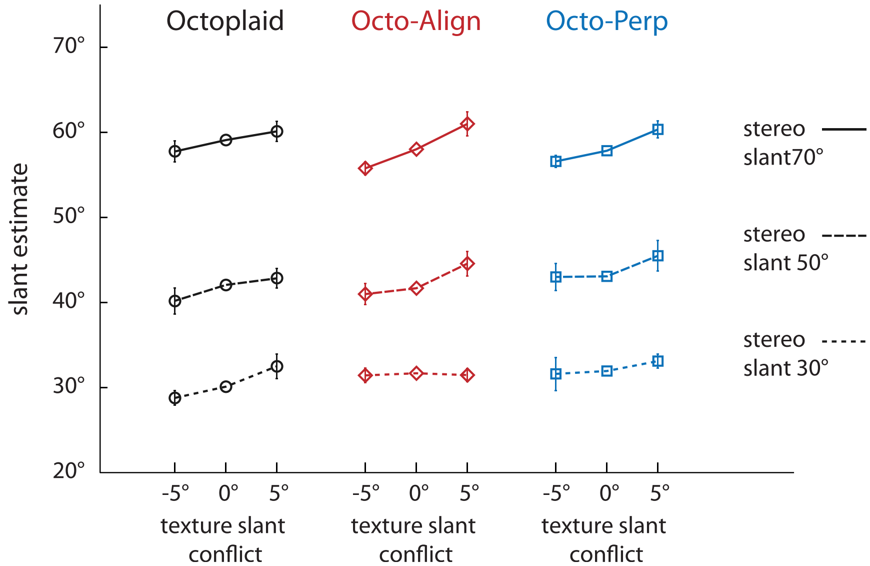

Figure 10. Mean slant estimates in the cue-conflict conditions of Experiment 2 for the Octoptropic, Octo-Align, and Octo-Perp textures. Each set of points shows results from conditions with the same stereo slant but different slant from texture. A non-zero slope indicates an influence of the conflicting texture information.

In the monocular viewing conditions, the main effect of experiment was not significant, $F(1, 18) = 3.12$, $p = 0.094$, partial $\eta^2 = 0.148$, but there was an interaction between slant and experiment, $F(5, 90) = 13.72$, $p < 0.001$, partial $\eta^2 = 0.433$. Slant estimates in Experiment 2 were lower for simulated slants of 50°–70°, $F(1, 18) > 4.34$, $p < 0.052$, partial $\eta^2 > 0.194$, but there was no difference for simulated slants of 20°–40°, $F(1, 18) < 1.53$, $p > 0.233$, partial $\eta^2 < 0.078$. This effect is most likely due to the smaller FOV, rather than increased viewing distance, so can be interpreted as evidence that larger FOV provides better information for perception of slant from texture.

For binocular viewing conditions, the change in FOV and viewing distance had no detectable effects on slant estimates. An ANOVA found no overall difference across experiments, $F(1, 18) = 0.88$, $p = 0.361$, partial $\eta^2 = 0.047$, nor an interaction between experiment and simulated slant, $F(5, 90) = 0.91$, $p = 0.476$, partial $\eta^2 = 0.048$. The addition of strong binocular information appears to override the effect of differing texture information that was observed in the monocular conditions.

The overall texture weights appear to be higher in Experiment 1 than in Experiment 2 (Figure 11, right panel), but this apparent difference was not statistically significant. We averaged the texture weights around 50°

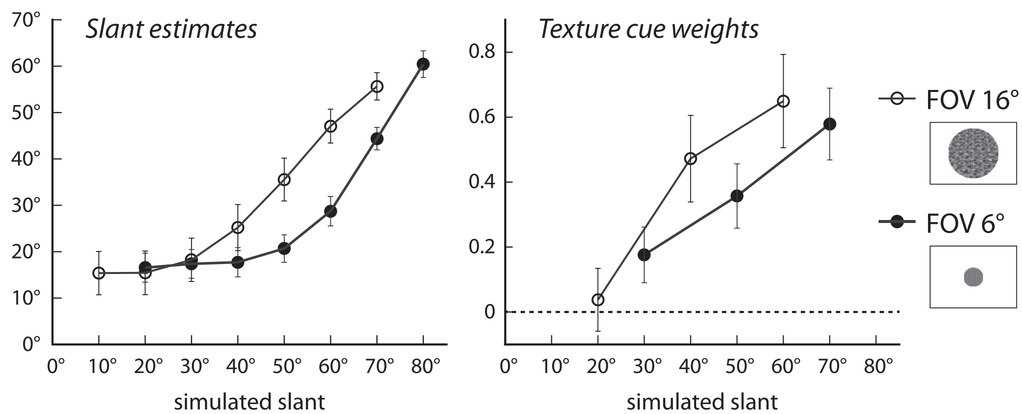

Figure 11. Slant estimates and texture cue weights from Experiments 1 and 2 plotted together for comparison. The two graphs plot mean slant estimates in monocular conditions (left) and mean texture cue weights (right) after averaging across texture types. Open circles show results from 16° FOV stimuli (Experiment 1) and filled circles show results from 6° FOV stimuli (Experiment 2). Slant estimates showed more bias toward frontal in the 6° FOV conditions, and there was a trend toward less influence of texture relative to stereo in cue conflict conditions.

as before, and also merged slant estimates across the texture types to further reduce variability, but found no significant difference between the two experiments, $t(18) = 1.36$, $p = 0.192$, Cohen's $d = 0.606$. Statistical power was limited by the fact that this analysis was between-subjects, and the specific slants were not matched. The trend in the data suggests that field of view affects the weighting of texture relative to stereo, but further study would be required to confirm this possible effect.

Discussion

The general pattern of results in Experiment 2 was similar to Experiment 1. In the binocular conditions with cue conflicts, slant estimates showed a significant influence of texture information for all three texture types. The psychometric functions in the monocular conditions were again highly nonlinear, with little differences in slant estimates across conditions with low slants, and increased modulation by slant at higher slants. The smaller FOV used in Experiment 2 resulted in more overall bias toward the frontal plane than with larger FOV stimuli used in Experiment 1, and higher simulated slants were required for subjects to reliably perceive nonzero surface slant (Figure 11). These findings are consistent with the differences in the information provided by texture for different slants and FOV.

Slant estimates in Experiment 2 did not appear to crucially depend on the presence of a spectral component aligned with the tilt direction, for either monocular or binocular viewing. The Octo-Align texture without the aligned component did result in greater underestimation in some monocular conditions. This effect suggests that when FOV is small, aligned spectral components help to convey slant even when other texture cues are available. On the other hand, the difference in perceptual bias was small and only detectable at some slants, and the relative weighting of texture information in binocular conditions showed no differences across the three texture conditions. The results of Experiment 2 provide evidence that aligned spectral components do contribute to slant perception, but the contribution relative to other texture cues may be limited.

The effect of aligned components observed in Experiment 2 was not observed in Experiment 1, which tested conditions that were identical except for FOV. This difference could be explained by the effect of FOV on information from texture scaling. A small FOV reduces the overall amount of change in texture scaling across a projected image. When texture scaling becomes unreliable, the visual system would have to rely on other texture cues, such as the orientation modulation of oriented spectral components.

While the effectiveness of texture scaling would be highly dependent on FOV, texture compression can be computed in local regions of an image, so would be less dependent on FOV. For the Octo-Align textures that lack aligned spectral components, texture compression would remain informative even for the small FOV stimuli in Experiment 2, and might therefore be the primary source of information used to perceive slant from these textures in monocular conditions. The nonlinear psychometric functions are also consistent with reliance on texture compression. Texture compression changes very little at low slants. If texture compression were the primary information used to perceive slant in the small FOV conditions, it could explain why subjects had difficulty distinguishing stimuli with slants in this range.

One limitation of local texture compression as a slant cue is that it the tilt direction has a sign ambiguity. From local texture compression alone, one could not distinguish positive and negative slants around the same axis of rotation. To determine slant from texture compression, some other information would be needed to resolve this sign ambiguity, such as the change in texture scaling across an image or the perspective convergence of aligned spectral components.

In Experiments 1 and 2, the surfaces were always slanted in the same direction, so the direction of surface tilt would not have to be perceived from the stimuli. This might have artificially allowed subjects to rely on the ambiguous information provided by texture compression, rather than having to perceive the direction of surface tilt based on the texture information itself. If so, the role of aligned components may have been underestimated, particularly in Experiment 2. We tested this possibility in Experiment 3 by including conditions with both positive and negative slants.

Experiment 3

In Experiment 3, the conditions included surfaces with both positive and negative slants, so subjects would have to determine the sign of surface slant using texture information rather than relying on prior knowledge. Because it is physically difficult to align the hand with negative slant and vertical tilt direction, we also changed the tilt directions to be horizontal and used a different slant alignment task.

Method

Subjects

Twelve subjects (six men, six women) at East China Normal University participated the experiment. The subjects had an average age of 26.6 years and all had normal or corrected-to-normal visual acuity. The procedures were approved by and conform to the standards of the Human Research Ethics Committee of East China Normal University.

Apparatus and stimuli

In Experiment 3, subjects rotated a wood board around a vertical axis to match the perceived slant of the simulated surfaces. A Bluetooth electronic compass (WitMotion BWT901CL; WitMotion, ShenZhen Co., Ltd., Shenzhen City, China) was fixed on the top of the board to measure the orientation of the board.

Experiment 3 tested both 16° and 6° fields of view, like in Experiments 1 and 2, in separate sessions with counterbalanced order. The stimuli were the same as in the monocular conditions of the previous experiments with the following exceptions. The tilt direction was left or right, rather than vertical. The 16° and 6° FOV conditions used the same viewing distance of 80 cm. Simulated slants were ±30°, ±50°, and ±70° for the test conditions, with a smaller number of filler trials with slants of 0°, ±20°, ±40°, and ±60° to discourage categorical responses.

Procedure

At the start of a trial, subjects were required to move the board to within ±5° of fronto-parallel before the start of a trial. A simulated surface was then presented, and subject rotated the board to match the perceived surface.

Subjects performed four blocks of trials in a one hour session, two with 16° FOV and two with 6° FOV. The order of blocks followed an ABBA design, counterbalanced across subjects. Each block consisted of 135 trials with randomized order. For the conditions of ±30°, ±50°, and ±70°, there were 12 trials in each FOV and texture condition, and for the filler trials, each FOV and texture condition had only two trials.

Analysis

Ambiguity in the perceived direction of surface slant could potentially lead to bimodal responses, so we fit the data using a mixture model that allows for this possibility. For a pair of matched conditions with slants of +S and −S, responses were assumed to be distributed as a mixture of two t distributions with peaks at positive and negative values ($\mu_0 - \mu_S$) and ($\mu_0 + \mu_S$),

Positive slant:

$$R_k \sim \begin{cases} dt(\mu_0 + \mu_s, \tau_s, v), & if\ F_k = 0 \\ dt(\mu_0 - \mu_s, \tau_s, v), & if\ F_k = 1 \end{cases} \quad F_k \sim dbern\left(p_{guess} \times (1 - p_{bias})\right)$$

Negative slant:

$$R_k \sim \begin{cases} dt(\mu_0 - \mu_s, \tau_s, v), & if\ F_k = 0 \\ dt(\mu_0 + \mu_s, \tau_s, v), & if\ F_k = 1 \end{cases} \quad F_k \sim dbern\left(p_{guess} \times p_{bias}\right)$$

where τ_S and v are the precision and degrees of freedom parameters of the t distributions, where μ_0 is an overall constant bias for a given subject, μ_S is the average magnitude of estimated slant relative to the baseline for a matched pair of conditions, F_k are Bernoulli variables that select whether responses on the kth trial are distributed around the peak with the correct sign or the opposite sign, p_{guess} is a guessing rate parameter representing the probability that the sign of slant is perceived ambiguously, and p_{bias} is a guessing bias parameter representing the probability of responding with positive slant in cases when sign of slant is ambiguous.

The data from all subjects and conditions was analyzed together with a hierarchical Bayesian model, using Gibbs sampling to estimate the posterior probability distributions of the unknown parameters given the observed data. We used the JAGS package for Gibbs sampling to implement the model (Plummer, 2003), and generated a chain of 10,000 samples. The JAGS code for specifying the hierarchical model is given in the Appendix. We computed the 95% highest density intervals (HDI) from the samples for the variables of interest and differences across conditions, and used the HDIs as measures of the credible ranges for the values and differences.

Results and discussion

Slant estimation bias

Figure 12 shows the mean slant estimates as a function of simulated slants for the different texture types and FOVs. In all conditions, responses were highly compressed toward zero for the low slant conditions, resulting in nonlinear functions. Removing the perpendicular component had no detectable effect on slant estimates (right), but removing aligned components produced more bias toward frontal in some conditions.

Figure 13 shows the comparison between the Octo and Octo-Align conditions in more detail. The top row shows estimated posterior distributions for the average magnitude of slant estimates. The three black curves on each plot show results from the full Octotropic plaid conditions with 30°, 50°, and 70° slants, and the red curves show the corresponding results for the Octo-Align plaids. The left and right graphs show results for the 6° FOV and 16° FOV conditions, respectively. For both FOVs, one can see a shift toward zero for the texture without the aligned component. The second row shows posterior distri-

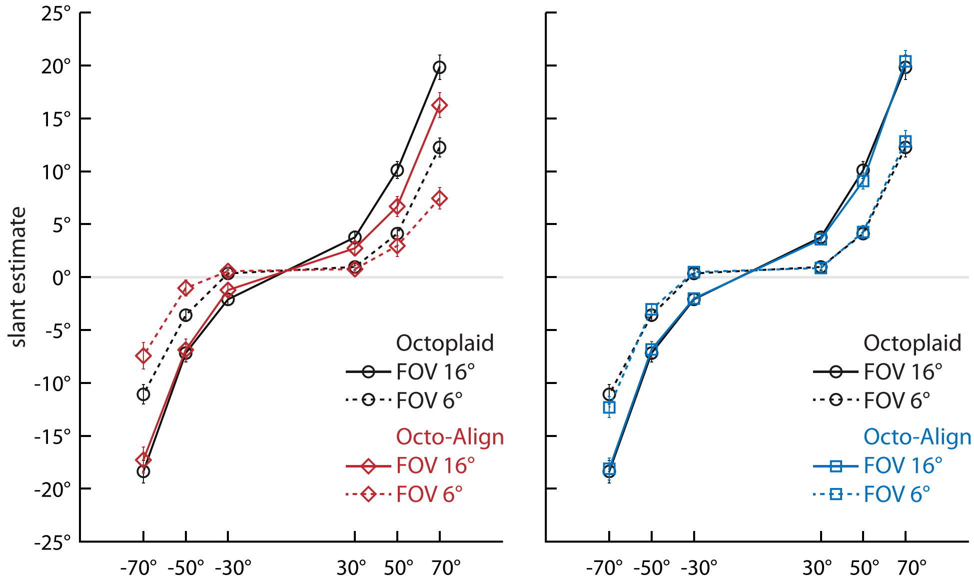

Figure 12. Mean slant estimates as a function of simulated slant in Experiment 3. The left graph shows results from the Octoplaid and Octo-Align conditions, and the right graph shows results from the Octoplaid and the Octo-Perp textures. The solid and dashed lines correspond to the 16° and 6° FOV conditions, respectively. Error bars depict 95% HDIs of the estimated posterior distributions.

butions for the difference between Octo and Octo-Align for each of the FOV and slant conditions. The shaded regions depict 95% HDIs. For the 6° FOV, the HDIs for the differences do not contain zero for either the 50° slant or 70° slant conditions, indicating evidence for a difference. For the 16° FOV, there is evidence for an effect of the aligned component in the 30° and 50° slant conditions, and a similar trend for the 70° slant condition, though the magnitude of these differences were smaller for the 16° FOV conditions than in the 6° FOV conditions.

There was also an overall effect of FOV on slant estimates, with smaller FOV resulting in more bias toward frontal. The 95% HDIs for the difference between 6° and 16° FOV conditions were entirely positive for all textures and simulated slants, indicating an effect of FOV in all cases.

Sign ambiguity

Unlike in the previous experiments, the direction of slant varied across trials, so subjects had to perceive the direction of slant from the stimuli. If subjects relied primarily on information from texture compression, which is ambiguous with respect to sign, then they

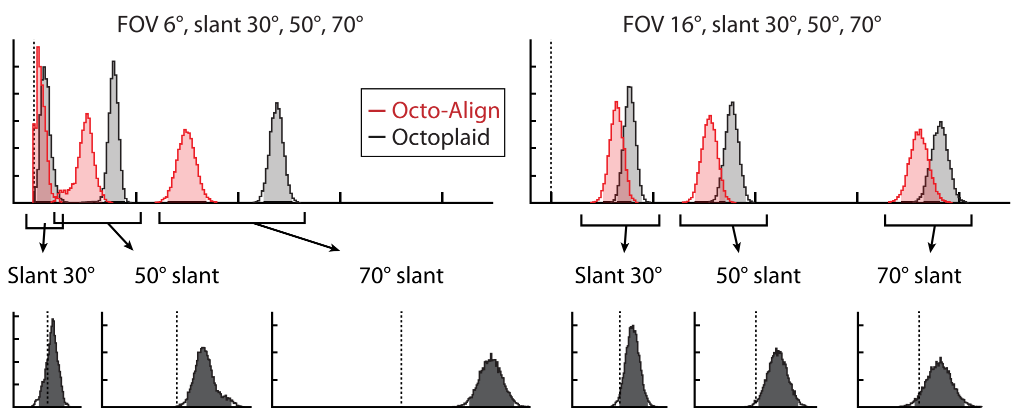

Figure 13. The upper graphs plot the estimated posterior probability distributions for the average magnitude of slant estimates from Octoplaid textures (black) and Octo-Align textures (red) with 30°, 50°, and 70° slant. The left and right graphs show results from 6° FOV and 16° FOV conditions. The lower row plots the estimated posterior distributions of the mean differences between slant estimates in the Octoplaid and Octo-Align conditions for the six FOV and slant conditions. Shaded regions depict the 95% HDIs. In cases where the HDIs for the differences are entirely positive, the results imply that there is at least 95% probability that the average slant estimate in the Octotropic conditions is larger than in the Octo-Align condition.

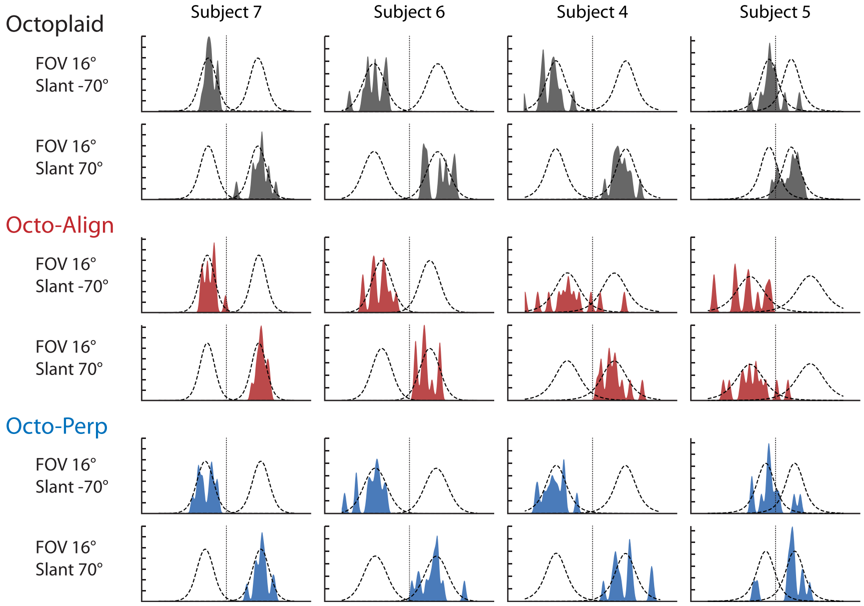

Figure 14. Distributions of responses of individual trials from four sample subjects (columns) in conditions with 16° FOV, ±70° slant, and the three texture types (Octoplaid, gray; Octo-Perp, blue; Octo-Align, red). For the two left subjects, responses on all trials have the correct direction of slant. The third subject had one or two responses with sign-reversals. The fourth subject was atypical and showed the most sign-reversals, almost all of which were in the Octo-Align condition.

might show some responses with non-zero slant but reversed sign.

Figure 14 shows examples of responses in the 16° FOV and 70° slant condition for three typical subjects, and one subject that showed an atypically large number of sign reversals. This condition produced the highest slant settings, making it easiest to evaluate possible sign reversals. The left two subjects show no sign reversals for any of the textures, and more bias toward zero for the texture without the aligned component. The third subject showed a few trials with sign reversal, and a similar difference in bias. The fourth subject made the largest number of responses with reversed sign. For the conditions shown in Figure 14, this subject appeared to be unable to detect the sign of surface slant for the Octo-Align textures, but made fewer errors for the other textures. This subject was an atypical case; most subjects' responses were similar to the other three examples, with very few cases of sign reversals.

To quantify the frequency of sign reversals, we performed an analysis to identify individual trials for which there was strong evidence of reversal. An individual trial was classified as sign-reversed if the model selection parameter of the mixture model selected the incorrect model in 95% or more of the posterior samples. Out of 5,184 total trials, only 28 were classified as reversed by this criterion. Of these, 22 were from the Octo-Align condition (19 from a single subject), and the other six were from the Octo or Octo-Perp conditions. This analysis can only detect sign reversals when the distributions of positive and negative slant responses have some separation, so the conditions with responses close to zero could have had sign reversals that were not detected. For conditions in which the stimuli were reliably perceived as slanted, our analysis reveals that subjects did not have difficulty distinguishing the sign of slant.

Comparison to Experiments 1 and 2

The pattern of results in Experiment 3 was similar to the previous experiments. For all the textures, the psychometric functions were highly nonlinear, with low slant stimuli being perceived as almost frontal, and slant estimates were more biased with small FOV. For the 6° FOV condition of Experiment 3, we observed an effect of removing aligned spectral components, as in Experiment 2. In Experiment 3, we also observed an effect of aligned components in the 16° FOV conditions, which was not detected in Experiment 1. Otherwise, the qualitative results were the same.

The overall magnitude of slant estimates in Experiment 3 was smaller than the previous experiments. We suspect that the difference is due to response scaling rather than perceived slant. The slant estimation task in Experiment 3 was less intuitive and direct than in Experiment 1 and 2. Rather than aligning their hands with the perceived surface, they had to align a separate board with the perceived surface, which may have required some mental transformation of coordinates. Apart from the overall scaling, the psychometric functions were similar to those in the previous experiments.

General discussion

Role of aligned spectral components

The experiments in this study compared slant estimates for octotropic textures with and without aligned spectral components to test the role of such components when other texture cues are available. Our results suggest that the visual system utilizes multiple texture cues for perception of 3D slant, including perspective convergence from oriented texture components. Removing aligned spectral components produced some small but detectable differences in slant estimates.

An effect of aligned spectral components on slant perception is consistent with some previous results. Saunders and Backus (2006) observed better slant discrimination around the frontal plane for textures with oriented spectral components that were aligned with the slant direction. Tam et al. (2013) tested slant discrimination with cue conflict stimuli and found that observers relied on oriented components to discriminate slants around the frontal plane, but not for slant discrimination around 30°. The latter finding appears to conflict with the results in Experiments 2 and 3 in our conditions with similar FOV, which showed a benefit from aligned spectral components even at higher slants ($\geq$50°). This could be due to the difference in task: Tam et al. (2013) assessed improvement in discrimination while we compared biases in slant estimates.

While there were detectable effects of removing aligned spectral components, the effects were relatively small and only observed in some slant and FOV conditions. This suggests that observers relied primarily on other texture cues like scaling and compression, which could be used to perceive slant from the Octo-Align texture that lacks aligned spectral components. Previous evidence also supports the contribution of these texture cues to perception of 3D slant and shape (Rosenholtz & Malik, 1997; Knill, 1998a, 1998c; Saunders, 2003; Todd et al., 2005; Todd et al., 2007; Todd & Thaler, 2010; Todd et al., 2010). To the extent that these cues contribute to perception of 3D slant from texture, performance in our Octo-Align condition would be similar to performance in the other texture conditions that include an aligned spectral component, as we observed in many conditions.

Aligned spectral components had the most effect for stimuli with a small FOV. For stimuli with a 16° FOV, there was little difference between slant estimates in the Octo and Octo-Align conditions. Experiment 3 found a small difference between Octo and Octo-Align for 50° simulated slant and trends toward differences at other slants, while Experiment 1 did not detect any differences in either perceptual biases or texture cue weights. For the smaller 6° FOV stimuli, the effect of removing aligned components was more pronounced. Reduction of slant estimates in the Octo-Align condition was detected in both Experiments 2 and 3, and magnitude of difference was larger. If the visual system utilizes multiple texture cues to perceive slant, then aligned components would be expected to have more influence when other cues are less reliable. A smaller FOV reduces the reliability of texture scaling information, which could explain why there was a larger influence of aligned components.

Aligned spectral components on deeply corrugated surfaces

Our results appear to be in conflict with Li and Zaidi's studies (Li & Zaidi, 2000, 2001a, 2001b, 2004; Zaidi & Li, 2002). Using shapes and textures like shown in Figure 3, Li and Zaidi have found that observers could not effectively perceive shape from texture without oriented spectral components aligned with the direction maximum curvature. However, our findings suggest that such components are not crucial for perception of 3D slant of surface patches; observers could systematically estimate slant from textures with and without the aligned components. Why then were aligned spectral components crucial for the corrugated surfaces in the previous studies?

Todd and Oomes (2002) argue that the effects reported by Li and Zaidi (2000) were due to non-generic shape and viewing conditions that provide degenerate texture information. One key factor identified by Todd and Oomes (2002) is the rapid change in 3D slant relative to the observer across Li and Zaidi's (2000) stimuli. They point out that rapid changes would make it difficult to analyze changes in texture across an image, and that this situation would only occur with an unusual combination of shape and viewing position. Todd and Oomes (2002) present examples demonstrating that textures without an aligned component are much more effective when surface slant changes more gradually.

We agree that the degraded texture information in Li and Zaidi's (2000) conditions most likely explains the difficulty in perceiving shape without aligned spectral components. In particular, rapid depth changes in a small FOV make it difficult to measure and compare texture scaling at different local areas of the image, preventing use of texture scaling to perceive shape. For the planar surface patches used in our study, in

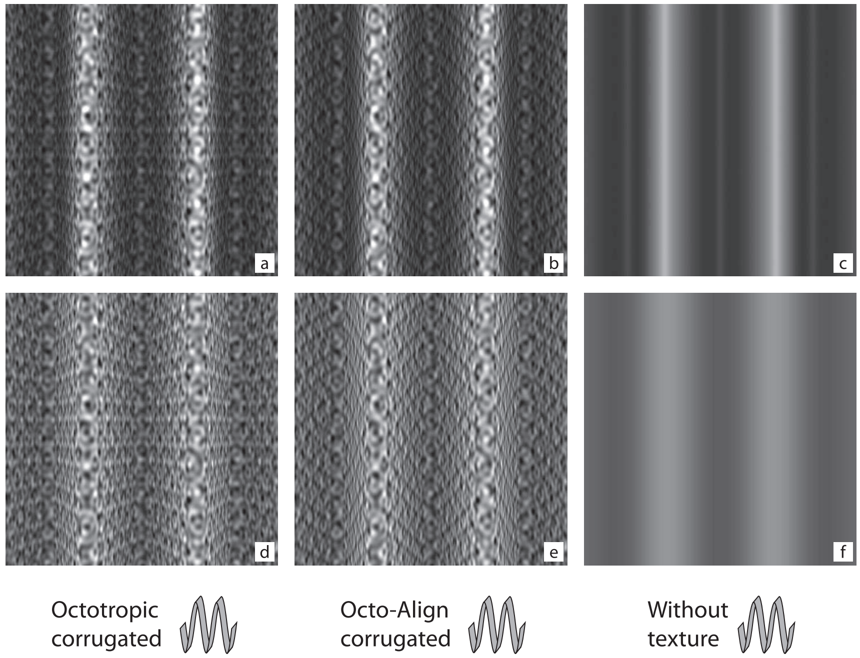

Figure 15. Illustration of how shading information can interact with texture information to perceive 3D shape. The three columns show corrugated surfaces with the full Octotropic plaid texture (left), the Octo-Align texture (middle), or no texture (right). The images in the top row are renderings of matte surfaces under diffuse illumination, including shadows and inter-reflections. To generate the images in the bottom row, we blurred the rendered image with only shading and reduced contrast, and then applied the resulting shading variations to renderings of the textured surfaces without shading. With shading variations, the surfaces with or without aligned spectral components appear similar. The unrealistic shading cue does not effectively convey the appearance of a corrugated surface by itself (bottom right), so perceived shape of the textured surfaces with this shading (bottom right and middle) is due to combined texture and shading rather than solely the shading cue.

contrast, slant and depth change gradually across the image, especially in a large FOV (16°) condition. We believe that this difference accounts for why oriented spectral components had a large effect in Li and Zaidi's (2000) conditions but not in our conditions.

Although texture-scaling information is degraded in stimuli like Figure 3, the stimuli still provide texture compression information. If texture compression is used to perceive slant from texture, why isn't this information effective in the case of a corrugated textured surface without aligned spectral components? An explanation is that texture compression is informative but provides a bimodal cue, consistent with a high slant in either the positive or negative direction. As long as this sign ambiguity can be resolved, texture compression could be used to perceive 3D slant and shape. However, in unusual cases where sign of surface tilt remains ambiguous, texture compression would not be effective.

By this explanation, adding information that resolves the sign ambiguity should improve perception of shape from textures without aligned spectral components. Figure 15 demonstrates that an aligned texture component is no longer necessary to perceive qualitative shape with the addition of shading information. When shading is varied from near to far regions, it becomes easy to see a 3D corrugated surface either with or without aligned spectral components. The top row shows renderings of matte surfaces with diffuse illumination, which included effects of occlusion and inter-reflections. In this case, the appearance might be primarily determined by the shading itself. The images in the bottom row demonstrate that perceived shape of the textures surfaces can also be modulated by a less realistic shading cue with lower contrast, which is not perceived as a deeply curved surface when presented in isolation. The appearance of Figure 15e is likely due to an interaction between texture and shading, consistent with the idea that the texture information had sign ambiguity.

In contrast, the small planar patches texture in Experiment 3 were sufficient to perceive the sign of surface slant even without aligned spectral components. Slant estimates showed more bias without the aligned components, but there was little evidence for sign ambiguity. We believe that the deeply corrugated surfaces tested in Li and Zaidi's studies exaggerate the influence of oriented spectral components because other texture information that would typically be available has been degraded. In these special cases, aligned spectral components have a large influence on perceived shape. In other cases, aligned spectral components contribute as one of multiple texture cues and would have smaller influence, as in our results.

Effect of field of view on slant from texture

We observed an effect of field of view on slant estimates even for the full Octotropic textures that provide perspective convergence as well as other texture cues. Slant estimates in monocular viewing conditions showed larger bias toward underestimation with the small 6° aperture than with the larger 16° aperture. Previous studies have reported systematic effects of FOV on perceived slant (Todd et al., 2005; Todd et al., 2007; Todd et al., 2010), which were in the same direction as observed here.

Todd et al. (2007) have proposed that perceived slant from texture is based on an optical variable termed *scaling contrast*, which they argue can account for observed effects of FOV on slant estimates. Scaling contrast is a measure of the overall change in texture scaling across an image relative to the average texture scaling. For a planar surface, scaling contrast is a function of FOV as well as the surface slant, so use of scaling contrast to perceive slant would predict systematic biases when FOV is varied. Across a range of conditions, Todd and colleagues observed a strong linear correlation between scaling contrast and slant estimates (Todd et al., 2005; Todd et al., 2007; Todd et al., 2010), consistent with use of this cue.

The predictions of a model based on scaling contrast can be quantitatively compared to our results. For a planar surface with limited FOV, as in our conditions, scaling contrast varies as an approximately linear function of FOV. If perceived slant were a direct function of scaling contrast, perceived slant in our 16° FOV conditions would therefore be about 2.7 times as large as in the 6° FOV conditions with the same slant. For simulated slants less than about 50°, the predicted difference would be consistent with our results. At higher slants, however, the ratios of slant estimates in the 6° and 16° FOV conditions were much smaller than would be expected based on the difference in scaling contrast. Thus, a simple version of the model of Todd et al. (2007) could partially account for the effect of FOV observed in our experiments, but some other factor would be required to explain the results at higher simulated slants.

An effect of FOV on slant estimates could also be explained by a Bayesian model. Saunders and Chen (2015) have proposed that underestimation of slant perception in monocular viewing conditions is a consequence of weak texture information combined with either a frontal prior or conflicting frontal cues (e.g., accommodation). In our previous study, we observed that perceptual gain and cue weights both increased with simulated slant, consistent with the increased reliability of texture slant information at higher slants. The current results also show a reduction in bias and increase in texture cue weights as a function of simulated slant (Figures 5 and 6). FOV also affects reliability of texture information (Knill, 1998b), so another prediction is that decreasing FOV would produce more underestimation of perceived slant from texture, and lower weighting of texture information relative to stereo information. We observed an effect of FOV on perceptual bias and a trend toward a difference in texture cues weights (Figure 11). Based on results of Knill (1998c), the difference in texture reliability for 6° and 16° FOV would be modest, so effects on cue weights may be hard to detect with our method. The current results are not a strong test of the Bayesian explanation, but are generally consistent with such a model.

Conclusion

The experiments investigated the role of aligned spectral components in perception of slant from texture. An oriented spatial frequency component that is aligned with the direction of surface slant potentially provides a strong perspective cue to 3D slant, and the presence of aligned components has been found to influence 3D perception in some conditions (Li & Zaidi, 2000, 2001a, 2001b, 2004; Zaidi & Li, 2002; Tam et al., 2013). We compared perceived slant from texture across conditions that provide the same texture compression and scaling cues but differed in the presence of oriented spectral components. Removing aligned spectral components had only limited effect on slant perception, and largely restricted to conditions with a small FOV. Our findings are consistent with the notion that the visual system utilizes multiple sources of texture information for 3D perception.

Keywords: slant, texture, cue combination

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Appendix: JAGS code for Experiment 3 analysis

```
# model of responses
for(k in 1:ntrial)
{
  # s[k]: slant condition of kth trial, 1-3 neg 4-6 pos
  # c[k]: texture and FOV condition of kth trial
  # sbj[k]: subject number of kth trial

  # model selection variable
  flip[k] ~ dbern(pflip[s[k],c[k],sbj[k] ])

  # mean for trial is either from correct condition (s[k]) or sign reversed (s[7-k])
  predicted[k] <- (1-flip[k]) * mcond[s[k],c[k],sbj[k]] + flip[k] * mcond[7-s[k],c[k],sbj[k] ]

  # responses are a t-distribution around predicted
  resp[k] ~ dt(predicted[k],taucond[s[k],c[k],sbj[k] ],nu[sbj[k]])
}

# set hyperpriors for the hierarchical variables
for(kcond in 1:6)
{
  for(kmag in 1:3)
  {
    # prior for mean response relative to zero point
    # distribution across subjects modeled as gamma distribution
    m_ga[kmag,kcond] ~ dgamma(1.01,0.01)
    m_gb[kmag,kcond] ~ dgamma(1.01,0.01)
    # prior for variability parameter, by slant mag and condition
    tau_ga[kmag,kcond] ~ dgamma(1.01,0.01)
    tau_gb[kmag,kcond] ~ dgamma(1.01,0.01)
  }
}
```

```
# set priors for variables by condition, subject, and slant
for(kcond in 1:6)
{
 for(ksubj in 1:nsubj)
 {
  for(kmag in 1:3)
  {
    # mean magnitude of slant, relative to zero point
    m[kmag,kcond,ksubj] ~ dgamma(m_ga[kmag,kcond],m_gb[kmag,kcond])

    # mzero ± m to get pos and neg centers for responses
    mcond[4-kmag,kcond,ksubj] <- mzero[kcond,ksubj] - m[kmag,kcond,ksubj]
    mcond[3+kmag,kcond,ksubj] <- mzero[kcond,ksubj] + m[kmag,kcond,ksubj]

    # prior for probability of guessing sign, same for pos / neg
    # not hierarchical, so freely varies across subjects and conditions
    pguess[kmag,kcond,ksubj] ~ dunif(0,1)

    # probability of flipping, combining guess rate and bias
    # for negative slant, multiply by bias, for positive, by (1-bias)
    pflip[4-kmag,kcond,ksubj] <- pguess[kmag,kcond,ksubj] * guessbias[ksubj]
    pflip[3+kmag,kcond,ksubj] <- pguess[kmag,kcond,ksubj] * (1-guessbias[ksubj])

    # priors for variance, same for pos / neg
    tau[kmag,kcond,ksubj] ~ dgamma(tau_ga[kmag,kcond],tau_gb[kmag,kcond])
    taucond[4-kmag,kcond,ksubj] <- tau[kmag,kcond,ksubj]
    taucond[3+kmag,kcond,ksubj] <- tau[kmag,kcond,ksubj]

  }
 }
}


# hyperprior for the variability of constant bias
# weakly informative to prevent unrealistic zero
mzero_tau ~ dgamma(6,20) # mode 0.25 (sigma 2), mean 0.3 (sigma 1.82)

# hyperpriors for deg of freedom parameter
nu_a ~ dgamma(1.01,0.01)
nu_b ~ dgamma(1.01,0.01)

# priors for the constant bias and DF parameters
for(ksubj in 1:nsubj)
{
  # deg of freedom param for the t distribution
  nu[ksubj] ~ dgamma(nu_a,nu_b)

  # guessbias when sign is ambiguous, not hierarchical
  guessbias[ksubj] ~ dunif(0,1)
  # constant bias, varies by subject and testing block (FOV)
  mzeroblock[1,ksubj] ~ dnorm(0,mzero_tau)
  mzeroblock[2,ksubj] ~ dnorm(0,mzero_tau)

  # conditions 1-3 were block 1, conditions 4-6 were block 2
  mzero[1,ksubj] <- mzeroblock [1,ksubj]
  mzero[2,ksubj] <- mzeroblock [1,ksubj]
  mzero[3,ksubj] <- mzeroblock [1,ksubj]
  mzero[4,ksubj] <- mzeroblock [2,ksubj]
  mzero[5,ksubj] <- mzeroblock [2,ksubj]
  mzero[6,ksubj] <- mzeroblock [2,ksubj]

}
```