

Early dynamics of stereoscopic surface slant perception

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Surface orientation is an important visual primitive that can be estimated from monocular or binocular (stereoscopic) signals. Changes in motor planning occur within about 200 ms after either type of signal is perturbed, but the time it takes for apparent (perceived) slant to develop from stereoscopic cues is not known. Apparent slant sometimes develops very slowly (Gillam, Chambers, & Russo, 1988; van Ee & Erkelens, 1996). However, these long durations could reflect the time it takes for the visual system to resolve conflicts between slant cues that inevitably specify different slants in laboratory displays (Allison & Howard, 2000). We used a speed–accuracy tradeoff analysis to measure the time it takes to discriminate slant, allowing us to report psychometric functions as a function of response time. Observers reported which side of a slanted surface was farther, with a temporal deadline for responding that varied block-to-block. Stereoscopic slant discrimination rose above chance starting at 200 ms after stimulus onset. Unexpectedly, observers discriminated slant from binocular disparity faster than texture, and for stereoscopic whole-field stimuli faster than stereoscopic slant contrast stimuli. However, performance after the initial deviation from chance increased more rapidly for slant-contrast stimuli than whole-field stimuli. Discrimination latencies were similar for slants about the horizontal and vertical axes, but performance increased faster for slants about the vertical axis. Finally, slant from vertical disparity was somewhat slower than slant from horizontal disparity, which may reflect cue conflict. These results demonstrate, in contradiction with the previous literature, that the perception of slant from disparity happens very quickly—in fact, more quickly than the perception of slant from texture—and in comparable time to the simple perception of brightness from luminance.

Introduction

Slanted surfaces are ubiquitous in the environment. The three-dimensional position of a planar surface, relative to an observer's line of sight, is fully described by its distance and two angles. These two angles can be described by the magnitude with which the orientation deviates from gaze-normal, or *slant*, and the direction of the deviation, or *tilt* (Gårding, 1992; Gibson, 1950; Stevens, 1980; Witkin, 1981). A large body of literature describes how tilt and slant are estimated from signals measured by the visual system. These signals correspond to numerous visual cues that can be manipulated in the laboratory. A robust finding has been that the perception of slant from stereoscopic cues (binocular disparity) is very slow (Gillam, Chambers, & Russo, 1988; van Ee & Erkelens, 1996). However, this result is puzzling, because if stereoscopic slant perception were slow, then perception could not contribute to navigation through the environment (Gibson, 1950), nor to the control of motor function (Greenwald, Knill, & Saunders, 2005; Mamassian, 1997). In principle, binocular disparity could be used for actions such as navigation and motor behaviors without any contribution from perceptual appearances (Goodale & Milner, 1992), but even if this were the rule, it would be peculiar for the system to wait seconds for perception given that appearances are needed for methodical decision-making and complex behaviors (for discussion see Backus, 2009).

In fact, numerous studies have addressed the time course of stereoscopic slant perception, using response times, display duration, and masking. Here we use a

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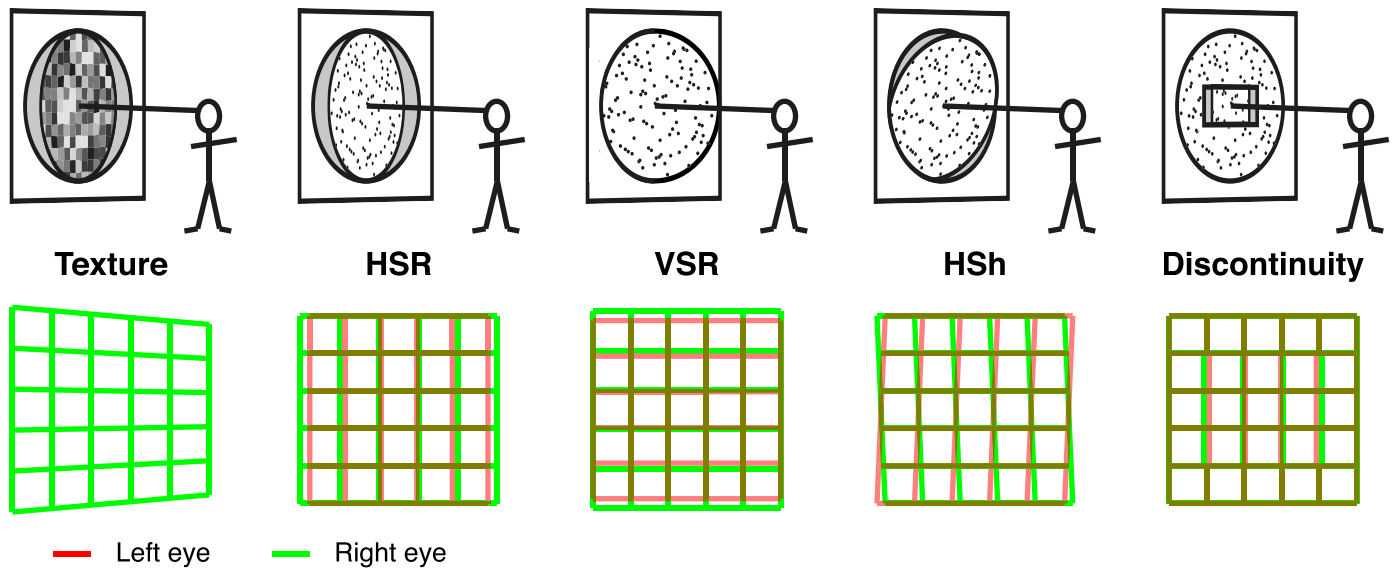


Figure 1. Stimuli used in the experiments. Top row represents how the stimuli appeared to the observers. Bottom row represents the transformations that were performed on the stimuli. Green lines represent the right eye and red lines represent the left eye. Slant was defined by texture, horizontal size ratio (geometric effect), vertical size ratio (induced effect), horizontal shear (scissor effect), or horizontal size ratio with a disparity discontinuity (slant contrast relative to a background).

different, better-suited technique, that employs the speed–accuracy tradeoff function (SATF) to compare the early dynamics of perception from various monocular and binocular slant cues. The rationale behind the use of the SATF is described in the literature (e.g., Heitz, 2014; Luce, 1986) and in earlier studies that used this technique (e.g., Caziot, Valsecchi, Gegenfurtner, & Backus, 2015; Salinas, Shankar, Costello, Zhu, & Stanford, 2010). In brief, the SATF technique allows one to estimate the time at which responses first deviate from chance level, called the *residual latency*, and the rate at which performance improves over time, called the *slope* or *accumulation rate*.

The residual latency measures the time required for initial visual processing prior to making the perceptual decision plus the motor response. Assuming equal time for motor responding in two appearance-based tasks, the difference between their residual latencies can be interpreted as the difference between the processing times at which perceptual representations first become available to do those tasks. Performance is, by definition, at chance levels during the residual latency. After that, performance improves rapidly as the perceptual representation develops over time. The slope of the SATF therefore describes the rate of change in the internal representation, which depends in turn on both the strength of the signal in the physical stimulus and the rate at which the system can extract and utilize this signal to make the perceptual decision.

Thus, so long as the motor component is kept constant across tasks—which we do by keeping the

response identical—the SATF technique can estimate the difference between the tasks in (a) the processing time required to initiate perception and (b) the rate at which information about the stimulus accumulates over time within the perceptual representation (see General discussion for additional commentary on use of the SATF).

Figures 1 and 2 describe our four experiments. Monocular cues that provide information about tilt and slant include texture cues—various signals such as linear convergence, foreshortening distortion, or density gradient (Gibson, 1950; Marr, 1982; Saunders & Backus, 2006; Stevens, 1980; Velisavljevic & Elder, 2006; Witkin, 1981)—and other monocular cues that are not studied here, such as motion parallax (Allison, Rogers, & Bradshaw, 2003; Rogers & Bradshaw, 1993) and focus cues (Watt, Akeley, Ernst, & Banks, 2005). Experiment 1 compared whole-field texture to whole-field stereoscopic cues for perceiving slant about a vertical axis (tilt of 0°).

Binocularly, tilt and slant are specified by the pattern of horizontal and vertical disparity. We used three whole-field disparity manipulations in Experiments 1 through 4: horizontal size ratio (HSR), vertical size ratio (VSR), and horizontal shear disparity (HSh). HSR is the angle subtended horizontally by the stimulus in the left eye, divided by the same angle in the right eye (Backus, Banks, van Ee, & Crowell, 1999; Rogers & Bradshaw, 1993); it is equivalent to the horizontal gradient of horizontal disparity. An increase of HSR causes the apparent slant of a surface to be more right-side far, (i.e., it appears more slanted about the vertical axis; tilt of 0°). This effect was named the

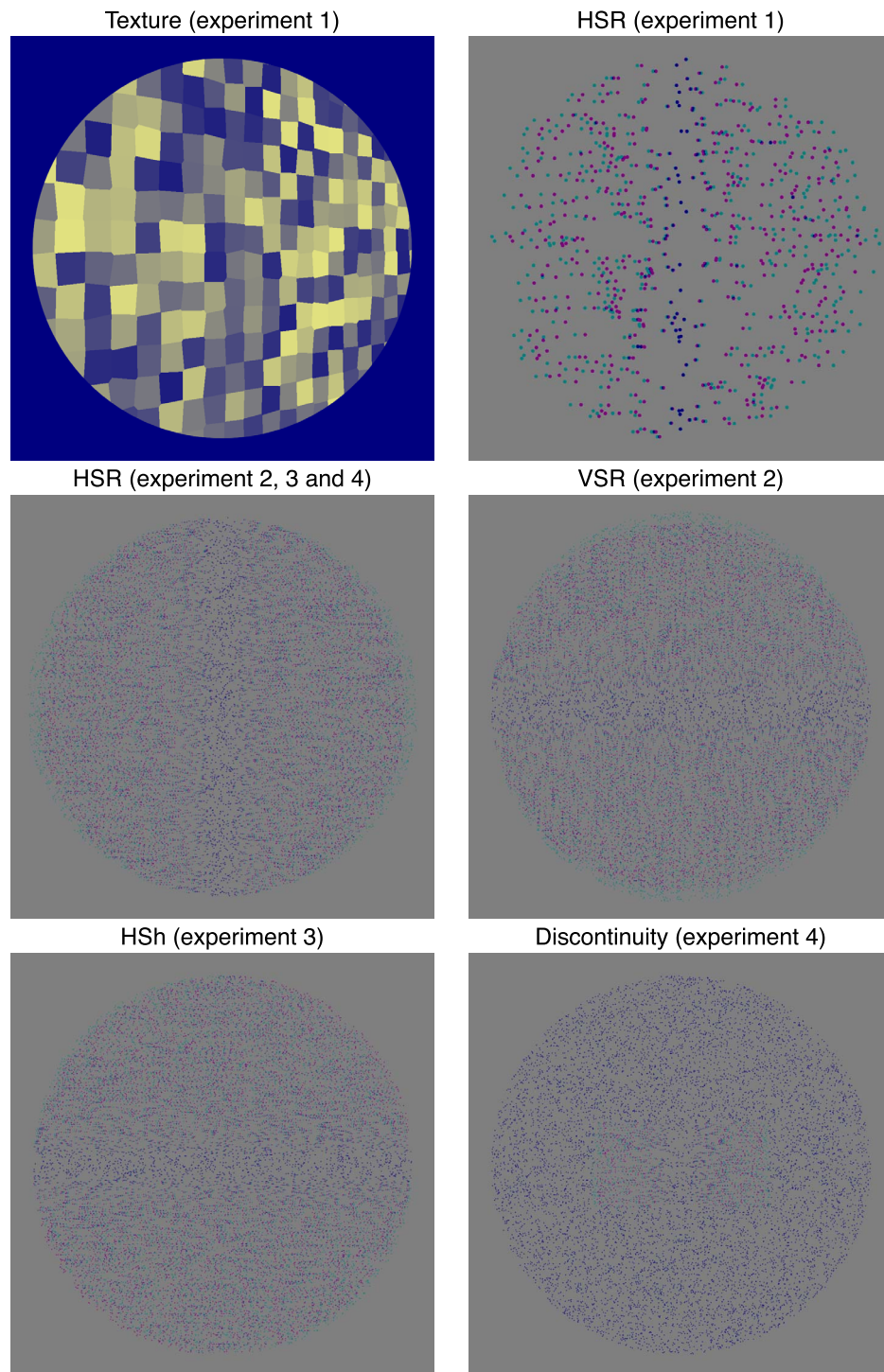


Figure 2. Anaglyph versions of the stimuli used in the experiments. Red dots are visible as dark when seen through a green filter and vice versa. From left to right, top to bottom: (1) Texture stimulus. The stimulus boundary simulates the physical diaphragm aperture that was in front of the observers' right eye and was not displayed on screen during the experiment. The left eye was occluded. (2) Horizontal size ratio stimulus for Experiment 1. Here, the left eye (green dots) is magnified by one value, about 10% relative to the right eye, causing the surface to appear slanted by about 45° counter-clockwise seen from above (geometric effect). Other slants were 15° , 30° , and 60° . (3) Horizontal size ratio stimulus for Experiments 2, 3, and 4. Here, the left eye is magnified 6% relative to the right eye, causing the surface to appear slanted by about 30° counter-clockwise, seen from above. (4) Vertical size ratio stimulus for Experiment 2. Here, the left eye is magnified vertically relative to the right eye, causing the surface to appear slanted clockwise, seen from above from the induced effect. Slant is not easily perceivable in this figure because the surrounding elements also have a VSR of 1, but stimuli in the experiment appeared clearly slanted. (5) Horizontal shear stimulus for Experiment 3. Here, the left eye is sheared 3.3° clockwise relative the right eye causing the surface to appear slanted 30° about the horizontal axis (90° tilt). (6) Slant-contrast stimulus for Experiment 4. Here, the horizontal magnification is applied to a rectangle area at the center of the stimulus only, creating relative disparity discontinuities between the target rectangle and the background.

geometric effect by Ogle (1950) as it can be explained directly from the binocular geometry of the visual scene (Lippincott, 1917).

Vertical size ratio (VSR) is equivalent to the vertical gradient of vertical disparity. When relative magnification is vertical, slant in the opposite direction from the geometric effect is perceived, also at a tilt of 0° (Green, 1889; Lippincott, 1889; Ogle, 1938, 1950). This *induced effect* also derives from the geometry of the visual scene but it reflects a correction, made by the visual system during the estimation of slant from horizontal disparity, that compensates for when the surface is in eccentric gaze (Backus et al., 1999; Gårding, Porrill, Mayhew, & Frisby, 1995; Gillam, Chambers, & Lawergren, 1988; Gillam & Lawergren, 1983; Mayhew & Longuet-Higgins, 1982). Another cue that specifies when a surface is not straight ahead that also contributes to stereoscopic slant perception is felt eye position (Backus et al., 1999; Banks, Hooge, & Backus, 2001), but eye position was not manipulated here.

Horizontal shear disparity (HSh) is equivalent to the vertical gradient of horizontal disparity (Ames, 1946; Ogle, 1950), or *scissor effect*. HSh is like HSR, in that both can be understood simply as causing one half of the stimulus to appear farther away for having uncrossed horizontal disparity relative to the other half, either the top half relative to the bottom (HSh), or left side relative to right (HSR). Slant about a horizontal axis (tilt of 90°) is also called *inclination*.

Finally, the perception of slant from horizontal disparity is strongly facilitated by the presence of a background or reference surface. A given HSR creates an apparent slant of greater magnitude when the surface is presented against a larger background surface that is frontoparallel, so these *slant contrast* stimuli have been of significant interest in comparison to whole-field HSR stimuli in previous studies (Gillam, Chambers, & Russo, 1988; Gillam, Flagg, & Finlay, 1984; van Ee, Banks, & Backus, 1999; van Ee & Erkelens, 1996).

In Experiment 1 we compared slant from texture to slant from HSR at different slant angles. In Experiment 2 we compared slant from HSR to slant from VSR. In Experiment 3 we compared slant from HSR to slant from HSh. Lastly, in Experiment 4 we compared whole-field slant from HSR to HSR-based slant contrast. Figure 1 represents the different types of stimuli used in the experiments. We chose these four specific comparisons because they have been studied previously, sometimes with contradictory results between studies. To anticipate, our results contradict the widely held belief that stereoscopic slant perception is a slow process.

General methods

Observers

Observers were students and faculty at the SUNY College of Optometry. All observers had normal or corrected-to-normal vision, and stereoacuity of 20 arcsec or better as measured with the Randot stereoacuity test (Precision Vision, La Salle, IL). Five observers participated in all of the experiments and additional observers participated only in some of them. Approximately one third of the potential observers, including one of the authors (BC), were excluded because they were unable to perceive slant from stereopsis reliably, which is a fairly typical proportion (Hibbard, Bradshaw, Langley, & Rogers, 2002). The number of observers for whom data were collected and analyzed was 8, 10, 10, and 10 in Experiments 1 to 4, respectively. Observers were paid for their participation and gave written consent. The study was conducted in accord with the Declaration of Helsinki and protocols approved by the Institutional Review Board of SUNY College of Optometry.

Apparatus

Stimuli were displayed on a stereoscopic LCD computer screen (54×30 degrees of visual angle; Asus VG248QE, Taipei, Taiwan) at a viewing distance of 57 cm. Active shutter glasses (3D Vision P854; nVidia, Santa Clara, CA) were used to create a 120-Hz stereoscopic display (60 Hz in each eye). The right eye looked at the monitor through an iris diaphragm (Oriental Instruments, Irvine, CA) mounted on a X-Y-Z translation stage (Edmund Optics, Barrington, NJ) allowing precise positioning of the aperture. At the beginning of the experiment, observers adjusted the chair height and chinrest to be comfortable for the fixed height of the aperture, then adjusted the aperture size so as to see the entire stimulus but not the borders of the monitor with their right eye. Because of the aperture, there was no binocularly matched frame of reference surrounding the stimulus. For the texture condition, an occluder was placed in front of the left eye.

General procedure

Experiment 1 consisted of two sessions of about 1 hr each, and Experiments 2 through 4 consisted of one session only. The order of the experiments was pseudorandomized to be counterbalanced across observers. All comparisons are made between conditions

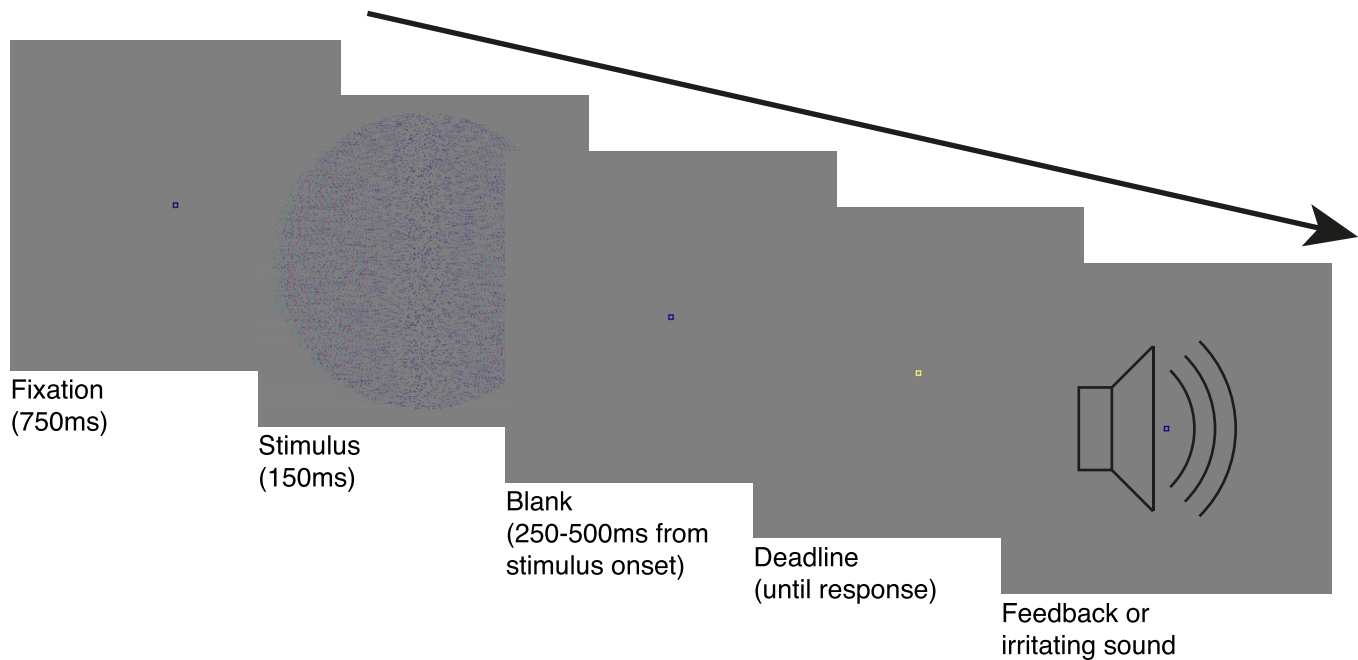


Figure 3. Time course of a trial. After a 750-ms fixation period, the stimulus was displayed for 150 ms then blanked. After a deadline that varied between blocks within 250 ms and 500 ms from stimulus onset, the fixation turned white if the observers had not yet answered, indicating that the deadline was missed. Observers were instructed to try to meet the deadline. When they did, a normal feedback sound was played; otherwise, they heard an irritating sound.

that were run within the same session; in Experiment 1, the data from the two separate sessions were pooled together for analysis and all conditions were collected within each session.

Each trial started with a 750-ms fixation, followed by a 150-ms stimulus, followed by a blank screen (Figure 3). The task of the observer was to indicate which side of the surface was farther by pressing the left “4” or right “6” key on a numeric keypad. After a deadline to respond, the fixation square, initially black, turned white. The deadline was fixed within a block of trials and always decreased from one block to the next, as it was easier for observers to adjust to a shortening deadline than to a lengthening one. To avoid training or fatigue effects, one experimental session consisted of several decreasing ramps of deadlines. Specific variations of this design are described later. The purpose of varying the deadline was to broaden the total distribution of response times. The deadline itself was not an important independent variable.

Normal feedback was given when the observer respected the deadline: a high-pitched tone signaled a correct response and low-pitched tone signaled an incorrect response. When the observer responded after the deadline, a penalty sound, composed of 10 disharmonic pure tones randomly chosen between 50 Hz and 2k Hz, was played at twice the intensity of normal feedback. Observers were instructed to be as accurate as possible, and that respecting the deadline was more important than being accurate, but that some

missed deadlines were necessary for them to know how much time they had. All responses were recorded and analyzed regardless of whether the observer met the deadline on that trial.

Analysis

Data at the top and bottom 2.5% of the reaction time distribution were trimmed for each observer in each condition, to remove outliers. Trimming was based on response times without regard to the deadline under which it was collected. Then, a SATF was fitted to the data for each observer and condition using maximum likelihood estimation. The SATF had two free parameters: delay and time constant. It was constant at 0.5 (chance accuracy) during the delay, then increased to reach 1 as an exponential approach function. To verify the robustness of our results, we fitted another SATF, which consisted of a rectified cumulative normal function (linear accumulation over time in z -score). The correlation between parameters from the two fitting techniques was higher than 0.95 in all four experiments, and statistics on the parameters of either fitted function yielded similar conclusions. Thus, the results described here were not sensitive to the particular form of the SATF used to fit the data.

The trials were statistically resampled, with replacement, 10,000 times for each individual and each condition separately, and a SATF was fitted on each

resample. We used the distribution of fit parameters to determine a confidence interval for the parameter difference between conditions (Experiments 2, 3, and 4) or for regression coefficients across slant values (Experiment 1).

Experiment 1: Texture, horizontal disparity, and slant angle

In Experiment 1 we compared the dynamics of slant from texture to slant from horizontal size ratio (HSR). The reliability of slant estimates from texture and stereopsis varies with slant angle, with HSR being better for small slants and texture being better for large slants (Backus et al., 1999; Hillis, Watt, Landy, & Banks, 2004; Knill, 1998a, 1998b), so we compared these cues across multiple slant angles.

Methods

Stimuli

Surface slant was specified either by stereopsis or texture. In the stereoscopic condition, 500 dots were uniformly distributed within a 25°-wide window. Dots subtended 17 arcmin. The background and dot luminances were approximately 8 and 2 cd/m², respectively, after taking the stereoscopic shutter glasses into account. One eye was magnified by an HSR as calculated by Backus et al. (1999; see also Ogle, 1950; van Ee & Erkelens, 1996):

$$HSR = \exp(-\mu \tan S)$$

with μ the binocular vergence angle in radians and S the slant. In the texture condition, a texture was generated by using a Voronoi tessellation of a square grid. Cell centers were 2° apart and were jittered randomly with a Gaussian distribution ($\sigma = 6$ arcmin). Each cell had a luminance randomly chosen within the range of 4 to 40 cd/m² (before viewing through the stereoscopic glasses). The textured surface was then rotated in 3D according to the slant, and then back-projected onto a plane orthogonal to the right eye's visual axis. The stimuli subtended 25° in the stereoscopic condition and approximately 31° in the texture condition. However, because the monocular aperture was smaller than the monitor, the stimuli both subtended about 25° and all the dots were binocularly matched (visible to both eyes) in the stereoscopic condition. Examples of stimuli can be seen in Figure 2. Surface slant had one of eight values: $\pm 15^\circ$, $\pm 30^\circ$, $\pm 45^\circ$, and $\pm 60^\circ$, corresponding to a magnification in the right or left eye of 2.81%, 5.96%, 10.1%, and 16.8% (HSR of 1.03, 1.06, 1.10, or 1.17, and their reciprocals).

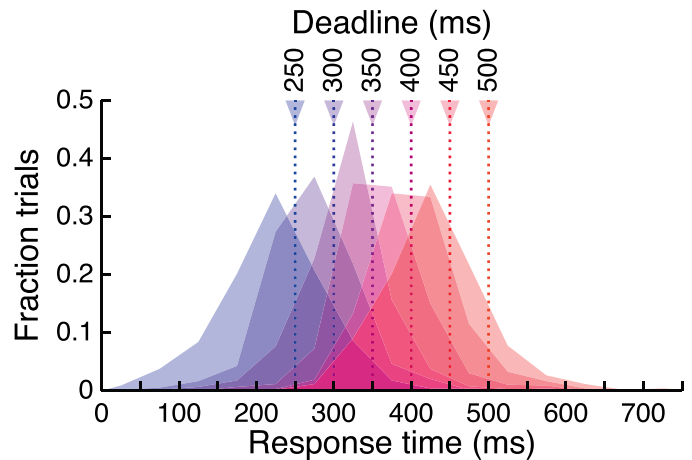


Figure 4. Distribution of response times for one observer as a function of the deadline. The deadline varied from 500 ms (red) to 250 ms (blue) from block to block. The observers were instructed to answer before the deadline. The deadline procedure successfully modulated the distribution of response times allowing us to sample trials from the entire speed–accuracy tradeoff function of an observer.

Procedure

The deadline had six possible values ranging from 500 to 250 ms after stimulus onset within separate blocks of 50 trials. Six blocks of trials, all having the same stimulus type and slant angle magnitude, were run successively, with six-block sequences of the stereoscopic task alternated with six-block sequences of the texture task. The eight possible conditions (four levels of slant for two types of stimuli) were pseudorandomized: decreasing ramps of deadlines always alternated between stereoscopic and texture conditions. Observers ran two sessions of this experiment to collect 4,800 trials in total (2 sessions \times 2 stimuli \times 4 slants \times 6 deadlines \times 50 trials), or 600 trials per SATF. The starting condition, texture or stereopsis, was counter-balanced across observers and sessions.

Results and discussion

Figure 4 shows an example of distributions of response times from one observer. The distribution of response times was shifted toward shorter values when the deadline contracted because the observers had to answer faster to respect the deadline, at the cost of accuracy. Figure 5 shows this tradeoff: accuracy (fraction correct) is plotted as a function of response time for the two stimulus conditions and four slant angles. The data exhibited a typical speed–accuracy tradeoff effect, with performance at chance until about 200 ms, whereupon it abruptly deviated from chance and increased with response time.

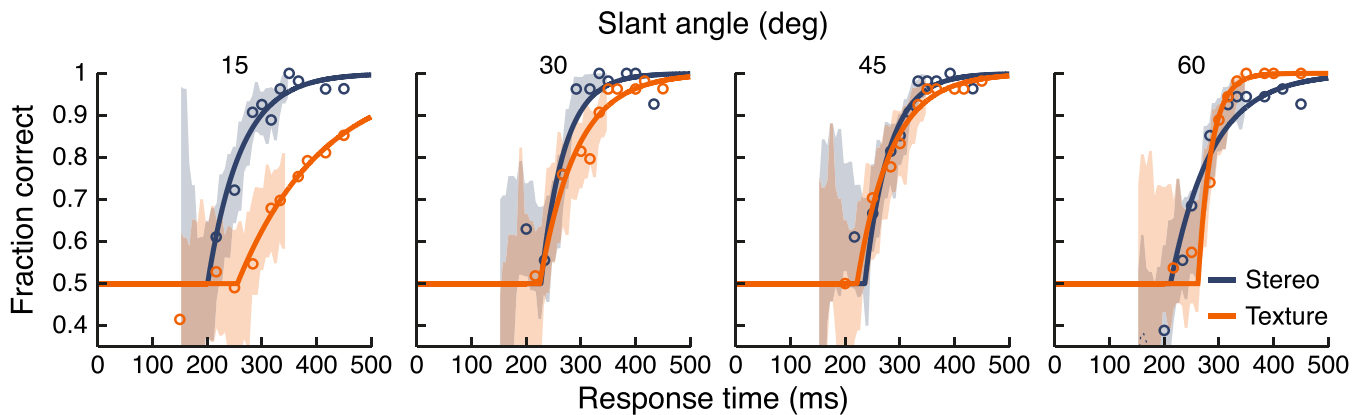


Figure 5. Example of data for one observer (same as Figure 4). Lattice plot of accuracy (ratio correct) as a function of response time for the stereoscopic (blue) and texture (orange) stimuli and for the four slant angles (15°, 30°, 45°, and 60°, from left to right). Circles are binned data, thick lines are fitted SATFs, and shaded areas are 95% binomial confidence intervals for a 20-ms sliding window between 150 and 350 ms. The time at which performance deviates from chance is the residual latency and the time constant of the exponential is the reciprocal of the accumulation rate. These two parameters were estimated for each individual, for each slant angle, and for each stimulus type.

Figure 6 shows the delay parameter and time constant as a function of slant angle and stimulus condition for the eight observers. Surprisingly, the delay parameter was higher for the texture condition than for the stereoscopic condition at all slant angles. The mean delay parameter was 208.9, 210.4, 215.0, and 211.6 ms for 15°, 30°, 45°, and 60° slant, respectively, in the stereoscopic condition, and it was 270.5, 249.8, 247.8, and 252.2 ms in the texture condition. The difference in delay parameter was significant at all four slant angles (bootstrap of the individual differences, $p < 0.001$, uncorrected for multiple comparisons). We estimated the effect of slant angle by regressing the delay fit parameters separately for each individual and stimulus condition. The delay parameter did not significantly increase or decrease for either stimulus

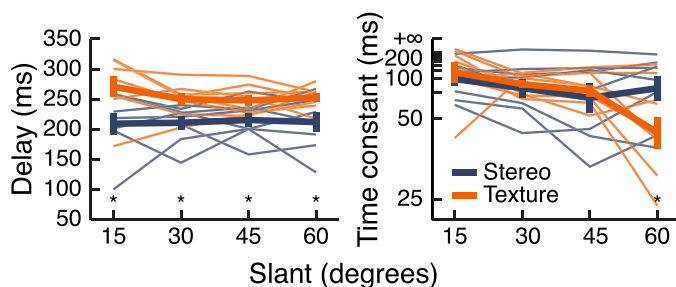


Figure 6. (A) Residual latencies (delay parameter from fitted SATFs) in microseconds as a function of slant angle in degrees for stereopsis (blue) and texture (orange). Thin lines are individual observers, thick lines are average, and vertical lines are standard errors across observers. (B) Same as (A) for the time constant in microseconds. Asterisks above x-axis tick marks show the slants for which there were significant differences between the stereoscopic and texture condition. The y-axis is scaled for reciprocal values, then inverted.

type (bootstrap of the individual regression parameter, $p = 0.38$ and $p = 0.11$ for the stereoscopic and texture conditions, respectively). Thus, even though the delay parameter was different for stereoscopic and texture, it was not strongly modulated by slant angle.

The mean time constants in the stereoscopic condition were 99.9, 81.4, 68.0, and 81.3 ms for slants of 15°, 30°, 45°, and 60° of slant, respectively. In the texture condition, they were 120.5, 88.5, 77.5, and 42.8 ms, respectively. The time constant was significantly smaller for the texture stimulus than the stereoscopic stimulus at the largest slant of 60° only (bootstrap of the individual differences, $p = 0.28$, $p = 0.31$, $p = 0.30$, and $p < 0.001$ for slant angles of 15°, 30°, 45°, and 60°, respectively, uncorrected for multiple comparisons). The time constant did not change as a function of slant angle for the stereoscopic stimulus, but it significantly decreased with angle for the texture stimulus (bootstrap of the individual regression parameter, $p = 0.10$ and $p < 0.0001$ for the stereoscopic and texture conditions, respectively).

Thus, accuracy departed from chance earlier in the stereoscopic condition than in the texture condition. On average, observers started to be able to discriminate slants 41 ms earlier when it was defined by stereoscopic than by texture. However, for large slants, accuracy increased faster in the texture condition than in the stereoscopic condition. This effect is made obvious in Figure 7, in which plots reported slant direction as a function of slant angle for response times within 50 ms windows centered between 150 and 500 ms. The psychometric functions become steeper as response time increases. For the stereoscopic condition, responses are random up to 200 ms. At 250 ms, observers' responses were already clearly mediated by

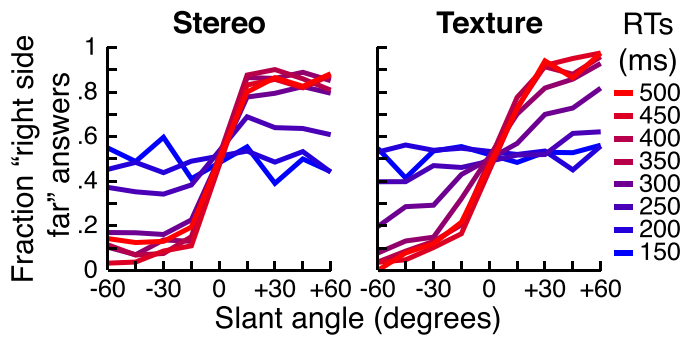


Figure 7. Ratio of “right-side far” answers as a function of slant angle for responses made within a 50-ms window centered on eight values ranging from 150 to 500 ms (blue to red, respectively), for the stereoscopic condition (left) and texture condition (right).

the slant angle. In the texture condition, responses were still close to chance at 250 ms. However, by 350 ms, accuracy was better in the texture condition than in the stereoscopic condition at $\pm 45^\circ$ and $\pm 60^\circ$ of slant.

Results from this experiment demonstrate that not only was the stereoscopic cue available early for slant discrimination, it was in fact, available earlier than texture.

Experiment 2: Vertical disparity

In Experiment 2, we studied the dynamics of the induced effect, or slant from vertical disparity, compared to the geometric effect. Fukuda, Kaneko, and Matsumiya (2006) found a longer integration window for slants from VSR than for slants from HSR, but other studies found no difference in the build-up of perceived slant from VSR as compared to HSR (Allison, Howard, Rogers, & Bridge, 1998; van Ee & Erkelens, 1998).

Technically, the horizontal gradient of horizontal disparity and the vertical gradient of vertical disparity were always defined in our stimuli; however, for simplicity we use “slant from HSR” when the VSR was fixed at 1, and “slant from VSR” when the HSR was fixed at 1. We estimated the SATFs for discriminating the sign of slant from HSR ($\pm 6\%$ horizontal magnification) or the sign of slant from VSR ($\pm 6\%$ vertical magnification).

Methods

Sparse random-dot stereograms were composed of 10,000 dots, each subtending about 3 arcmin. This difference from Experiment 1 was not expected to affect within-experiment comparisons. The magnifica-

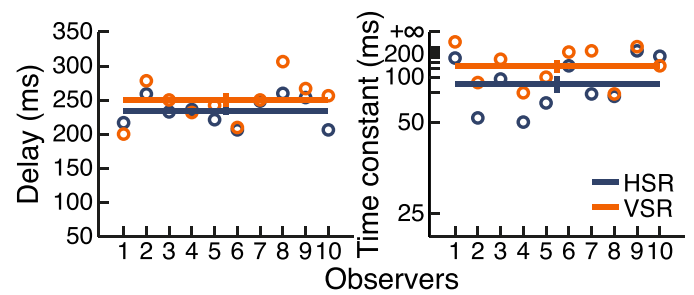


Figure 8. (A) Residual latencies (delay parameter from fitted SATFs) in microseconds for the HSR (blue) and VSR (orange) conditions. Circles are individuals, horizontal line is average, and vertical line is standard error. (B) Same as (A) for the time constant parameter in microseconds.

tion factor for both HSR and VSR stimuli was fixed to $\pm 6\%$, corresponding to a slant of about 30° . Apparent slant magnitude from VSR was less than that from HSR (Backus et al., 1999). Because the stimuli looked very similar (Backus, 2002), we mixed HSR and VSR conditions within blocks. The deadlines decreased from block to block of 70 trials in 16 values from 500 ms to 250 ms. The 16 blocks were repeated twice, and were randomly distributed in four decreasing ramps of eight blocks.

Results and discussion

Figure 8 plots delay and slope fit parameters as a function of stimulus condition. The mean delay was 234.3 ms and 249.7 ms for the HSR and VSR stimuli, respectively, which was significantly different (bootstrap of the individual differences: $p < 0.005$, confidence interval $[-28.1, -3.4]$). The time constant was 87.0 ms and 133.0 ms for the HSR and VSR stimuli, respectively, which was also significantly different (bootstrap of the individual differences: $p < 0.0001$, confidence interval $[+23.2, +132.5]$).

Thus, observers were able to start discriminating slant slightly earlier for slants from HSR than slants from VSR. Moreover, their performance increased faster for the HSR than the VSR stimuli. As described above, these conditions did not isolate horizontal disparity from vertical disparity; instead they were both present in the two stimuli. Implications for this are described in General discussion.

Experiment 3: Tilt

A strong perceptual discrepancy, or *anisotropy*, exists between slants about a vertical axis and slants about a horizontal axis (respectively 0° and 90° tilt), in

favor of slants about a horizontal axis. Slant thresholds are lower (Rogers & Graham, 1983), perceived slant is greater (Gillam & Ryan, 1992), discrimination latency is shorter (Gillam, Chambers, & Russo, 1988), and perceived slant develops faster (van Ee & Erkelens, 1996). In this experiment, we asked whether this anisotropy is present early enough to affect the residual latency or slope of the SATF. Thus, we measured observers' SATF for discriminating the sign of slant produced respectively by HSR or by HSh.

Methods

Stimuli were similar to Experiment 2, except as specified otherwise. The magnification factor for HSR was fixed to $\pm 6\%$. The horizontal shear geometrically giving an identical slant angle is calculated by (Banks et al., 2001; van Ee & Erkelens, 1996):

$$Hr = \tan^{-1}(\mu \tan S)$$

with S the slant, Hr the shear angle and μ the vergence. The shear angle was $\pm 4.25^\circ$. The residual latency of a SATF, as measured by the delay parameter, comprises both visual processing and motor execution (see Figure 11 in General discussion). To avoid response compatibility effects and thus better compare residual latencies across the two tilt conditions, we instructed observers to indicate which part of the surface was far, in both conditions, using the opposite diagonal keys of the numeric keypad (the 1 and 9 keys).

Deadlines were identical to those in Experiment 2. Trials were blocked by condition to prevent attention to one type of stimulus appearance from hindering performance for the other type of stimulus. Each of the four blocks had a decreasing ramp for the deadline, and contained trials from one condition only. The conditions varied in an ABBA pattern across the session. Half of the observers started with the HSR condition and the other half started with the HSh condition.

Results and discussion

Figure 9 plots delay and slope fit parameters as a function of stimulus condition. The mean delays were 221.0 ms and 233.9 ms for the HSR and HSh stimuli, respectively, which was not significantly different (bootstrap of the individual differences, $p = 0.12$, confidence interval $[-10.1, +30.2]$). The mean time constants were 93.7 and 146.0 ms for the HSR and HSh stimuli, respectively, which was significantly different (bootstrap of the individual differences, $p = 0.015$, confidence interval $[+1.5, +184.6]$).

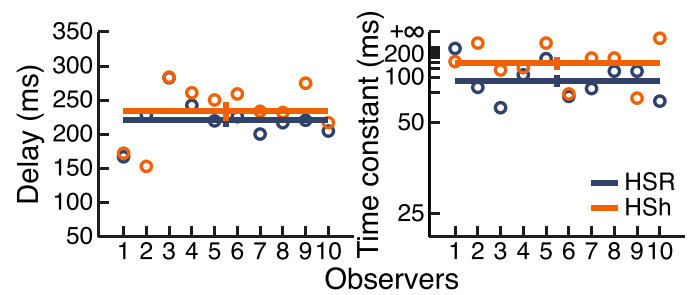


Figure 9. (A) Residual latencies (delay parameter from fitted SATFs) in microseconds for the HSR (blue) and HSh (orange) conditions. Circles are individuals, horizontal line is average, and vertical line is standard error. (B) Same as (A) for the time constant parameter in microseconds.

Thus, the data do not confirm our prediction, based on the literature, that slants at 90° of tilt (horizontal axis) would be discriminated faster than slants at 0° of tilt (vertical axis). In fact, for our stimuli, observers were able to discriminate between slants with 0° and 90° of tilt with similar delays, and their performance actually increased faster when slants were about the vertical axis.

Experiment 4: Slant contrast

Slant from HSR is defined by a smooth disparity gradient. It has been found that slant is processed more accurately (Brookes & Stevens, 1989; Stevens & Brookes, 1988; van Ee et al., 1999; van Ee & Erkelens, 1995) and faster (Gillam, Chambers, & Russo, 1988; Gillam et al., 1984; van Ee & Erkelens, 1996) when a reference frame is provided, because across short distances within the visual field, relative disparity is measured very robustly (Backus & Matza-Brown, 2003; Blakemore, 1970; Chopin, Levi, Knill, & Bavelier, 2016).

We asked whether this effect is present early enough to affect residual latencies or the slope of the SATF. One stimulus contained a whole-field HSR, as in Experiments 2 and 3. The other stimulus was similar except that only a central rectangle had nonzero stereoscopic slant, while the surrounding field was stereoscopically fronto-parallel.

Methods

The whole-field stimulus was identical to the HSR stimulus in Experiments 2 and 3. In the *slant-contrast* stimulus, with discontinuities, only a 6° tall \times 12° wide central rectangle was slanted. All the dots inside this rectangle had an HSR of 1.06 (or $1/1.06$), while those

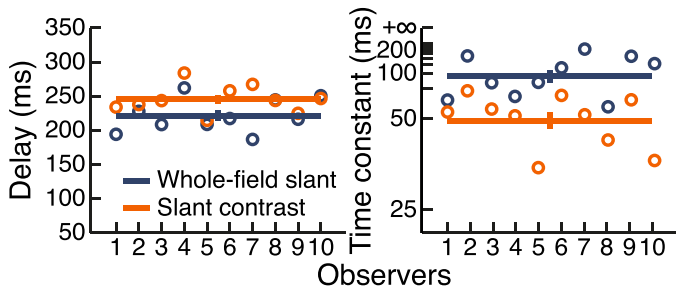


Figure 10. (A) Residual latencies (delay parameter from fitted SATFs) in microseconds for the whole-field slant (blue) and slant-contrast (orange) conditions. Circles are individuals, horizontal line is average, and vertical line is standard error. (B) Same as (A) for the time constant parameter in microseconds.

outside had an HSR of 1.00. The experiment design was otherwise identical to Experiment 3.

Results and discussion

Figure 10 plots delay and slope fit parameters as a function of stimulus condition. The mean delays were 221.8 ms and 245.5 ms for the whole-field and slant-contrast stimuli, respectively, which was significantly different (bootstrap of the individual differences: $p < 0.0001$, confidence interval $[-40.2, -10.0]$). The mean time constants were 94.6 and 49.1 ms for the whole-field and slant-contrast conditions, respectively, which was also significantly different (bootstrap of the individual differences: $p < 0.0001$, confidence interval $[-13.7, -6.3]$).

Thus, whole-field slant was initially processed faster, but accumulated more slowly, than slant-contrast.

General discussion

In this series of experiments, we used a speed–accuracy tradeoff function (SATF) analysis to study the time course of slant discriminability in a two-alternative forced choice task. Our main conclusion is that slant from stereopsis is available early for perceptual discriminations. Observers started to be able to discriminate between two slants at about 200 ms. This latency did not depend on the specific slant angle we used, but was instead quite stable over a large range of slant angles, including slant angles used in the previous literature. It was also relatively similar across different slant cues. This 200-ms latency for stereoscopic slant perceptual discrimination is similar to the latency for simple stereoscopic depth and luminance comparisons that were reported by Caziot et al. (2015). Observers typically reached 100% correct within 1 s, with most observers at 100% correct at 350 to 500 ms.

Comparisons between cues for slant

Slanted surfaces give rise to a variety of signals from which the slant and tilt of the surface can be inferred. These different slant cues are presumably extracted by different neural filters and then processed by separate mechanisms, so knowing their different time courses is of interest as it would help us identify the neural mechanisms of surfaces’ 3D orientation (Murphy, Ban, & Welchman, 2013; Nguyenkim & DeAngelis, 2003; Orban, 2011; Rosenberg, Cowan, & Angelaki, 2013;

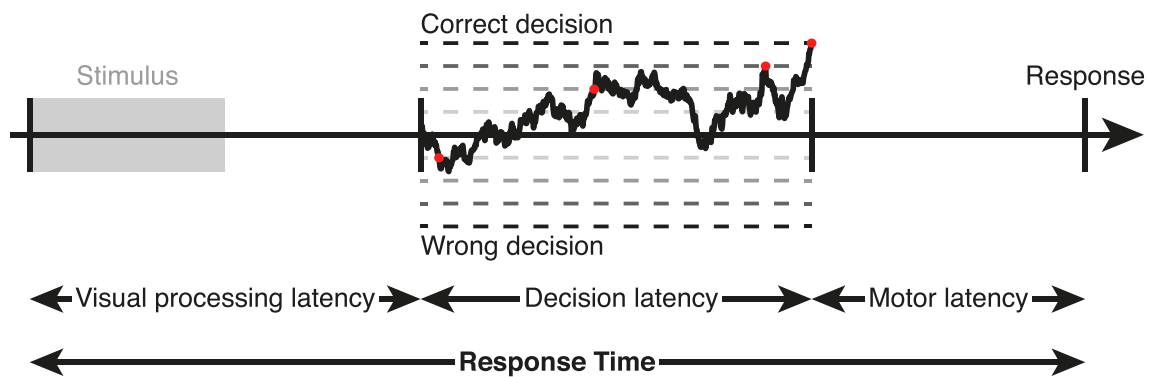


Figure 11. Components of response time. The visual processing latency starts at stimulus presentation and proceeds until the extracted signal first becomes available in the decision variable (jagged curve). This variable accumulates to a decision boundary (dashed lines), whereupon a motor response is initiated when the boundary is crossed (red dots)—either the correct one or the incorrect one. A liberal criterion (lighter gray dashed lines) reduces the mean accumulation time but also increases the error rate, because the signal-to-noise ratio is lower at the time of decision. In the present experiment, we used a deadline procedure to reduce the response time until accuracy in the task was at chance. Reproduced with permission from Caziot, B., Valsecchi, M., Gegenfurtner, K. R., & Backus, B. T. (2015). Fast perception of binocular disparity. *Journal of Experimental Psychology: Human Perception and Performance*, 41, 909–916.

Taira, Tsutsui, Jiang, Yara, & Sakata, 2000; Tsutsui, Sakata, Naganuma, & Taira, 2002).

Stereo and texture

Experiment 1 compared the SATFs for discriminating slants from stereopsis, as specified by a disparity gradient, and from texture, as specified by the texture gradient. Surprisingly, the residual latency for stereopsis was shorter than that for texture. Of course, either cue can be made more or less reliable by manipulating the stimulus, but the fact remains that slant from disparity was surprisingly fast. It is possible that visual system estimates of slant from texture would be more reliable, and thus faster, using a different texture, but this improvement is likely to be negligible because our stimuli already contain very rich slant-from-texture cues (Gibson, 1950; Marr, 1982; Saunders & Backus, 2006; Stevens, 1980; Velisavljevic & Elder, 2006; Witkin, 1981). Stereopsis was faster for smaller slants (lower SNR) and texture was faster for larger slants, as would be expected from their relative reliabilities across slant angles (Hillis et al., 2004).

Slant from texture has been compared to slant from stereopsis for motor tasks. Greenwald & Knill (2009) and Greenwald et al. (2005) found that hand attitudes during fast reaching movements were adjusted more quickly after in-flight disparity perturbations than after in-flight texture perturbations. Thus, slant from stereopsis was processed faster than slant from texture for the purpose of controlling hand movement (however, see van Mierlo, Louw, Smeets, & Brenner, 2009). Our results show that, like the in-line control of reaching, slant perceptual discriminations can be done more quickly using binocular disparity than using texture.

HSR and VSR

Experiment 2 compared slant from horizontal size ratio (HSR; geometric effect, horizontal gradient of horizontal disparity) to slant from vertical size ratio (VSR; induced effect, vertical gradient of vertical disparity; Backus et al., 1999; Gillam & Lawergren, 1983; Mayhew & Longuet-Higgins, 1982). Lippincott (1917), Ames (1946), and Ogle (1938, 1950) reported that the induced effect was smaller in magnitude and slower to develop than the geometric effect. On the other hand, two quantitative studies on the build-up of apparent slant did not find obvious differences between these two effects (Allison et al., 1998; van Ee & Erkelens, 1998), although perceived slant remained lower for VSR than HSR. Fukuda et al. (2006) found that for flickering opposite VSR, slant perception was destroyed at frequencies of more than 2 Hz, while the slants of flickering opposite HSRs were still perceived.

They concluded that vertical disparities were integrated over a window of 500 ms or more, much longer than the 70-ms integration window for horizontal disparities (Kane, Guan, & Banks, 2014; Nienborg, Bridge, Parker, & Cumming, 2005). In Experiment 2 we found a small difference between the residual latencies for the geometric versus induced effect, with the former being faster. We also found a longer time constant for the induced effect than the geometric effect. Both of these findings are consistent with slant from HSR being measured more reliably than slant from VSR.

Importantly, manipulating VSR affects only one of two stereoscopic means for estimating slant, namely *slant from HSR and VSR*, whereas HSR manipulation affects both slant from HSR and VSR and *slant from HSR and eye position* (Banks & Backus, 1997). This difference accounts for the greater apparent slant of HSR manipulations, but it may also account for the difference in time course. When VSR is manipulated, HSR and eye position continue to specify an absence of slant. The conflict between the two stereoscopic slant cues, inherent in VSR manipulation, may well explain the slower build-up of performance in our VSR condition and suggests slant perception can be slowed by conflicts between cues—even if HSR and VSR can be measured with equal speed by the visual system.

Observers discriminate luminances and stereoscopic depths with near-identical residual latencies, even though the stereoscopic integration window lasts much longer than the window for luminance (Caziot et al., 2015). Similarly, we showed here that observers were not obliged to wait for the entire span of the 500 ms VSR integration window to be able to discriminate slants. Instead, as with stereoscopic depth, the initial contents of the stereoscopic slant accumulator are made available quickly for perception.

HSR and HSh

Experiment 3 compared slants from HSR to slants from horizontal shear (HSh; scissor effect, vertical gradient of horizontal disparity). These two stimuli have similar appearance except that HSR corresponds to a tilt of 0° (slant about the vertical axis) while HSh corresponds to a tilt of 90° (slant about the horizontal axis, sometimes called inclination). We found a difference in SATFs in an unexpected direction for HSR and HSh: the residual latencies were similar, but the slopes were steeper for the HSR condition than the HSh condition. Slants with 90° of tilt are usually discriminated better—discrimination thresholds are smaller—than slants with 0° tilt (Bradshaw & Rogers, 1999; Rogers & Graham, 1983). Why this effect is not reflected in the time-course of slant perception is unclear. Three studies found a difference in the rate of build-up of apparent slant, favoring HSh, across tilt

angles (Allison & Howard, 2000; Bradshaw, Hibbard, & Gillam, 2002; Gillam, Chambers, & Russo, 1988), while three other studies did not (Allison et al., 1998; van Ee & Erkelens, 1996, 1998). In any case, that the residual latencies were similar in these conditions suggests that the anisotropy between slant and inclination is not caused by the initial extraction of disparity (Cagenello & Rogers, 1993; Hibbard et al., 2002; Hibbard & Langley, 1998) but rather by some later stage of processing, as suggested by Mitchison and McKee (1990).

Whole-field slant versus slant contrast

Perhaps the most intriguing result is from Experiment 4. In this experiment, we compared the HSR-specified slants of whole-field surfaces to the HSR-specified slants of smaller surfaces embedded within fronto-parallel reference planes. It has long been known that an abrupt change in disparity at the edge of a surface patch is highly trusted by the visual system as an indicator of depth (Gillam, Chambers, & Russo, 1988; for discussion of this literature see van Ee et al., 1999). Our data confirm this finding. We found, in agreement with prior literature (Allison & Howard, 2000; Bradshaw et al., 2002; Gillam, Chambers, & Russo, 1988; Gillam et al., 1984; van Ee et al., 1999; van Ee & Erkelens, 1996, 1998), a steeper accumulation rate for slant contrasts than for whole-field slants.

However, we also found a shorter latency for whole-field slant than for slant contrast. This finding was new, unexpected, and potentially important. An extra stage of processing might reasonably explain this effect: inferring the slant of a small patch from the relative disparity at its edges requires first estimating the slant of the reference, followed by summing with the relative slant of the small patch. In our stimuli, the reference was always unslanted, so the time constant for correctly judging its slant as being positive or negative is infinite. However, its slant can be quickly estimated as being close to zero. After that, the signal needed to judge the sign of slant of the small patch would presumably accumulate quickly, consistent with the fact that relative slant is estimated with very high reliability (van Ee et al., 1999). This interpretation must be qualified by noting that latencies are sometimes faster in peripheral vision (Carrasco, McElree, Denisova, & Giordano, 2003), and the whole-field stimulus is of course larger than a small embedded patch. Thus, the shorter latency for the whole-field patch could, in principle, be explained by its greater retinal eccentricity. We can, in any case, conclude that the slants of whole-field surfaces are not in general processed more slowly than the slants of embedded surfaces (c.f. Bradshaw et al., 2002; Gillam, Chambers, & Russo, 1988). Instead, the

whole-field slant of a large surface is seen earlier, while reliability increases more rapidly, as expected, for slant contrasts.

Slow stereo in the literature

The relationship between visual cues and the apparent slants they evoke has been studied extensively. These studies include slant from textures (e.g., Gårding, 1992; Gibson, 1950; Stevens, 1980; Witkin, 1981), stereopsis (e.g., Backus & Banks, 1999; Backus et al., 1999; Ogle, 1950; van Ee & Erkelens, 1995), or both (Allison & Howard, 2000; Gillam, 1968; Hillis et al., 2004; Stevens & Brookes, 1988). Yet, few studies have addressed the speed with which stereoscopic cues become available for perception. Interestingly, slant from stereopsis has been used to illustrate a purported sluggishness of binocular vision. Starting with the first published works on the geometric and induced effects, the time course of stereoscopic slant was described as very slow (Ames, 1946; Friedenwald, 1892; Lippincott, 1889, 1917; Ogle, 1950). In fact, Lippincott took stereopsis' sluggishness as evidence for the inefficiency of binocular vision.

Discrimination latency

In an influential study, Gillam, Chambers, and Russo (1988) recorded the time required for various kinds of stereoscopic slant stimuli to be discriminated. Observers reported when they first perceived the stimulus as fused, which happened quickly, and then which one of 12 possible stimuli was displayed. Observers required on average 7 to 38 s to identify the stimulus (twists, hinges, and whole-field slants). They found the shortest discrimination times for the twist stimuli, which contained stereoscopic edges (these slant-contrast stimuli produced “an instant slant response,” i.e., a latency of 7 s). The next-shortest time was for stimuli that had slant about the horizontal axis (HSh, about 15 s, vs. more than 30 s for slant about a vertical axis caused by HSR). For both of these stimuli, responding took many seconds. Concerning whole-field slants, Gillam, Chambers, and Russo (1988) concluded: “Conventional stereograms rarely portray slanted surfaces (although in real life slanted surfaces are the general case). This has precluded the fact that long stereoscopic latencies can occur for simple stimuli” (p. 171).

Why were the observers in our experiments so much faster to discriminate slants? First, observers in the older study had unlimited time to respond, whereas we gave observers a deadline. With unlimited time, the criterion for responding is at the observer's discretion. It seems likely that the 7-s mean response time for their (fastest) “twist” stimuli would have been much shorter

using a deadline-speeded task. Still, in our experiments observers reached near perfect performance in usually no more than 500 ms (e.g., Figures 5 and 7). Second, Gillam, Chambers, and Russo (1988) gave their observers 12 choices on each trial: 3 types \times 2 orientations \times 2 directions. , there were many more opportunities for confusion between stimuli. Finally, as noted by Allison and Howard (2000), long latencies could result from the time it takes for disparities to be sufficiently trusted to win out over the texture and other cues that specified a flat, fronto-parallel surface. We believe that these factors acting together account for the much longer response times previously observed in stereoscopic slant experiments.

Build-up of apparent slant over time

Van Ee and Erkelens (1996, 1998) investigated the time course of slant perception using a different approach: they varied stimulus display durations in a slant-matching task. Perceived slant, as reported with the matching task, increased with display duration. At their longest display duration of 20 s, apparent slant had not yet saturated. They concluded that, “For brief observation periods (of the order of 1 sec or less) slant is poorly perceived, particularly when no visual reference was present” (van Ee & Erkelens, 1996, p. 48).

Similar findings have been reported for stereoscopic slant cues other than HSR (Allison & Howard, 2000; Allison et al., 1998; Bradshaw et al., 2002; van Ee & Erkelens, 1998).

We suspect that the long latencies in previous slant estimation experiments must have been caused, at least in part, by cue conflicts, as suggested by Allison and Howard (2000). Our own stimuli were not devoid of cue conflicts: dot density and the aspect ratio of the field of dots specified that the surface was fronto-parallel. However, we took pains to minimize these cues and observers reported that they perceived clearly slanted surfaces even when our stimuli were presented very briefly.

Still, we did not measure the build-up of apparent slant over time. This raises questions: Was it only the difference in task that caused stereoscopic slant perception to be fast in our study? Was the *sign* of slant available just as early to observers in the previous slant estimation studies, and would apparent slant have built up as slowly for our stimuli as it did for theirs? If so, then stereoscopic slant perception could still be said to be slow, but this is unlikely. First, it is noteworthy that in our experiments, the delay parameter for different magnitudes and types of slant was similar from one condition to another. Perceived slants therefore became discriminable at similar times in the various conditions of our experiments. This outcome would be unlikely if slant developed slowly, since it would require the rapid development of equally

reliable slant percepts across all of the stereoscopic slant conditions, despite their large differences in stereoscopically specified slant. It is more likely that perceived slant developed quickly in all of the conditions.

Second, if the slow build-up of perceived slant in previous work was caused by the conflicting non-stereoscopic cues that specified a fronto-parallel surface, as we claim, and if the speed of stereoscopic slant perception was fast for our stimuli because these conflicting cues were more effectively removed, then observers should perceive slants in our stimuli, even for brief presentations. This is indeed what we found, using a slant-matching task similar to van Ee and Erkelens (1996, 1998; see Supplementary Material). We conclude that cue conflicts in older experiments did indeed cause a dramatic underestimation of the speed at which stereoscopic slant is processed by the visual system.

We can also conclude that stereoscopic slant accumulates very quickly in real scenes. Of course, stereoscopic and nonstereoscopic slant cues generally agree with each other in real scenes, so perceived slant from all cues presumably develops just as fast, if not faster, for real scenes than for laboratory stimuli in which only the stereoscopic cues specify a deviation in slant from fronto-parallel.

Interpretation of delay and slope parameters of fitted SATFs

In this paper we have appealed to the reader’s intuition for the meanings of the residual latency and slope parameters when the data are fitted by SATFs. For completeness, we now make this intuition more formal. SATFs are composed of two parts (Heitz, 2014; Luce, 1986; Pachella, 1974; Schouten & Bekker, 1967; Wickelgren, 1977). As time progresses after stimulus presentation, performance remains at chance until some duration at which it abruptly deviates from chance to reach an asymptotic performance with a time course approximated by exponential decay (see Figure 5). In our experiments, we used super-threshold stimuli in order to avoid confusing the slope of the SATF with its asymptote; however, Figure 7 clearly shows the buildup of the entire psychometric function with response times. Accumulation-to-threshold decisional models (Gold & Shadlen, 2001; Luce, 1986; Ratcliff & Rouder, 1998; Vickers, 1979) are convenient to interpret the parameters of the SATFs. In these frameworks, the residual latency is accounted for by nondecisional components of the response time (afferent/sensory and efferent/motor) and the slope is accounted for by an accumulation rate (signal-to-noise ratio) within the decisional process.

Only after the decision variable has grown sufficiently does the subject initiate a response. Accordingly, a

change in signal strength, or the system's ability to measure the signal, could affect both the initial visual processing latency and the accumulation rate. However, we found that the accumulation rate was generally more sensitive to stimulus manipulations than was the latency.

Conclusion

Perceiving slant from stereopsis is not slow or unreliable for display durations less than a few seconds, or inherently temporally limited by inefficiency of the stereoscopic system. Instead, we found very reliably that observers started being able to discriminate slants 200 ms after presentation, comparable to the time required for behavioral discrimination using other visual features such as slant from texture (Experiment 1), luminance or relative disparity (Caziot et al., 2015), color (Salinas et al., 2010; Stanford, Shankar, Massoglia, Costello, & Salinas, 2010), orientations (Carrasco et al., 2003), line lengths (Schouten & Bekker, 1967), letters (Dambacher & Hübner, 2013; Heitz & Engle, 2007), or object categories (Rousselet, Fabre-Thorpe, & Thorpe, 2002). Depending on the conditions, observers reached near 100% correct performance as early as 350 ms, and usually no later than 500 ms. Different disparity signals (HSR, VSR, HSh, slant contrast) had measurably different time courses, but all were fast. Because sensory cue combination is often near optimal (Backus & Banks, 1999; Clark & Yuille, 1990; Ernst & Banks, 2002; Hillis et al., 2004; Jacobs, 1999; Landy, Maloney, Johnston, & Young, 1995) it is highly probable that stereopsis contributes meaningfully and importantly to perceived slant in everyday situations.

Keywords: binocular vision, stereopsis, slant, dynamics, time course

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References

- Allison, R. S., & Howard, I. P. (2000). Temporal dependencies on resolving monocular and binocular cue conflict in slant perception. *Vision Research*, *40*, 1869–1886.
- Allison, R. S., Howard, I. P., Rogers, B. J., & Bridge, H. (1998). Temporal aspects of slant and inclination perception. *Perception*, *27*, 1287–1304.
- Allison, R. S., Rogers, B. J., & Bradshaw, M. F. (2003). Geometric and induced effects in binocular stereopsis and motion parallax. *Vision Research*, *43*, 1879–1893.
- Ames, A., Jr. (1946). Binocular vision as affected by relations between uniocular stimulus-patterns in commonplace environments. *American Journal of Psychology*, *59*, 333–357.
- Backus, B. T. (2002). Perceptual metamers in stereoscopic vision. In T. G. Dietterich, S. Becker, & Z. Ghahramani (Eds.), *Advances in neural information processing systems 14: Proceedings of the 2001 conference* (Vol. 2, pp. 1223–1230). Cambridge, MA: MIT Press.
- Backus, B. T. (2009). The mixture of Bernoulli experts: A theory to quantify reliance on cues in dichotomous perceptual decisions. *Journal of Vision*, *9*(1):6, 1–6, doi:10.1167/9.1.6. [PubMed] [Article]
- Backus, B. T., & Banks, M. S. (1999). Estimator reliability and distance scaling in stereoscopic slant perception. *Perception*, *28*(2), 217–242.
- Backus, B. T., Banks, M. S., van Ee, R., & Crowell, J. A. (1999). Horizontal and vertical disparity, eye position, and stereoscopic slant perception. *Vision Research*, *39*, 1143–1170.
- Backus, B. T., & Matza-Brown, D. (2003). The contribution of vergence change to the measurement of relative disparity. *Journal of Vision*, *3*(11):8, 737–750, doi:10.1167/3.11.8. [PubMed] [Article]
- Banks, M. S., & Backus, B. T. (1997). Extra-retinal and perspective cues cause the small range of the induced effect. *Vision Research*, *38*(2), 187–194.
- Banks, M. S., Hooge, I. T. C., & Backus, B. T. (2001). Perceiving slant about a horizontal axis from stereopsis. *Journal of Vision*, *1*(2):1, 55–79, doi:10.1167/1.2.1. [PubMed] [Article]
- Blakemore, C. (1970). The range and scope of binocular depth discrimination in man. *Journal of Physiology*, *221*, 599–622.
- Bradshaw, M. F., Hibbard, P. B., & Gillam, B. (2002). Perceptual latencies to discriminate surface orientation in stereopsis. *Perception & Psychophysics*, *64*(1), 32–40.
- Bradshaw, M. F., & Rogers, B. J. (1999). Sensitivity to horizontal and vertical corrugations defined by

Allison, R. S., & Howard, I. P. (2000). Temporal

- binocular disparity. *Vision Research*, *39*, 3049–3056.
- Brookes, A., & Stevens, K. A. (1989). The analogy between stereo depth and brightness. *Perception*, *18*, 601–614.
- Cagenello, R., & Rogers, B. J. (1993). Anisotropies in the perception of stereoscopic surfaces: The role of orientation disparity. *Vision Research*, *33*(16), 2189–2201.
- Carrasco, M., McElree, B., Denisova, K., & Giordano, A. M. (2003). Speed of visual processing increases with eccentricity. *Nature Neuroscience*, *6*(7), 699–700.
- Caziot, B., Valsecchi, M., Gegenfurtner, K. R., & Backus, B. T. (2015). Fast perception of binocular disparity. *Journal of Experimental Psychology: Human Perception and Performance*, *41*, 909–916.
- Chopin, A., Levi, D., Knill, D., & Bavelier, D. (2016). The absolute disparity anomaly and the mechanism of relative disparities. *Journal of Vision*, *16*(8):2, 1–17, doi:10.1167/16.8.2. [PubMed] [Article]
- Clark, J. J., & Yuille, A. L. (1990). *Data fusion for sensory information processing systems*. New York: Springer.
- Dambacher, M., & Hübner, R. (2013). Investigating the speed–accuracy trade-off: Better use deadlines or response signals? *Behavioural Research*, *45*, 702–717.
- Ernst, M. O., & Banks, M. S. (2002). Humans integrate visual and haptic information in a statistically optimal fashion. *Nature*, *415*(6870), 429–433.
- Friedenwald, H. (1892). Binocular metamorphopsia produced by correcting glasses. *Archives of Ophthalmology*, *21*, 204–212.
- Fukuda, K., Kaneko, H., & Matsumiya, K. (2006). Vertical-size disparities are temporally integrated for slant perception. *Vision Research*, *46*, 2749–2756.
- Gårding, J. (1992). Shape from texture for smooth curved surfaces in perspective projection. *Journal of Mathematical Imaging and Vision*, *2*, 327–350.
- Gårding, J., Porrill, J., Mayhew, J. E. W., & Frisby, J. P. (1995). Stereopsis, vertical disparity and relief transformations. *Vision Research*, *35*(5), 703–722.
- Gibson, J. J. (1950). The perception of visual surfaces. *American Journal of Psychology*, *63*, 367–384.
- Gillam, B. (1968). Perception of slant when perspective and stereopsis conflict: Experiments with aniseikonic lenses. *Journal of Experimental Psychology*, *78*(2), 299–305.
- Gillam, B., Chambers, D., & Lawergren, B. (1988). The role of vertical disparity in the scaling of stereoscopic depth perception: An empirical and theoretical study. *Perception & Psychophysics*, *44*(5), 473–483.
- Gillam, B., Chambers, D., & Russo, T. (1988). Postfusional latency in stereoscopic slant perception and the primitives of stereopsis. *Journal of Experimental Psychology: Human Perception and Performance*, *14*(2), 163–175.
- Gillam, B., Flagg, T., & Finlay, D. (1984). Evidence for disparity change as the primary stimulus for stereoscopic processing. *Perception & Psychophysics*, *36*(6), 559–564.
- Gillam, B., & Lawergren, B. (1983). The induced effect, vertical disparity, and stereoscopic theory. *Perception & Psychophysics*, *34*(2), 121–130.
- Gillam, B., & Ryan, C. (1992). Perspective, orientation disparity, and anisotropy in stereoscopic slant perception. *Perception*, *21*, 427–439.
- Gold, J. I., & Shadlen, M. N. (2001). Neural computations that underlie decisions about sensory stimuli. *TRENDS in Cognitive Sciences*, *5*(1), 10–16.
- Goodale, M. A., & Milner, A. D. (1992). Separate visual pathways for perception and action. *Trends in Neurosciences*, *15*(1), 20–25.
- Green, J. (1889). On certain stereoscopical illusions evoked by prismatic and cylindrical spectacle-glasses. *Transactions of the American Ophthalmological Society*, *5*, 449–456.
- Greenwald, H. S., & Knill, D. C. (2009). A comparison of visuomotor cue integration strategies for object placement and prehension. *Visual Neuroscience*, *26*, 63–72.
- Greenwald, H. S., Knill, D. C., & Saunders, J. A. (2005). Integrating visual cues for motor control: A matter of time. *Vision Research*, *45*, 1975–1989.
- Heitz, R. P. (2014). The speed-accuracy tradeoff: History, physiology, methodology, and behavior. *Frontiers in Neuroscience*, *8*:150, 1–19.
- Heitz, R. P., & Engle, R. W. (2007). Focusing the spotlight: Individual differences in visual attention control. *Journal of Experimental Psychology: General*, *136*(2), 217–240.
- Hibbard, P. B., Bradshaw, M. F., Langley, K., & Rogers, B. J. (2002). The stereoscopic anisotropy: Individual differences and underlying mechanisms. *Journal of Experimental Psychology: Human Perception and Performance*, *28*(2), 469–476.
- Hibbard, P. B., & Langley, K. (1998). Plaid slant and inclination thresholds can be predicted from components. *Vision Research*, *38*(8), 1073–1084.
- Hillis, J. M., Watt, S. J., Landy, M. S., & Banks, M. S.

- (2004). Slant from texture and disparity cues: Optimal cue combination. *Journal of Vision*, 4(12): 1, 967–992, doi:10.1167/4.12.1. [PubMed] [Article]
- Jacobs, R. A. (1999). Optimal integration of texture and motion cues to depth. *Vision Research*, 39(21), 3621–3629.
- Kane, D., Guan, P., & Banks, M. S. (2014). The limits of human stereopsis in space and time. *The Journal of Neuroscience*, 34(4), 1397–1408.
- Knill, D. C. (1998a). Discriminating surface slant from texture: Comparing human and ideal observers. *Vision Research*, 38, 1683–1711.
- Knill, D. C. (1998b). Surface orientation from texture: Ideal observers, generic observers, and the information content of texture cues. *Vision Research*, 38, 1655–1682.
- Landy, M. S., Maloney, L. T., Johnston, E. B., & Young, M. (1995). Measurement and modeling of depth cue combination: In defense of weak fusion. *Vision Research*, 35(3), 389–412.
- Lippincott, J. A. (1889). On the binocular metamorphosis produced by correcting glasses. *Archives of Ophthalmology*, 18, 18–30.
- Lippincott, J. A. (1917). On the binocular metamorphosis produced by optical means. *Archives of Ophthalmology*, 46, 397–426.
- Luce, R. D. (1986). *Response times: Their role in inferring elementary mental organization* (Vol. 8). New York: Oxford University Press.
- Mamassian, P. (1997). Prehension of objects oriented in three-dimensional space. *Experimental Brain Research*, 114, 235–245.
- Marr, D. (1982). *Vision*. Cambridge, MA: The MIT Press.
- Mayhew, J. E. W., & Longuet-Higgins, H. C. (1982). A computational model of binocular depth perception. *Nature*, 297, 376–378.
- Mitchison, G. J., & McKee, S. P. (1990). Mechanisms underlying the anisotropy of stereoscopic tilt perception. *Vision Research*, 30(11), 1781–1791.
- Murphy, A. P., Ban, H., & Welchman, A. E. (2013). Integration of texture and disparity cues to surface slant in dorsal visual cortex. *Journal of Neurophysiology*, 110, 190–203.
- Nguyenkim, J. D., & DeAngelis, G. C. (2003). Disparity-based coding of three-dimensional surface orientation by macaque middle temporal neurons. *The Journal of Neuroscience*, 23(18), 7117–7128.
- Nienborg, H., Bridge, H., Parker, A. J., & Cumming, B. G. (2005). Neuronal computation of disparity in V1 limits temporal resolution for detecting disparity modulation. *The Journal of Neuroscience*, 25(44), 10207–10219.
- Ogle, K. N. (1938). Induced size effect: I. A new phenomenon in binocular space perception associated with the relative sizes of the images of the two eyes. *Archives of Ophthalmology*, 20(4), 604–623.
- Ogle, K. N. (1950). *Research in binocular vision*. Philadelphia, PA: Saunders.
- Orban, G. A. (2011). The extraction of 3D shape in the visual system of human and nonhuman primates. *The Annual Review of Neuroscience*, 34, 361–388.
- Pachella, R. G. (1974). The interpretation of reaction time in information-processing research. In B. H. Kantowitz (Ed.), *Human information processing: Tutorials in performance and recognition* (pp. 41–82). Oxford, UK: Erlbaum.
- Ratcliff, R., & Rouder, J. N. (1998). Modeling response times for two-choice decisions. *Psychological Science*, 9(5), 347–356.
- Rogers, B. J., & Bradshaw, M. F. (1993). Vertical disparities, differential perspective and binocular stereopsis. *Nature*, 361(6409), 253–244.
- Rogers, B. J., & Graham, M. E. (1983). Anisotropies in the perception of three-dimensional surfaces. *Science*, 221(4618), 1409–1411.
- Rosenberg, A., Cowan, N. J., & Angelaki, D. E. (2013). The visual representation of 3D object orientation in parietal cortex. *The Journal of Neuroscience*, 33(49), 19352–19361.
- Rousselet, G. A., Fabre-Thorpe, M., & Thorpe, S. J. (2002). Parallel processing in high-level categorization of natural images. *Nature Neuroscience*, 5(7), 629–630.
- Salinas, E., Shankar, S., Costello, M. G., Zhu, D., & Stanford, T. R. (2010). Waiting is the hardest part: Comparison of two computational strategies for performing a compelled-response task. *Frontiers in Computational Neuroscience*, 4(153), 1–17.
- Saunders, J. A., & Backus, B. T. (2006). Perception of surface slant from oriented textures. *Journal of Vision*, 6(9):3, 882–897, doi:10.1167/6.9.3. [PubMed] [Article]
- Schouten, J. F., & Bekker, J. A. M. (1967). Reaction time and accuracy. *Acta Psychologica*, 27, 143–153.
- Stanford, T. R., Shankar, S., Massoglia, D. P., Costello, M. G., & Salinas, E. (2010). Perceptual decision making in less than 30 milliseconds. *Nature Neuroscience*, 13(3), 379–386.
- Stevens, K. A. (1980). *Surface Perception from Local Analysis of Texture and Contour* (Technical Report No. AI-TR-512). Cambridge, MA: Computer Science and Artificial Intelligence Lab, MIT.

- Stevens, K. A., & Brookes, A. (1988). Integrating stereopsis with monocular interpretations of planar surfaces. *Vision Research*, *28*, 371–386.
- Taira, M., Tsutsui, K.-I., Jiang, M., Yara, K., & Sakata, H. (2000). Parietal neurons represent surface orientation from the gradient of binocular disparity. *Journal of Neurophysiology*, *83*(5), 3140–3146.
- Tsutsui, K.-I., Sakata, H., Naganuma, T., & Taira, M. (2002). Neural correlates for perception of 3D surface orientation from texture gradient. *Science*, *298*, 409–412.
- van Ee, R., Banks, M. S., & Backus, B. T. (1999). An analysis of binocular slant contrast. *Perception*, *28*(9), 1121–1145.
- van Ee, R., & Erkelens, C. J. (1995). Binocular perception of slant about oblique axes relative to a visual frame of reference. *Perception*, *24*, 299–314.
- van Ee, R., & Erkelens, C. J. (1996). Temporal aspects of binocular slant perception. *Vision Research*, *36*(1), 43–51.
- van Ee, R., & Erkelens, C. J. (1998). Temporal aspects of stereoscopic slant estimation: An evaluation and extension of Howard and Kaneko's theory. *Vision Research*, *38*, 3871–3882.
- van Mierlo, C. M., Louw, S., Smeets, J. B. J., & Brenner, E. (2009). Slant cues are processed with different latencies for the online control of movement. *Journal of Vision*, *9*(3):25, 1–8. [PubMed] [Article]
- Velisavljevic, L., & Elder, J. H. (2006). Texture properties affecting the accuracy of surface attitude judgments. *Vision Research*, *46*, 2166–2191.
- Vickers, D. (1979). *Decision processes in visual perception*. London, UK: Academic Press Inc.
- Watt, S. J., Akeley, K., Ernst, M. O., & Banks, M. S. (2005). Focus cues affect perceived depth. *Journal of Vision*, *5*(10):7, 1–29, doi:10.1167/5.10.7. [PubMed] [Article]
- Wickelgren, W. A. (1977). Speed–accuracy tradeoff and information processing dynamics. *Acta Psychologica*, *41*, 67–85.
- Witkin, A. P. (1981). Recovering surface shape and orientation from texture. *Artificial Intelligence*, *17*, 17–45.