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Perceptual learning without feedback and the stability of stereoscopic slant estimation

Raymond van Ee
Vision Science Program, University of California at Berkeley, Berkeley, CA 94720, USA;
and ¶ Helmholtz Institute, University of Utrecht, Princetonplein 5, 3584 CC Utrecht, The Netherlands;
e-mail: r.vanee@phys.uu.nl
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Abstract. Subjects were examined for practice effects in a stereoscopic slant-estimation task involving surfaces that comprised a large portion of the visual field. In most subjects slant estimation was significantly affected by practice, but only when an isolated surface (an absolute disparity gradient) was present in the visual field. When a second, unslanted, surface was visible (providing a second disparity gradient and thereby also a relative disparity gradient) none of the subjects exhibited practice effects. Apparently, stereoscopic slant estimation is more robust or stable over time in the presence of a second surface than in its absence. In order to relate the practice effects, which occurred without feedback, to perceptual learning, results are interpreted within a cue-interaction framework. In this paradigm the contribution of a cue depends on its reliability. It is suggested that normally absolute disparity gradients contribute relatively little to perceived slant and that subjects learn to increase this contribution by utilizing proprioceptive information. It is argued that—given the limited computational power of the brain—a relatively small contribution of absolute disparity gradients in perceived slant enhances the stability of stereoscopic slant perception.

1 Introduction

It is now well established that several monocular and binocular signals are involved in stereoscopically perceived surface orientation. Depending on the viewing situation, some of the signals are more reliable than others. Perceived surface orientation needs to be robust against unreliable signals. In this paper, perceptual learning[(1)] in the estimation of the orientation of large surfaces—which comprise a large portion of the visual field—is studied. On the basis of the experimental results—and with the help of findings in the literature—it is hypothesized that perceptual learning in perceived surface orientation can be regarded as a manifestation of changes in the reliabilities of conflicting cues. The experimental results are related to the stability of stereoscopic slant perception.

1.1 *Metrical aspects of stereoscopic vision*

Stereoscopic vision is often considered to be an important provider of (frequently inaccurately perceived) metrical aspects in the 3-D layout of our environment. Little is known about perceptual learning relating to metrical aspects of stereoscopic vision. Most studies relating to perceptual learning in stereoscopic vision have been devoted

¶ Address to which all correspondence and requests for reprints should be sent.

[(1)] Generally, knowledge about perceptual learning helps to develop hypotheses about the underlying mechanisms of percept construction in vision (Poggio et al 1992); learning demonstrates plasticity in the processing of the signals (Fiorentini and Berardi 1980). Bedford (1993, page 5) defined perceptual learning as follows: “The general function of perceptual learning is to improve sensory systems, which is particularly important if there is malfunction. The processes responsible for perceptual learning do not represent new information from the environment external to the organism. ... Perceptual learning can be observed if, as a result of experience, the same proximal stimulus leads to a new percept.” In the case of vision, perceptual learning will manifest itself by changes in what is actually seen as a result of practice. Note that, according to the definition, finding an effect of practice does not necessarily mean that perceptual learning has occurred.

to the improvements in perceiving relative distance (eg Fendick and Westheimer 1983; Kumar and Glaser 1993; Fahle et al 1995) or in recognizing shape (eg Ramachandran 1976; Bradshaw et al 1995). These studies involved non-metrical aspects of stereoscopic vision requiring only depth ordering. They cannot, therefore, be used to estimate changes in metrical aspects of perceived depth as a result of perceptual learning. The estimation of stereoscopically perceived surface orientation is a metrical task. In this study this task is examined when subjects have not been provided with any feedback about their performance.

Before we proceed, it is helpful to review a number of issues that play a relevant role in stereoscopically perceived surface orientation.

1.2 *Stereoscopic surface slant and disparity gradient*

The orientation of a surface is specified by the term slant. Slant is the angle between the surface and a reference. A surface that is slanted about the vertical axis creates a horizontal disparity gradient: the horizontal visual angle subtended by the left eye's view of the surface is different from the visual angle subtended by the right eye's view. Observers' performance can be quite impressive when the disparity gradient is the only available signal for slant: practiced observers are able to detect a change in perceived slant with a standard deviation in disparity gradient of about 7 s of arc per degree of visual angle (Ogle 1938; Backus and Banks 1999; Backus et al 1999).

Generally, an isolated disparity gradient (in otherwise completely dark surroundings) is an ambiguous signal for slant relative to the head (Helmholtz 1867/1962). For example, the gradient created by a frontoparallel planar stimulus that is presented straight ahead is identical to the horizontal disparity gradient of the same plane presented eccentrically with a different slant (Ebenholtz and Paap 1973; Gillam and Lawergren 1983; Backus et al 1999). This is illustrated in figure 1. In order to interpret an isolated disparity gradient for slant relative to the head, one must compensate for the position of the surface patch relative to the head. Signals about eye posture and several disparity types make this compensation possible (eg Mayhew and Longuet-Higgins 1982; Porrill et al 1990; Rogers and Bradshaw 1995; Banks and Backus 1998; Erkelens and van Ee 1998; Backus et al 1999).

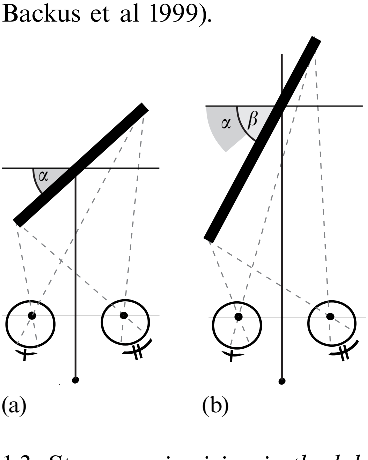

Figure 1. The horizontal disparity gradients are identical in panels (a) and (b). (a) Because the plane is slanted with the right side away from the observer, the retinal angle subtended in the right eye is larger than in the left eye. (b) In order to interpret a disparity gradient one needs to compensate for the location of the surface relative to the head.

1.3 *Stereoscopic vision in the laboratory*

If an observer knows the location of a slanted surface, then, theoretically, the disparity gradient contains all the information that she or he needs for correct slant estimation. However, even when the viewing conditions are well specified, slant estimates measured in the laboratory are often not in accordance with geometrical prediction. Artificially induced disparity gradients involve conflicting stereoscopic and monocular slant cues (Banks and Backus 1998). In each image of a stereogram, monocular cues indicate that the surface is parallel to the image plane. However, the disparity cues indicate that the surface is slanted. Thus, the different cues provide different estimates of surface slant.

When stereoscopic and monocular cues do not agree, estimated slant is usually considerably attenuated relative to slant predicted on the basis of the disparity gradient (Gillam et al 1984, 1988; Stevens and Brookes 1987, 1988; Collewijn et al 1991; Howard and Kaneko 1994; van Ee and Erkelens 1998; Allison et al 1998). Van Ee et al (1999) estimated the weight assigned to both the stereoscopic and non-stereoscopic slant estimates. In their experimental setup—where they used a cross-hatched pattern subtending roughly 40 deg $\times$ 40 deg that provided strong perspective signals—they found that the relative weight attached to the stereoscopic slant estimate was only of the order of 4% and 25% for a distance of 570 cm and 38 cm, respectively; the slant estimates were determined mainly by monocular cues. Obviously, the weight assigned to the slant estimates will depend upon the stimulus used. In general, however, the visual system can be said to be relatively insensitive to slant estimates based on an isolated disparity gradient and to be sensitive to slant estimates that are based on monocular cues. Note that when monocular cues are made uninformative (Backus et al 1999) or when care is taken to make them agree (as far as possible) with stereoscopic cues (van Ee et al 1999) stereoscopic slant perception is precise and accurate.

Usually, the presence of conflicting monocular cues is an unfortunate feature of a stereogram. In the present study, however, this feature is used to examine perceptual learning: given that, generally, we do not perceive two different slants of a single surface at the same time, somehow the conflicting cues are integrated into a single slant estimate. This integration might change over time with learning. Consider first in more detail which cues are available to a subject who wishes to estimate the slant of a static surface that is presented by means of a stereogram on a projection screen. The cues are divided into non-stereoscopic cues and stereoscopic cues. The analysis will be restricted to the integration of cues that are relevant in the experiment.

The relevant conflicting non-stereoscopic cues include accommodation of the eye's lens (Gogel and Sturm 1972; Fisher and Ciuffreda 1988), brightness (Dosher et al 1986), perspective cues from foreshortening of the elements in the display (Stevens 1981) as well as foreshortening of the outline of the depicted shape (Kumar and Glaser 1992), and, finally, texture cues from the shapes, sizes, and densities of the elements in the display (eg Cutting and Millard 1984; Turner et al 1991). These cues are said to be conflicting because they indicate that the slant of the plane is zero whereas the disparity gradient indicates a certain slant.[(2)]

We have already considered the disparity gradient as a binocular cue for perceived slant. The presence of a second surface can be considered an important additional visual cue. Gillam and colleagues were the first to show systematically that a second frontal surface has a facilitating effect on stereoscopic slant perception. Perceived slant in the presence of the second surface develops faster and is closer to the slant predicted from geometrical considerations than perceived slant in the absence of a second surface (Gillam et al 1984, 1988; van Ee and Erkelens 1996b). With a second frontal surface present, the display contains more stereoscopic information about the relative slant of the two surfaces because additional relative disparity (Gillam et al 1984; Erkelens and Collewijn 1985b) and an additional disparity gradient (Gillam et al 1988; Gillam and Blackburn 1998; van Ee et al 1999) are present.

[(2)] The integration of disparity and changing accommodation (Grant 1942; Gogel 1972), brightness (Dosher et al 1986), texture cues (Cumming et al 1993; Johnston et al 1993; Frisby et al 1995), and perspective cues (Gillam 1968; Youngs 1976; Gillam and Ryan 1992; Ryan and Gillam 1994; Banks and Backus 1998; van Ee et al 1999) has been described elsewhere. In those experiments the strength of the nonstereo cues was varied in order to investigate the perceptual influence of the counter-cues relative to the stereo cue.

Experimental conditions in which there is an isolated disparity gradient will be referred to as 'without-reference' conditions, whereas 'with-reference' conditions indicate that an additional visual stimulus (like a second surface) is present.

1.4 *Motivation for the present study*

In summary, both stereoscopic and non-stereoscopic slant estimates are involved in stereoscopically perceived slant. Some of the slant estimates are more reliable than others. From an evolutionary point of view, it is sensible to assume that the brain relies most on slant estimates that can be processed in a simple and accurate way, and that slant perception in signal-conflict situations is based on a combination of slant estimates in which the most reliable or stable ones are given most weight (Maloney and Landy 1989; Young et al 1993; Landy et al 1995). An interesting question is: how plastic is the assignment of the reliability of a slant estimate? A perceptual learning experiment informs us about the relative robustness and stability of slant estimates over time.

So far there have been no systematic experiments concerning the effect of perceptual learning in stereoscopically estimated slant. Van Ee (1995) ran a preliminary experiment that consisted of repetitive slant-estimation sessions. He studied perceived slant as a function of presentation duration in stereograms subtending 70 deg × 70 deg. The subject had to perform the same slant estimation session three times. There was a one-month interval between the three sessions. Figure 2 shows the results of his study. He found that estimation of slant in the absence of a visual reference was affected considerably more by practice than estimation of slant in the presence of a visual reference (the visual reference consisted of a transparent zero-slant stimulus like the one depicted in figure 3). As shown in figure 2, the effect of practice was most pronounced for short observation periods. Figure 2 makes it clear that it is not a ceiling effect that is responsible for the finding that only the without-reference condition shows an effect of practice; the perceived slants in the with-reference condition are greatly underestimated, but there is no reason why these estimates could not improve over time. Moreover, slant estimations increased considerably after feedback (van Ee 1995).

Van Ee et al (1996) determined how much practice was necessary to show an effect; there were considerable differences between subjects, and a few subjects did not show

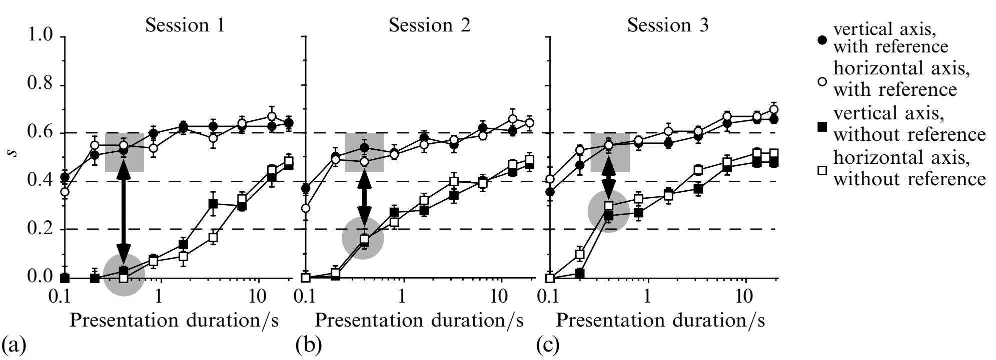

Figure 2. Estimated slant as a fraction of predicted slant (s) of large stereoscopically defined surfaces versus the presentation duration in the study by van Ee (1995). The subject (JZ) had to perform the same slant-estimation session three times [in the order: panels (a), (b), and (c)]. There was a one-month interval between the three sessions. No feedback was given during the experiment. Slants were about the horizontal as well as about the vertical axis. Slant estimation in the absence of a visual reference is affected significantly more by practice than slant estimation in the presence of a reference. This effect is very pronounced for an observation period of 400 ms (at the arrow). The estimated slant remains approximately constant across the three sessions in the with-reference condition (gray square patches) but increases significantly over the three sessions in the without-reference condition (gray circular patches). Each data point is based on 49 slant judgments. Error bars indicate standard deviations.

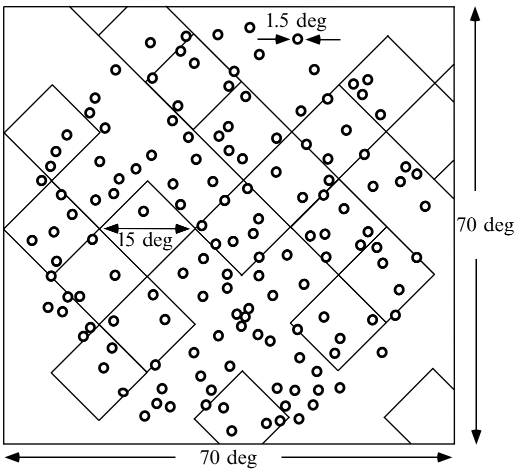

Figure 3. A schematic illustration of the stimulus. The pattern of circles (diameter 65 deg) contained a disparity gradient and was perceived as a slanted surface. The density of the small circles was such that they covered about 10% of the stereogram. Each circle had a diameter of 1.5 deg. The cross-hatched pattern was shown in the with-reference conditions. It was always projected binocularly, with zero slant. The diagonals of the individual squares were 15 deg. To prevent wallpaper effects (fixation on false depth planes) the pattern was made irregular; not every possible square was shown (approximately six out of ten). Each trial consisted of a different, randomly chosen configuration of circles and squares.

any practice effect even after several thousands of trials. Interestingly, in both studies consistent and significant effects of practice were found in the absence of feedback. These studies were not completely systematic in that the various subjects were subjected to different experimental procedures and different numbers of trials.

In the present study, practice effects in stereoscopic slant estimation were examined in nine subjects systematically: each subject had to perform the same slant-estimation session on three occasions at one-week intervals. The non-stereoscopic cue was kept constant throughout the experiment, but the slant indicated by the stereoscopic cue was varied. Findings are interpreted within the framework of a cue-interaction paradigm in which the contribution (or weight) of a cue depends on the reliability of the signal—as estimated by the subject—that is associated with the cue (Maloney and Landy 1989; Young et al 1993; Landy et al 1995). The paradigm of these authors did not explicitly relate reliability-based re-weighting to perceptual learning. In this paper the re-weighting paradigm is extended to include re-weighting with practice.

Here it is proposed that subjects follow a learning strategy that results in a greater contribution of the absolute disparity gradient in perceived slant, despite the fact that the quality of stereoscopic information relative to non-stereoscopic information within a given display did not change (see also section 5).

2 Methods

2.1 *Apparatus*

The apparatus has been described previously (van Ee and Erkelens 1996b). Subjects sat in front of a screen subtending 70 deg × 70 deg. Viewing distance was 1.5 m. Head movements were restricted by a chin-rest. The images were presented by means of an anaglyphic (red – green) stereogram that was back-projected onto the screen. The left and right images of the stereogram were presented in each trial afresh at 70 Hz. Subjects viewed the images through filters matched to the emission spectra of the red and green phosphors of the TV; no crosstalk was observed. The relative brightness of the red and green half-images was adjusted to look equally bright when viewed through the glasses. This was done after a 6-min dark adaptation.

2.2 *Stimuli*

The viewed stereogram was circular (about 65 deg diameter). The plane for which slant was estimated was rendered by sparsely distributed small circles (see figure 3). The distribution of the circles was such that they covered about 10% of the total area of the stereogram. Each circle had a diameter of 1.5 deg and a different, randomly chosen configuration of circles was presented in each trial. Data were collected in two conditions: with and without the presence of a second surface (reference) in the visual field that provided a relative disparity gradient and thereby facilitated perceived slant (Gillam et al 1984; van Ee and Erkelens 1996a; Gillam and Blackburn 1998). Without-reference data were collected in a completely dark room, nothing being visible except the stimulus. During the series of trials in which there was a visual reference, a transparent cross-hatched zero-slant pattern was projected in the plane of the screen (see figure 3). The cross-hatched pattern was made up of a field of adjacent diagonal squares with diagonals of 15 deg. This pattern was changed randomly every time a new stimulus appeared. To prevent wallpaper effects (fixation on false depth planes), only six out of every ten squares were shown. With-reference data were collected in a dimly lit room, which to a large extent reduced depth contrast (Werner 1938) and prevented the reference pattern from being perceived as slanted.

A range of slant angles was presented so that subjects were encouraged to make use of the magnitude of the stereoscopic slant cue. Otherwise, subjects could have based their responses solely on the sign of the slant. In that case, the data might have shown no effect of learning, even though perceived slant was changing. The slants that were presented were randomly chosen from the following set: $\{-64^\circ, -54^\circ, -35^\circ, 0^\circ, 35^\circ, 54^\circ, 64^\circ\}$.[(3)] Positive slants are defined as right side away in the case of slant about the vertical axis (figure 1) and lower edge away in the case of slant about the horizontal axis.

Non-stereoscopic cues were weakened by using no horizontal and vertical line elements, because rectangular shapes can act as perspective cues; these might counteract too strongly the slant evoked by disparity. The outline of the stimuli was circular with irregular boundaries, and the density of pattern elements was kept low to minimize reliance on conflicting implicit configural outline-shape cues (Ryan and Gillam 1994). The use of regular circular elements makes it possible to compare the results with the results of several recent studies (Howard and Kaneko 1994; Kaneko and Howard 1996; van Ee and Erkelens 1998).

2.3 *Task*

Subjects were instructed to fixate a mark in the center of the screen before the stereogram appeared, but were free to make eye movements while viewing the stereogram (during which time the fixation mark was no longer visible). Subjects were asked to estimate the slant of the stimulus plane (consisting of the small circles) about a vertical or horizontal axis, relative to the plane of the (invisible) screen. After each trial, two binocular line segments, one fixed and one rotatable, appeared on the screen as a flat 2-D pattern (see also figure 3 in van Ee and Erkelens 1996b). The orientation of one of the segments was fixed (horizontal in the vertical-axis condition and vertical in the horizontal-axis condition) and the orientation of the other could be adjusted by moving the computer mouse. The fixed line segment represented the frontoparallel plane,

(3) The step sizes between these slant angles might look irregular. However, in previous studies, slant about the vertical axis has been specified as the percentage of horizontal magnification between two eyes' half-images, and slant about the horizontal axis as degrees of differential rotation of the vertical meridian (horizontal shear) in the two half-images (Howard and Rogers 1995; van Ee and Erkelens 1995). The chosen slant angles correspond to regular ranges of −9%, −6%, −3%, 0%, 3%, 6%, 9% magnification and −5.1, −3.4, −1.7, 0, 1.7, 3.4, 5.1 deg horizontal shear for slant about the vertical and horizontal axes, respectively.

so observers adjusted the orientation of the other segment until it indicated the inducer's perceived slant relative to the frontoparallel plane. Because the lines were displayed in the plane of the screen, they also served as a zero-slant reference between successive stimuli. All observers participated in a 28-trial training session in which they estimated the perceived slant of real planes; feedback was given during this training session. Generally, subjects do not consider this task as being unnatural, and after a short training session their slant estimates are usually surprisingly veridical [see van Ee et al (1999) who systematically measured slant estimates of real planes with this method].(4)

2.4 *Procedure*

Subjects were tested during three experimental sessions, at intervals of one week. Each session was divided into two series, separated by a 2 h break: one series for the without-reference condition, followed by one for the with-reference condition. Both the with-reference and without-reference conditions contained slant about the vertical and horizontal axes randomly intermixed. The series without a visual reference were preceded by a dark-adaptation period of 6 min. In each series, three presentation durations were used: 0.2 s, 0.8 s, and 3.2 s. Figure 2 suggests that a learning effect is most likely to occur at such durations.

Each series consisted of seven successive trial blocks. In each trial block, all trials appeared once, in random order. This random order varied across trial blocks. Each trial block consisted of 42 trials deriving from 7 slant angles ($-64°$, $-54°$, $-35°$, $0°$, $35°$, $54°$, $64°$), 2 slant axes (horizontal and vertical), and 3 presentation durations (0.2, 0.8, 3.2 s). Each series consisted of 294 (42×7 repetitions of each stimulus) trials. Each session consisted of 2 series (with-reference and without-reference conditions), resulting in 588 trials. In the complete experiment, subjects estimated a total of 1764 slants derived from 3 sessions $\times$ 588 trials.

2.5 *Subjects*

Nine subjects participated. They were checked for normal stereoscopic vision by means of partially decorrelated Julesz random-dot test images. Candidates were then tested for consistency in their responses when estimating the slants of both real and dichoptically presented planes. Subjects were never informed about the purpose of the experiment. They were inexperienced in stereoscopic experiments. Refractive anomalies were corrected by their own glasses or contact lenses; no subject showed other visual or oculomotor pathologies.

2.6 *Data analysis*

The data were analyzed in the manner described earlier (van Ee and Erkelens 1996b): estimated slant was determined as a function of geometrically predicted slant separately for each combination of subject, condition, transformation, and presentation duration (see examples in figure 4). Estimated slant as a function of geometrically predicted slant was fitted by a line. Previous work has shown that the relationship between estimated and predicted slant is approximately linear (eg van Ee and Erkelens 1996b). The slope of this line, s, represents estimated slant as a fraction of predicted slant. These s-values (each one based on 49 trials derived from 7 trial repetitions $\times$ 7 magnitudes of transformation) characterize subjects' behavior and are used for further analysis (figures 5, 6, 7, and 9). A subject who performed the task veridically (based on stereoscopic cues) would consistently exhibit s-values equal to unity. In order to assess, quantitatively, the change in s that occurred with practice, a linear regression coefficient was fitted to the s-values.

(4) Note that this result is not trivial: the settings are determined not only by the perceived slant but also by the function that maps percepts onto responses. Because we do not know the form of that mapping function, there are no grounds on which to determine what set of responses would indicate veridical percepts.

3 Results and discussion of experiment 1

As an illustration of the method of data analysis, the means of the raw estimated slants as a function of predicted slant for one subject (JN) are shown in figure 4. In this particular example, the slant axis was vertical and the presentation duration was 0.8 s. The left (right) panel of figure 4 shows results obtained in the absence (presence) of the visual reference that had zero slant. The results show, in good approximation, a linear relationship between estimated and predicted slant. The slopes of the fitted linear functions (as given in the top left of the panels of figure 4) represent the fraction of predicted slant that is estimated by the subject. These are the s-values, defined above. The lines used to fit the data (in order to find the slopes s) accounted for most of the variance between mean slant settings throughout the experiment. r^2 (obtained by a least-squares method) was always larger than 0.94 and in most cases larger than 0.98. Figure 5 shows the effect of session on estimated slant as a fraction of predicted slant (s-values) for the six subjects for an observation duration of 0.2 s. Figures 6 and 7 show the results for the observation durations 0.8 s and 3.2 s, respectively.

The lower panels (c) and (d) of figures 5, 6, and 7 show little change in estimated slant with session repetition. However, the upper panels (a) and (b) of these figures show an increase in estimated slant over session repetitions. Linear regressions—characterizing

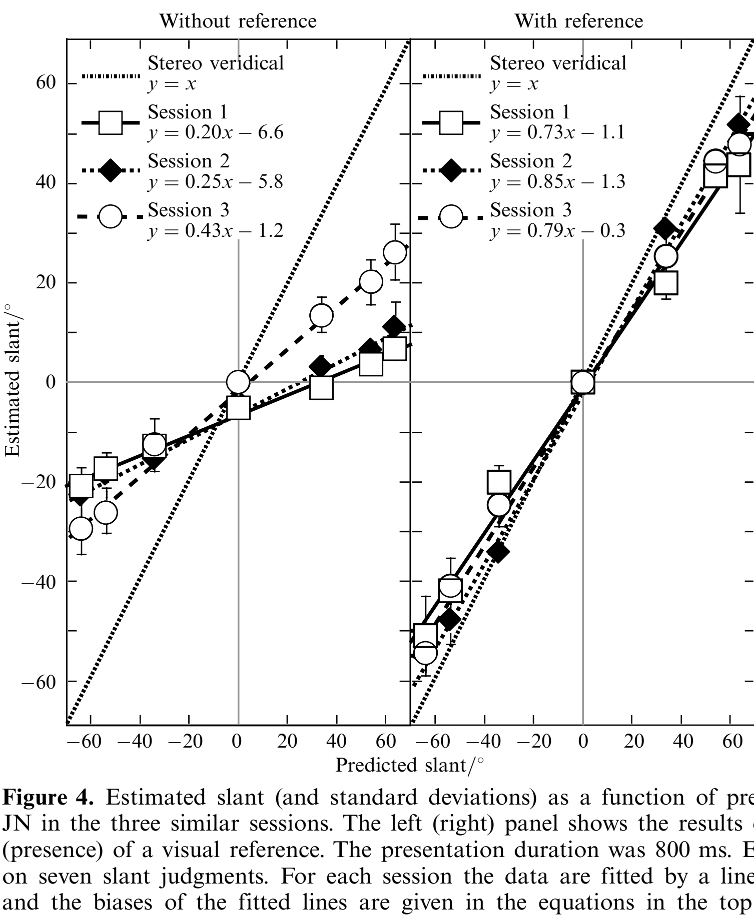

Figure 4. Estimated slant (and standard deviations) as a function of predicted slant for subject JN in the three similar sessions. The left (right) panel shows the results obtained in the absence (presence) of a visual reference. The presentation duration was 800 ms. Each data point is based on seven slant judgments. For each session the data are fitted by a linear function. The slopes and the biases of the fitted lines are given in the equations in the top left part of the panels (y denotes estimated slant, x denotes predicted slant). The slopes, in other words the s-values (see text), are essential for further data analysis. They characterize the performance of the subject. The particular s-values of the data in this figure are represented by the open square symbols in panels (a) and (c) of figure 6.

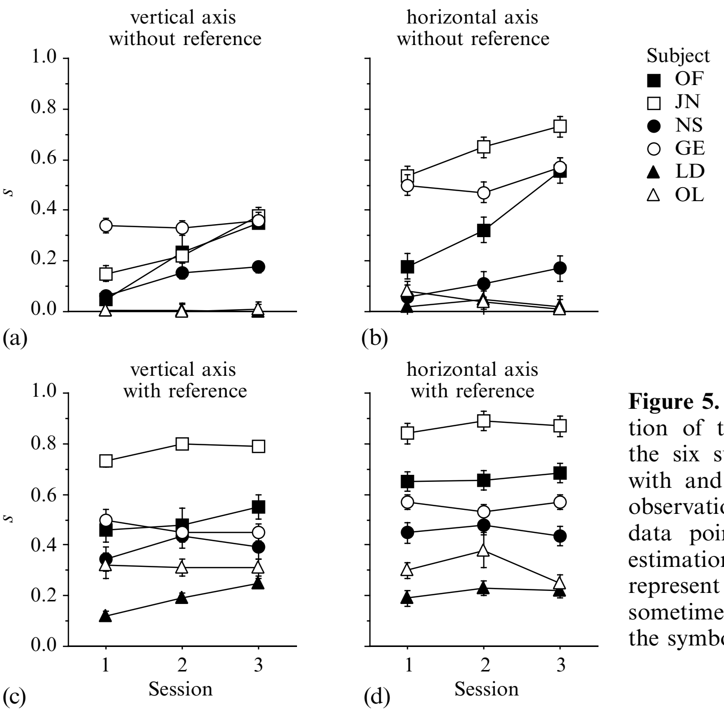

Figure 5. Estimated slant as a fraction of the slant predicted (s) by the six subjects for the conditions with and without a reference. The observation duration was 0.2 s. Each data point is based on 49 slant estimations. The error bars (which represent standard deviations) are sometimes smaller than the size of the symbol.

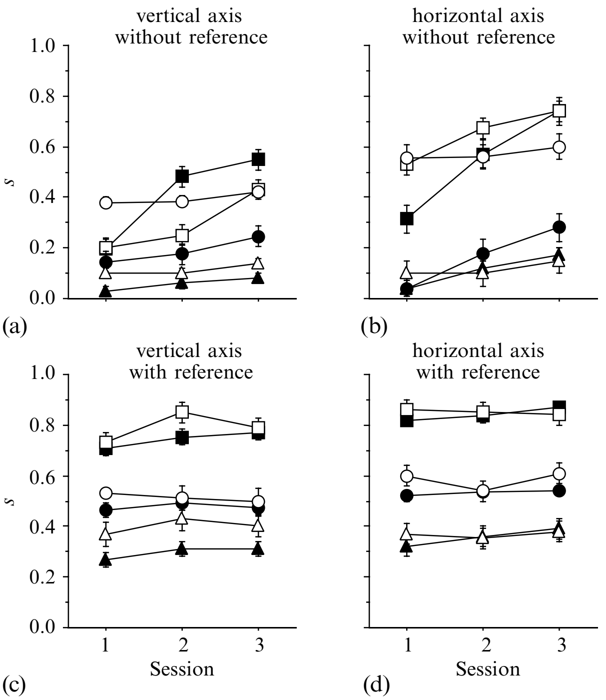

Figure 6. Same as figure 5 but for an observation duration of 0.8 s.

the change in s with practice in figures 5, 6, and 7—are plotted in figure 8 for all subjects, conditions, and presentation durations. Figure 8 shows that slant estimation without a visual reference was significantly influenced by practice in subjects OF, JN, and NS for all presentation durations. Subjects OF and JN show a large effect of practice; the marked difference between slant estimation in the presence and in the

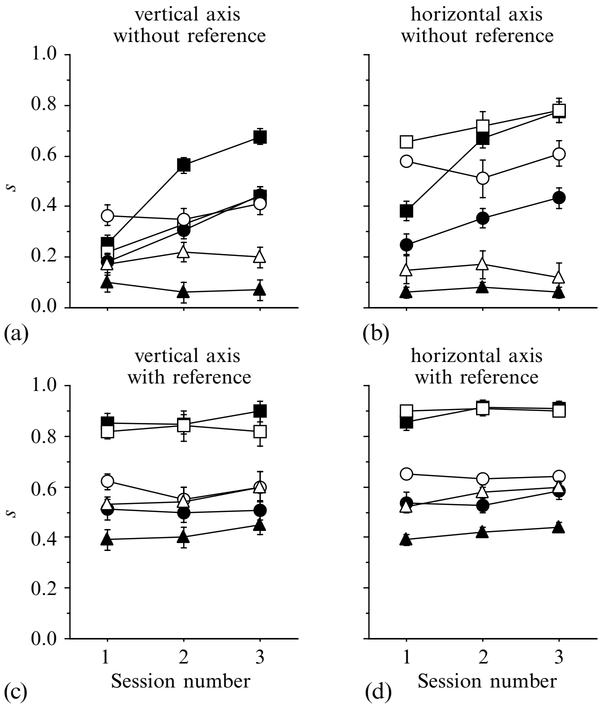

Figure 7. Same as figure 5 but for an observation duration of 3.2 s.

absence of a visual reference which existed in the first session is greatly decreased by the third session, especially for a presentation duration of 3.2 s (figure 7). Subject OF increased his estimates by a factor of about 3 from session 1 to session 3. Subject NS shows a significant effect of practice, but estimated slants in the presence of a reference remained larger than without a reference. Figure 8 shows that slant estimation in the presence of a visual reference [small panels (c) and (d)] is not significantly influenced by practice in any subject for any presentation duration.

Figure 4 might give the impression that a ceiling effect is responsible for the finding that only the without-reference condition shows a learning effect. However, in general, the perceived slants in the reference condition are greatly underestimated. Figures 2, 5, 6, and 7 show that even in the with-reference condition estimated slant is on average not much better than 50% of disparity-specified slant. There is no reason why these estimates could not increase over time. In addition, generally, estimated slant is veridical (so on average 100% larger than in our with-reference condition) when subjects view real slanted planes or when they view stereograms containing patterns in which all of the controllable stereoscopic and monocular cues indicate a slanted plane (van Ee et al 1999). In addition, van Ee (1995) showed that after feedback slant estimates increased considerably.

Comparison of figures 5, 6, and 7 shows that estimated slants increase with presentation duration. This effect is largest for subjects OL and LD in the case of slant about the vertical axis without a reference: compare the estimated slants of OL and LD for the three presentation durations [small panels (a)]. Estimated slants in the presence of a visual reference reach a higher level than estimated slant without a visual reference: compare, for instance, the slant settings of subject LD in panels (b) and (d) for the three presentation durations. Little slant is perceived in the absence of a visual reference, especially in the first session of the experiment [small panels (a) and (b) in figures 5, 6, and 7]. All of these findings are in accordance with accounts in the literature: it has been reported that the presence of a frontal visual frame of reference

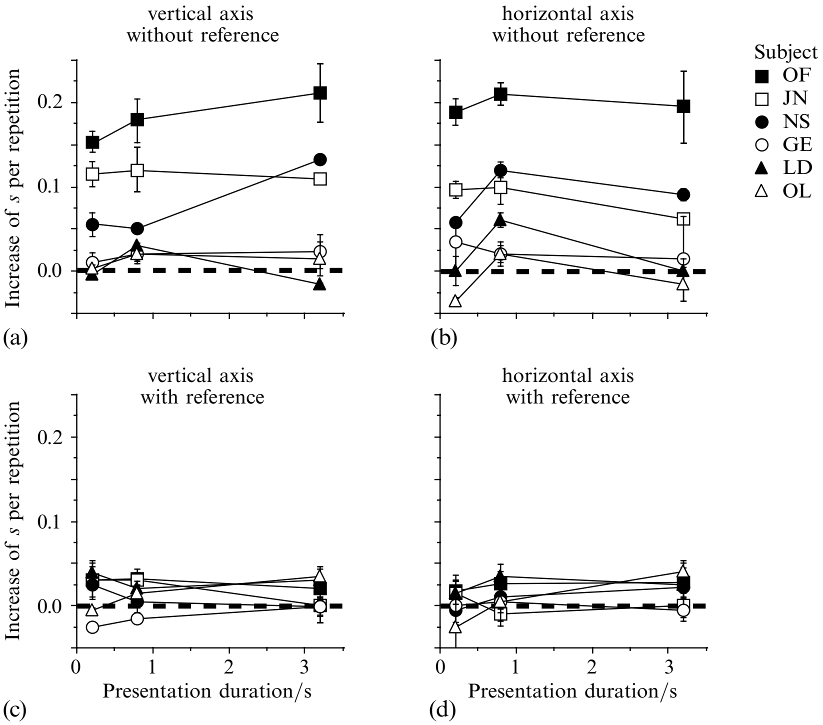

Figure 8. Change in slope values *s* (estimated slant as a fraction of predicted slant) from the first to the third session for the six subjects versus the presentation duration. Without a visual reference, the subjects OF, JN, and NS exhibit a significant increase in estimated slant per session repetition for all three presentation durations. With a reference none of the subjects exhibits a significant effect of practice for any of the presentation durations. The error bars represent the standard deviation in the slope of the linear fit to the particular individual fractions of figures 5 to 10. Occasionally, the error bar is smaller than the size of the symbol.

has a facilitating effect on perceived slant of a given stimulus (Gillam et al 1984, 1988; Stevens and Brookes 1987, 1988; Collewijn et al 1991; van Ee and Erkelens 1998) and that estimated slants in the presence of a visual reference increase faster and to a higher level than without a visual reference (Gillam et al 1984), although there is a considerable difference between subjects (van Ee et al 1996; van Ee and Erkelens 1998).

There is the possibility that subjects were able to pick up depth cues provided by the frame of the anaglyph glasses or by low-contrast features in the surrounding. However, if this were the case one would expect this help to be independent of the presentation duration. The results depicted in figure 2 are not consistent with this idea.

3.1 *Slant-axis anisotropy*

Three subjects (OF, JN, GE) showed the well-known slant-axis anisotropy: estimated slant about the horizontal axis is larger than estimated slant about the vertical axis (Wallach and Bacon 1976; Rogers and Graham 1983; Mitchison and McKee 1990; Ryan and Gillam 1994; and others). This was particularly the case without the presence of a reference [small panels (a) and (b) in the data figures]. However, the anisotropy was less apparent than expected from the cited studies and three subjects showed no anisotropy at all (see also figure 2). Howard and Kaneko (1994) and Kaneko and Howard (1996) also found similar performance in the estimation of slant about the horizontal and vertical axes. They used a stimulus with circular elements, just as we do in this paper. Using exactly the same stimulus as used in this paper, van Ee and Erkelens (1996b) also found no anisotropy in performance about the horizontal and vertical axes. This is consistent with the finding reported by Ryan and Gillam (1994). They found that the anisotropy, on average, almost vanishes for vertical irregular lines when there is a minimum cue conflict between perspective and disparity. The perspective/texture cue may have been weak enough to explain why no marked anisotropy was found.

3.2 *Response bias*

The ordering of the series within a session (first without reference, then with reference) was intended to reduce the chance of response-bias effects. A plausible explanation for the practice effect based on reliability-based re-weighting will be presented below. Nonetheless, the possibility exists that the results reflect a response bias rather than a change in visual perception. A response bias would have to be specific to the without-reference condition. The only explanation for such response-bias selectivity is that subjects were biased by the larger range of their responses in the with-reference condition in the second half of the session of the preceding week. In order to investigate the effect of response bias, the above-described experiment is repeated in experiment 2 but this time without the presence of the with-reference condition.

4 Experiment 2

In this experiment, the previous experiment was replicated but with the following differences: only slants about the vertical axis were presented and only in the without-reference condition. So, in all, subjects estimated a total of 441 slants derived from 7 slant angles ($-64°$, $-54°$, $-35°$, $0°$, $35°$, $54°$, $64°$), 7 trial repetitions per session, 3 presentation durations (0.2, 0.8, 3.2 s), and 3 sessions at one-week intervals. Three subjects, who did not take part in experiment 1, participated. The method of data analysis was the same as in experiment 1.

Figure 9 shows the effect of session on estimated slant as a fraction of predicted slant (s) for the three subjects for the three observation durations. It shows an increase in estimated slant over session repetitions, especially for the shortest presentation duration. Linear regression coefficients—characterizing the change in the above-defined s with practice—are plotted in figure 10. Whereas all of the subjects show a practice effect in experiment 2, the practice effect is somewhat smaller than in experiment 1. This difference might be due to the fact that the number of trials in experiment 2 was reduced by a factor of 4 relative to the number in experiment 1 (because there was no with-reference condition and only one slant axis), or it could simply be due to the fact that different subjects were tested in this experiment.

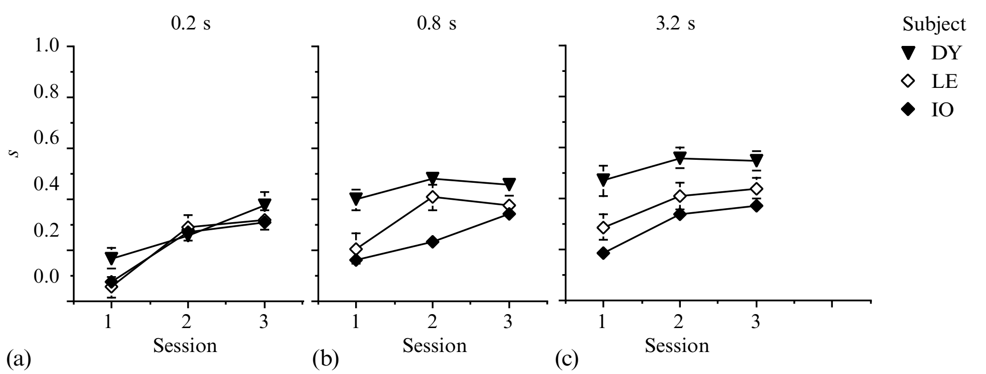

Figure 9. Estimated slant about the vertical axis as a fraction of the slant predicted (s) by the three subjects in experiment 2 in the absence of a reference. The observation duration was (a) 0.2 s, (b) 0.8 s, or (c) 3.2 s. Each data point is based on 49 slant estimations. Slants were about the vertical axis.

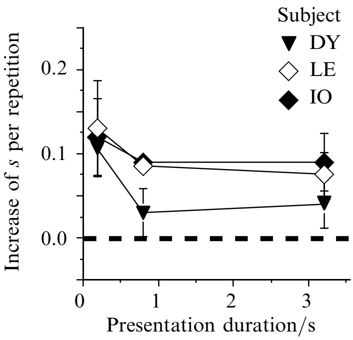

Figure 10. Change in slope values s (estimated slant as a fraction of predicted slant) from the first to the third session for the three subjects versus the presentation duration in experiment 2. All of the subjects exhibit a significant learning effect for all of the presentation durations. The error bars represent the standard deviation in the slope of the linear fit to the particular individual fractions of figure 9.

5 Discussion

Nine inexperienced subjects were examined for effects of practice in estimating the slant of a stereoscopically presented surface in the absence of feedback. Six subjects showed significant practice effects in the absence of a second surface that served as a visual reference but none of the subjects showed practice effects in the presence of the reference. As demonstrated in experiment 2, this differential practice effect is not caused by response bias. Apparently, the same visual information evoked a different percept in the course of the experiment. This means that perceptual learning has occurred. A consequence of the results is that future studies on slant perception involving isolated disparity gradients will have to take learning effects into account.

Interestingly, there was very little change in response magnitude during a session; the change in perceived slant occurred mainly between sessions. This suggests that some consolidation time is necessary for this type of learning (Karni and Sagi 1993). In support of this finding, Karni et al (1994) produced evidence that consolidation of long-term memory occurs during REM sleep. These findings are consistent with the results for subject JZ (figure 2) whose intersession period was four times as long as the intersession period for the subjects in this paper; the results for JZ were basically similar to those for the subjects in this experiment.

5.1 *Questions to be discussed*

The results of the present experiment support the preliminary measurements made by van Ee (1995) and van Ee et al (1996) which yielded similar results for seven subjects. The conclusion to be drawn from combining the results of these two studies with the results of the present study is that ten subjects exhibited a significant learning effect in the absence of the reference and none of the subjects exhibited a learning effect in the presence of it. In the remainder of this paper this striking difference will be referred to as a differential learning effect. Three important questions will be discussed:

(i) Why is there a differential learning effect?

(ii) How is the visual system informed that learning (without explicit feedback) ought to occur?

(iii) What is learned?

In order to find answers to these questions, the findings are interpreted within the framework of a reliability-based re-weighting paradigm. Estimation of surface slant has been described extensively and it is well established which cues play a role in this task. In the following analysis it is assumed that the brain relies most on signals that can be detected and processed in a simple and accurate way. Perceived slant is based on a combination of slant estimates in which the weights of the stereoscopic and non-stereoscopic slant estimates depend on the reliabilities as estimated by the subject (Maloney and Landy 1989; Young et al 1993; Landy et al 1995).

5.2 *Differential learning*

Why is there a differential learning effect? A plausible hypothesis is that, with practice, subjects increase the weight assigned to stereoscopic slant estimates relative to non-stereoscopic slant estimates more in the absence of a visual reference than in the presence of a reference. The rationale behind this proposition is as follows. First, consider the without-reference condition. Here it is hypothesized that, whereas the subject is able to estimate accurately the slant of surfaces based on isolated disparity gradients and proprioceptive posture signals [as demonstrated by Ogle (1938) and Backus et al (1999)], he or she may not be practiced in doing so. In daily circumstances the subject has a range of non-stereoscopic cues for the estimation of slant. The fact that it is often easy to estimate surface slant with just one eye means that stereoscopic cues are usually not needed for slant estimation. Note also that metrical stereoscopic tasks have to be performed less frequently than stereoscopic depth order tasks (McKee et al 1990; Gårding et al 1995; Glennerster et al 1996). McKee et al (1990) argued that in the first place stereopsis is for performing tasks at an arm's distance and for breaking camouflage (see also Fielder and Moseley 1996). Thus, according to the reliability-based re-weighting paradigm, it is hypothesized that normally subjects attach relatively little weight to slant estimates based on isolated disparity gradients. In the course of the experiment, however, they learn to attach more weight to these gradients. Second, consider the with-reference condition. Recovery of the slant between the reference surface and the test surface is theoretically not influenced (to a good approximation) by postural variation or perspective cues (van Ee and Erkelens 1996a; van Ee et al 1999). Therefore, a significant improvement in performance as a result of giving more weight to the stereoscopic slant estimate is not expected in the presence of a visual reference.

A mathematical analysis reveals that there are at least two alternative hypotheses that might be considered to account for the differential learning effect. These alternative hypotheses do not assume a change in weights. In the first hypothesis, there is no difference in whether the perceived slant improvements are due to a change in weights or to a change in the gain of slant estimation (Adams et al 2001). To see this, consider the following analysis. The formulation and notation of van Ee et al (1999) is used: We assumed the presence of two estimators: $\hat{S}_\mathrm{d}$ and $\hat{S}_\mathrm{p}$ (the subscripts d and p denote disparity and perspective, respectively), both of which are estimates of the physical slants S_d and S_p. The combined slant estimate is given by:

$$\hat{S} = w_\mathrm{d}\hat{S}_\mathrm{d} + w_\mathrm{p}\hat{S}_\mathrm{p} \quad (w_\mathrm{d} + w_\mathrm{p} = 1)\,,$$

with

$$\hat{S}_\mathrm{d} = g_\mathrm{d} S_\mathrm{d} \quad \text{and} \quad \hat{S}_\mathrm{p} \approx 0\,.$$

g_d denotes the gain of the slant estimator that is based on disparity. A change in g_d would have the same behavior as a change in w_d, so one is not able to distinguish a change (learning) in perceived slant caused by a weight change as opposed to a gain change. Notice that this analysis incorporates solely disparity and perspective as cues to slant. An extension to other slant cues is straightforward.

To this point in the analysis we have assumed that apparent frontoparallel corresponds to physical frontoparallel. In the second alternative hypothesis, it is assumed that a change in apparent zero slant explains the data. In the literature, there are analyses that assume that perceived frontoparallel is not identical to physical frontoparallel (Mitchison and Westheimer 1984; van Ee and Erkelens 1996a; Glennerster and McKee 1999; Adams et al 2001). It is straightforward to add a bias b_d in the slant estimator:

$$\hat{S}_\mathrm{d} = g_\mathrm{d}(S_\mathrm{d} - b_\mathrm{d})\,.$$

In this formulation the zero-slant bias and the presented slant have the same sign (Glennerster and McKee 1999). Now, if it is assumed that the effect of the presented slant on b_d is simply $b_\mathrm{d} = kS_\mathrm{d}$ (realistically, $0 \leqslant k \leqslant 1$), then $\hat{S}_\mathrm{d} = g_\mathrm{d} S_\mathrm{d}(1-k)$. If $k = 1$, $\hat{S}_\mathrm{d} = 0$, independent of the physically present slant. In terms of this equation, a hypothesis that $k > 0$ could, in principle, explain the results as satisfactorily as supposing $w_\mathrm{d} < 1$ (or $g_\mathrm{d} < 1$) (Glennerster and McKee 1999; Adams et al 2001). Glennerster and McKee (1999) measured the perceived depth of two lines presented in front of a regular grid that was either frontoparallel or slanted. They found that, in the presence of a slanted reference plane, the minimum threshold for detecting changes in disparity is at or close to the slant of this reference plane. Adams et al (2001) investigated the effect of wearing a horizontal magnifier in front of one eye for several days (introducing a prolonged absolute disparity gradient). They reported that the visual system adjusts to the new situation by changing the bias b_d. In the current learning experiment, the situation is different because in the without-reference condition the absolute disparity gradient changes randomly across trials. This makes the hypothesis that a change in b_d is responsible for the differential learning effect less likely.

In summary, in all of these hypotheses the contribution based on absolute disparity gradients relative to the contribution of non-stereoscopic slant information can be expected to change with practice and to change more without a reference than with a reference. This, then, is what causes differential learning.

5.3 *Underlying mechanisms for learning without feedback*

The idea of re-weighting without explicit feedback presupposes the existence of an underlying mechanism which informs the visual system about the necessity of weighting certain cues more than others.

It is possible that the subjects paid more attention to the part of the stimulus that varied between presentations. The non-stereoscopic cues are invariant across trials because they always indicate zero slant, whereas the stereoscopic cues change from trial to trial. This paradigm involves both the with-reference and the without-reference condition, which means that this possibility is less likely to be correct.

In daily circumstances, stereoscopic and non-stereoscopic cues occur in all kinds of combinations. The perceptual system needs a mechanism that provides information about the likelihood of estimates or the need to (re-)weight particular estimates more than others. For this purpose, Maloney, Landy, and coworkers introduced ancillary measures in vision science (Maloney and Landy 1989; Young et al 1993; Landy et al 1995). Ancillary measures are measures that serve to reduce the variability of estimates of a parameter. Ancillary measures do not in themselves provide information about depth in a scene, but instead provide information concerning the likely performance of different depth modules. For example, the amount and location of texture in a scene could affect the weight given to depth estimation derived from texture gradients (Maloney and Landy 1989). Throughout the experiment there was correlation between the postural state of the eyes (vergence and version) and the disparity gradient. It is possible that information about the postural state provided either by proprioception or the disparity field supplied feedback and served as ancillary measures.

5.4 *What is learned?*

Might proprioceptive eye posture signals have served as ancillary measures? As pointed out in section 1 there are two ways in which the proprioceptive eye posture signals can be involved in the estimation of slant relative to the head:

(i) Proprioceptive eye posture signals can be involved when scanning eye movements are being made across the slanted surface (Wright 1951). Any perceptual system needs to interact with its environment to calibrate its input. Scanning eye movements—just like grasping of the hand—probably serve such calibration purposes. Van Ee and Erkelens

(1999) found, however, that actively making large scanning eye movements across a slanted surface did not improve slant estimation relative to the condition where strict fixation was required. Although these authors did not study what effect scanning eye movements have on perceptual learning, their finding makes the involvement of proprioceptive eye posture signals in the learning effect less likely. The fact that there was no learning in the with-reference condition—whereas scanning eye movements would have affected both the with-reference and the without-reference conditions—also makes the involvement less likely.
(ii) Proprioceptive eye posture signals might also be involved in determining the location (relative to the head) of the surface patch that causes the horizontal disparity field. This would affect only the without-reference condition, because recovery of slant between two surfaces is theoretically hardly affected by vergence and version (van Ee et al 1999). Observers perceive the second surface as frontal and hence do not need to use any information about eye position. Also, the fact that the center of the stimulus was projected in the same location on the screen throughout the experiment helps the subject to rely more on the postural state of the eyes.

Note that the different learning possibilities could have occurred simultaneously.

5.5 *Little weight assigned to slant estimates based on isolated disparity gradients*
An important finding is that stereoscopic slant estimation evoked by isolated disparity gradients is not robust (or stable, or reliable) when there are conflicting non-stereoscopic cues. At the beginning of the experiment, the weight given to stereoscopic slant estimates relative to non-stereoscopic slant estimates was strikingly larger when there was a reference than when there was none. When stereoscopic and non-stereoscopic cues do not agree, estimated slant is usually considerably attenuated relative to slant predicted on the basis of the disparity gradient (Gillam et al 1984, 1988; Stevens and Brookes 1987, 1988; Collewijn et al 1991; Howard and Kaneko 1994; Kaneko and Howard 1996; van Ee and Erkelens 1998; Allison et al 1998).

In addition, the finding that subjects can learn to be more veridical (on the basis of stereoscopic cues) in stereoscopic slant tasks after feedback (Kumar and Glaser 1993; van Ee 1995) and without feedback (this study), and the finding that experienced observers perceive larger slant than inexperienced subjects, are consistent with the hypothesis that subjects increase the weight of stereoscopic slant estimates.

5.6 *Relative and absolute cues*
Relative disparity is not sufficient for slant perception: It is frequently stated that relative disparity (Westheimer 1979) rather than absolute disparity is the determinant of perceived depth. The advantage of relative disparities is that they are not affected by eye movements (Westheimer 1979; Erkelens and Collewijn 1985a, 1985b). In the present study we used stimuli with discrete elements. In other words, relative disparities were present all over the stimulus (Gillam 1993): each circle (see figure 3) had a disparity relative to its neighbor but also relative to any other circle. However, slant perception in the absence of a second surface is relatively poor and unstable. Thus, it follows that, in contrast to the above-mentioned relevance of relative disparities over absolute disparities, the presence of relative disparities is not sufficient for vivid and robust slant perception. The proposal of Gillam et al (1988) that it is a single gradient of disparity that is in fact poorly perceived is in accordance with the above-mentioned unreliability of isolated disparity gradients as a cue for veridical slant perception. Gillam et al (1988) and Gillam and Blackburn (1998) proposed that the main cues in the determination of surface slant are discontinuities in disparity gradients.

Note that low sensitivity to isolated disparity gradients is in agreement with lateral inhibition (Tyler 1974, 1991). The present analysis is consistent with the idea that stereopsis is in the first place for performing tasks at an arm's distance and for breaking camouflage (McKee et al 1990), because such tasks are not affected by the subject being relatively insensitive to isolated disparity gradients. Relative insensitivity to isolated disparity gradients benefits stability in stereoscopic slant estimation because it makes slant estimation less vulnerable to disparity gradients that are evoked by (noise in) postural variations (cf van Ee and Erkelens 1996a). However, it does not affect performance in tasks for which stereopsis is known to be essential. This low sensitivity to isolated gradients together with high sensitivity to relative disparity gradients (Gillam and Blackburn 1998) are the main components of a theory that explains Werner's (1938) slant contrast effect[5] as an artifact of stereograms containing cue conflicts (van Ee et al 1999).

5.7 *Intersubject variability and temporal aspects of slant estimation*

Several studies have demonstrated that the magnitude of perceived slant of a given stimulus develops over time and that in this development there are large differences between subjects (Gillam et al 1984, 1988; Allison and Howard 2000). All of these studies used an artificial way of inducing disparity gradients. The conflict between stereoscopic and non-stereoscopic cues that is present in these studies has been held responsible for the perceived slant built up over time. Individual differences in the weights assigned to stereoscopic and non-stereoscopic slant estimates probably account for differences across subjects.[6] The same cue conflict presumably causes the learning effect to depend on time as well (as demonstrated in figure 2) and explains why we found a large variability among subjects in the amount of learning. Subjects OF and JN showed a strong learning effect after only 294 trials, whereas other subjects did not show any effect even after 2000 trials. Van Ee et al (1996) found that a number of subjects did not show a practice effect after more than 4400 trials, which is about twice the number of trials presented in this study. A number of studies on practice effects in stereoscopic depth ordering (McKee and Westheimer 1978; Kumar and Glaser 1993; Fahle et al 1995; Fahle and Henke-Fahle 1996) have also reported a large variability across subjects.

5.8 *In conclusion*

The perceptual learning paradigm provided results that are useful for investigating the reliability of conflicting cues in metrical aspects of stereoscopic vision. First, the cues involved in slant estimation were divided into stereoscopic and conflicting non-stereoscopic cues. The existing cue re-weighting paradigm, in which the contributions of the stereoscopic and non-stereoscopic slant estimates depend on their reliability as estimated by the subject, was extended to include re-weighting as a result of perceptual learning.

[5] When a small frontoparallel test strip is surrounded by a larger slanted surface (an inducer), the test strip is perceived as slanted in the direction opposite to the inducer (Werner 1938). In demonstrations of this slant-contrast effect, the inducer's slant is specified by stereoscopic signals, and other signals, such as the texture gradient, specify that it is frontoparallel. Van Ee et al (1999) presented a theory of slant estimation that determines surface slant via the linear combination of various slant estimators; the weight of each estimator is proportional to its reliability. The theory explains slant contrast because the absolute slant of the inducer and the relative slant between test strip and inducer are both estimated with greater reliability than the absolute slant of the test strip. Slant contrast is greatly reduced when the stereo- and nonstereo-specified slants of the inducer are made consistent with one another.

[6] Gillam (1967, 1993) reported perceived slants to be in the direction opposite to that predicted. In her study, subjects viewed a stimulus with rich perspective cues (a brick wall) while one of the retinal images was horizontally scaled relative to the other. She proposed that reverse slants result from an interaction between perspective and binocular disparity cues. One of our subjects (for whom the data are not included in this paper) showed the reversed slant effect in the stimulus that was used in this study. This subject showed consistently reversed slants only for roughly the first 25 responses of a session. The rest of his responses were in the predicted direction. The number of slant reversals decreased over one-week-interval sessions but did not disappear.

In the experiment, the strength of the conflicting cues was kept constant whereas the strength of the stereoscopic cues increased as a result of learning. The results support the hypothesis that modification of the relative contribution of the absolute disparity gradient can occur without external feedback. Future studies on stereoscopic slant perception involving isolated disparity gradients will have to take the effect of practice into account even when there is no feedback.

It is suggested that subjects learned to use proprioceptive cues about eye posture. These cues are in accordance with the stereoscopic cues and—following the ideas of Landy, Maloney and coworkers—this accordance might have led to the increased reliability of stereoscopic cues. It was argued that relative insensitivity to isolated disparity gradients is beneficial for the stability in stereoscopic slant estimation because it makes slant estimation less vulnerable to disparity gradients that are evoked by (noise in) postural variations.

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