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Tilt dependency of slant aftereffect

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Abstract

Slant aftereffect (SAE), the negative aftereffect of slant induced after prolonged observation of a surface, is considered as evidence that slant is encoded in the visual system. Because slant and tilt are mathematically independent dimensions, Stevens (Stevens, K. A. (1983a). *Biological Cybernetics*, *46*, 183–195) assumed that slant and tilt are processed independently in the visual system. To confirm this assumption, we investigated whether SAE is induced independently of the difference in tilt between the adapting and test stimuli. The stimuli were displayed by simulating the motion disparity of rotating disks. After adaptation to a surface of 60° slant, the subjective 0° slants of the test stimulus were measured with the tilt differences of 0, 45, 90, 135 and 180°. The magnitude of SAE was greatest when the tilt difference was zero, and decreased with increasing tilt difference. The results suggest that slant and tilt are not processed independently in the visual system and that the slant detector in the visual system is sensitive not only to slant but also to tilt.

Keywords: Slant; Tilt; Slant aftereffect (SAE); Surface; Structure-from-motion

1. Introduction

Of the many kinds of geometrical information about perceived three-dimensional (3-D) shape, surface orientation has attracted attention of many researchers. To name a few, Gibson (1950) included surface orientation in the list of the essential properties of perceived surfaces, and Marr and Nishihara (1978) considered surface orientation as an important component of the 2 1/2-D sketch. To date, many computational theories of 'shape from X' have been formulated as methods for obtaining surface orientation using shading, texture, surface contours, or other information (e.g. Stevens, 1981; Witkin, 1981; Pentland, 1984).

Fig. 1 shows examples of surface orientation by using images of a disk. Each disk has a needle sticking out from its center. This needle represents the surface normal. In Fig. 1A, the angles between the surface normal and the line of sight are 0, 30, 60 and 90°. This angle is termed slant. The disks in Fig. 1A and B have the same slants, but they are facing different directions (except for the case of 0° slant). This direction is termed tilt and is formally defined as the orientation of the surface normal's image on the fronto-parallel plane. In Fig. 2, all the disks have a 60° slant, but their tilts are different. In this study, due right is set to represent 0° tilt, and tilt increases in the counterclockwise direction. A surface orientation can uniquely be described by using slant and tilt, and this slant–tilt representation can also be used for describing the local orientation on curved surfaces.

Although many studies have utilized the slant–tilt representation to describe both the surface orientation of stimuli and judgments about stimulus surface orientation by subjects (e.g. Gibson, 1950; Braunstein, 1968; Braunstein & Payne, 1969; Epstein, 1981; Stevens, 1983a,b; Mingolla & Todd, 1986; Stevens & Brookes, 1987, 1988; Epstein & Babler, 1989; Gillam & Rogers, 1991; Koenderink, van Doorn & Kappers, 1992; Cagenello & Rogers, 1993; Koenderink, van Doorn & Kappers, 1994a,b; Knill & Liu, 1994; Johnston & Passmore, 1994a,b; Ryan & Gillam, 1994; Curran & Johnston, 1996; Mamassian & Kersten, 1996; Pollick, Watanabe & Kawato, 1996; Seyama & Sato, 1998),

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these studies do not necessarily suggest that the visual system actually uses the slant–tilt representation. Stevens (1983a), on the other hand, has argued that surface orientation is actually encoded in terms of slant and tilt in the visual system. His argument was based on the following three types of results. First, the perception of slant and that of tilt are different in terms of precision and accuracy (Stevens, 1983b; Koenderink et al., 1992). Second, during an observation of a surface, the impression of slant can change even if the impression of tilt is maintained (Bergman & Gibson, 1959; Smith, 1965). Third, prolonged observation of a surface orientation can induce the aftereffect of slant (Köhler & Emery, 1947; Bergman & Gibson, 1959; Wenderoth, Rodger & Curthoys, 1968; Wenderoth, 1970; Balch, Milewski & Yonas, 1977; Milewski & Yonas, 1977; Poom & Börjesson, 1999).

Bergman and Gibson (1959) studied an aftereffect specific to surface slant (slant aftereffect, SAE) under the following procedure. First, a slanted surface (adapting stimulus) was presented to the subject for a prolonged period (Fig. 3A). It was followed by a presentation of a surface with 0° slant (test stimulus) which appeared having a negative slant (Fig. 3B) to the subject. The subject was then asked to adjust the slant to 0°. From this experiment, they found that a few degrees of positive slant subjectively equaled the objective 0°.

Aftereffects have been considered to reflect functions of underlying mechanisms that selectively respond to adapting stimuli (Braddick, Campbell & Atkinson,

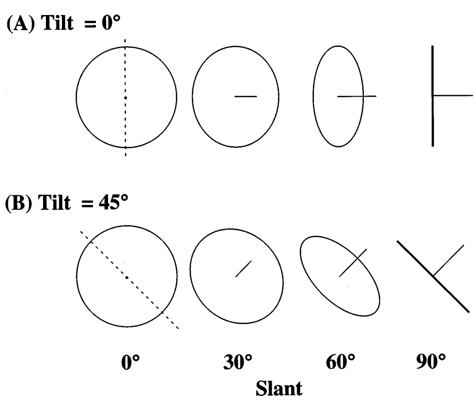

Fig. 1. Images of oriented disks showing examples of slants and tilts. The four disks in (A) and those in (B) have the same slants (0, 30, 60 and 90°). However, their tilts are different (0° for (A) and 45° for (B) (see Fig. 2)).

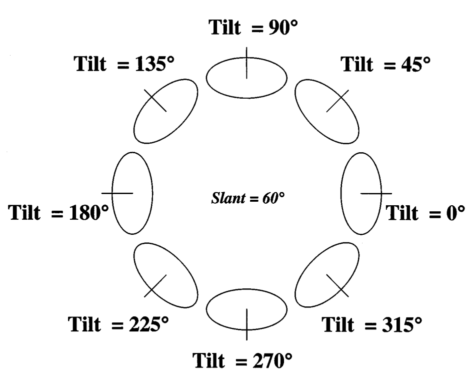

Fig. 2. Although all the disks have the same slant (60°), their tilts are different. In this paper, the tilt of a surface facing to the right is defined to be 0° and to increase in the counterclockwise direction.

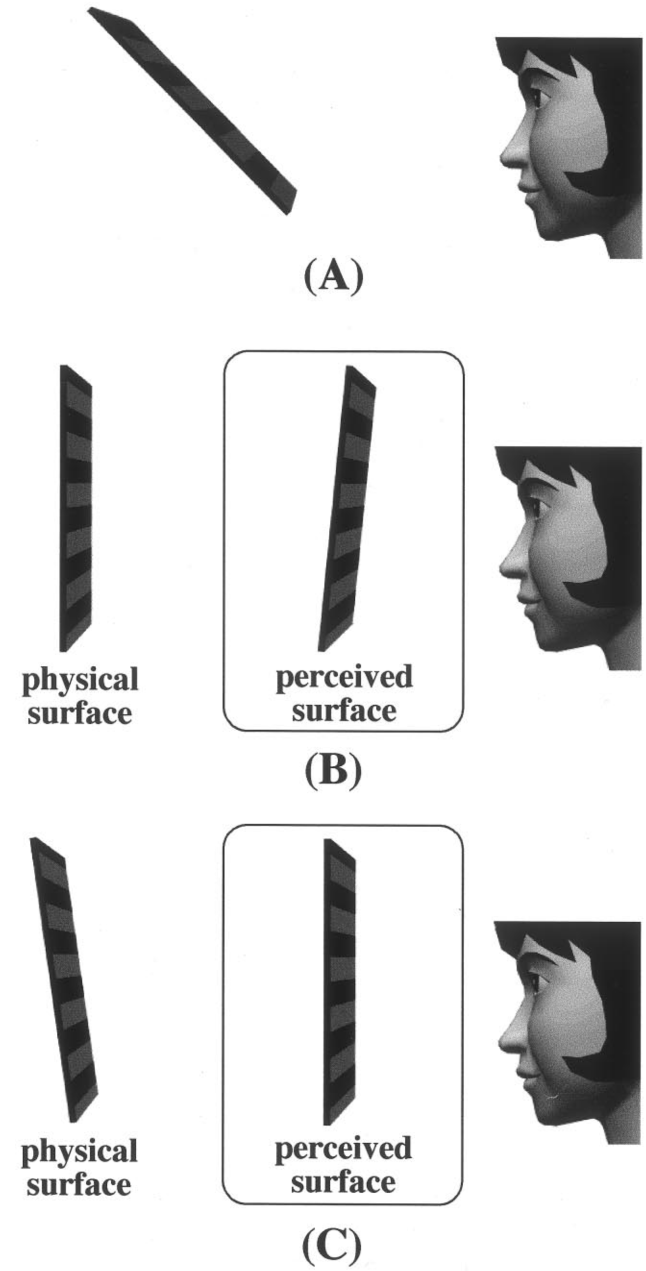

Fig. 3. The procedure used in Bergman and Gibson (1959) to measure slant aftereffect (SAE) is shown schematically. First, the subjects observed a slanted surface for 4 min (A). Then, a surface with 0° slant was presented. However, the perceived surface appeared to have a negative slant (B). After the subjects adjusted the slant of the surface to perceptual 0°, the physical surface had a positive slant (C).

1978). Visual attributes such as motion, orientation (two-dimensional tilt), spatial frequency, and color have been known to elicit aftereffects, and the existence of specific detectors for these attributes has been widely accepted (e.g. Frisby, 1979; De Valois & De Valois, 1988; Spillman & Warner, 1990; Wandell, 1995). Under these several assumptions, Coltheart (1971), Balch et al. (1977), and Poom and Börjesson (1999) attributed SAE to neural units selectively sensitive to slant, namely slant detectors. In their interpretation, the slant detectors were assumed to change their response characteristics as a result of prolonged exposure to a slanted surface, and this modification in response characteristics was supposed to be the basis of SAE.

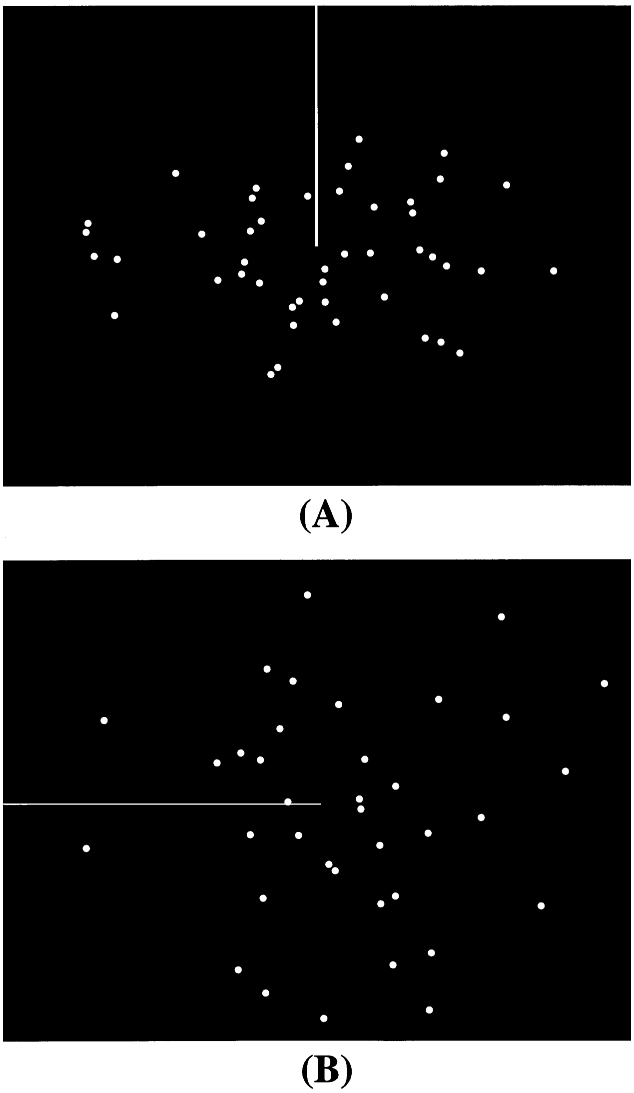

Fig. 4. A schematic presentation of the adapting stimulus and the test stimulus. Each of the white dots was shown by one pixel. The size of dots in this figure is exaggerated for clarity. (A) adapting stimulus (slant = 60°, tilt = 90°). All 46 dots are visible in the image. (B) test stimulus (slant = 45°, tilt = 180°). Some of the dots are not visible, since they are outside the display area.

Stevens (1983a) predicted that SAE could be observed with adapting and test stimuli of different tilts. This prediction was based on his assumption that a hypothesized slant detector is sensitive only to slant and not to tilt, an assumption yet to be tested. Although several lines of results support the idea that slant- and tilt-dimensions are actually implemented within the visual system, this does not necessarily mean that slant detectors function independently of tilts.

The main objective of this study is to investigate, by using SAE, whether the slant detector in the visual system functions independently of tilt. For this purpose, we have systematically varied the difference in tilt between the adapting and the test stimuli, and examined whether the magnitude of SAE is affected by the difference in tilt. If slant and tilt are detected by independent mechanisms, the magnitude of SAE should be independent of the tilt difference, as discussed by Stevens (1983a). However, if the slant detector does not function independently of tilt, then the tilt difference should affect the magnitude of SAE.

2. Experiment

2.1. Method

2.1.1. Subjects

One of the authors (JS) and six undergraduate students at the University of Tokyo served as subjects. All the undergraduates except one (TS) were unaware of the purpose and ongoing results of the experiment. All subjects had normal or corrected-to-normal vision. Subject TS participated under two different conditions (denoted as TS and TS1).

2.1.2. Apparatus

Stimuli were produced using an Apple Macintosh IIfx computer and displayed on a CRT monitor (Apple 13″ color). The monitor was viewed monocularly at a distance of 1 m in a darkened room. A head and chin rest restricted the subject's head and body movements.

2.1.3. Stimuli

The adapting and the test stimuli were rotating random-dot patterns comprising imaginary disks (Fig. 4). The pattern was rotated, at 30°/s about an axis passing through the center to create a compelling impression of a slanted surface. Since static stimuli gave no such impression, dot movement was a critical factor for producing a three-dimensional impression. Each dot consisted of one white pixel (0.367 mm or 1.2′ visual angle in diameter) against a black background. The positions of dots were calculated by using perspective projection where the distance from the viewpoint to the center of the displayed surface was 1 m. A green pixel served as a fixation point at the center of the displayed surface.

2.1.3.1. Adapting stimulus. Fig. 4A schematically shows an adapting stimulus with a slant of 60° and a tilt of 90°. The simulated radius of the adapting stimulus was 8.7 cm. The imaginary edge of the surface with this radius was projected within the screen of the monitor (23.5 × 17.6 cm). There were 46 dots on the adapting stimulus, eight of which were located on the edge of the surface at an interval of 45°, and another eight dots on an imaginary circle having a radius of 4.35 cm with the same 45° interval. The regular pattern produced by the fixed location of these 16 dots enhanced the impression of slant. The remaining 30 dots were randomly distributed over the surface excluding the area within 1 cm from the center. The distribution was varied from one trial to the next, and the direction of rotation was reversed every 360° to prevent a motion aftereffect.

2.1.3.2. Test stimulus. Fig. 4B schematically shows the test stimulus with a slant of 45° and a tilt of 180°. The simulated radius of the test stimulus was 19.4 cm. Thus, the edge of the surface extended beyond the CRT screen when the surface slant was between −50 and 50°. The 46 dots were randomly distributed over the surface excluding the area of 1 cm radius around the center. A total of 16 of the 46 dots were located within 8.8 cm from the center of the surface. These 16 dots were always visible on the monitor, but the other 30 dots were projected outside or inside the monitor according to their location on the surface, the rotation of the surface, and slant. The distribution of the 46 dots varied from trial to trial. The direction of rotation of the test stimulus was reversed every 30°.

Although the stimuli were produced by using perspective projection, both of the two tilts differing by 180° could be perceived for a stimulus. A needle similar to those shown in Figs. 1 and 2 was presented at the center of the surface (see Fig. 4) to reduce this ambiguity. This needle was a green line of one-pixel width, extending from the center of the surface to the edge of the CRT screen. Therefore, its length in the image did not depend on the slant of the surface. The needle vanished after the second reversal of the direction of rotation.

When the slant of the test stimulus is 0°, the image of the whole surface can be seen as a circular disk filled with dots. To prevent subjects from using this cue, the size of the test stimulus was made large enough so that its edge would project beyond the edge of the CRT screen (Fig. 4B). However, the circular orbits of the dots could still be used as a cue for 0° slant, so subjects were instructed to judge the slant based only on their general impression of the surface.

Test stimuli with 90 and 180° tilt were occluded differently by the edge of the CRT screen because the screen was not square. To erase this difference, the monitor was rotated 90° when the test tilt was 180°.

2.1.4. Procedure

The effect of adaptation was tested for each subject with two test stimuli varying in tilt angles and whose slant was changed automatically as described below. For each test stimulus, five different adapting stimuli were used. The tilt of the adapting stimuli differed from that of the test stimuli by 0, 45, 90, 135, and 180°, and their slant was fixed at 60°.

In each session, subjects were adapted to an adapting stimulus and tested repeatedly for ten times with a test stimuli. In one session, five adaptation phases were each followed by two successive measurements (test phase). The first adaptation lasted 3 min and subsequent ones were for 1 min. In each test phase, subjective 0° slant was measured. In this test phase, a test stimulus with 50° slant was displayed and then its slant automatically decreased at every reversal of the rotation of the dot pattern. The amount of slant decrease was constant during a trial, but varied randomly between 1 and 3° from trial to trial. The subject clicked a mouse-button when the test stimulus appeared to be fronto-parallel, and the slant at the moment was recorded. Then, another measurement was conducted in the same way. Subjects were instructed to fixate at the center of the disk.

Additional sessions to measure the baseline for 0° slant judgments were conducted. Therefore, each subject performed 12 or eight experimental sessions. The procedure for the baseline measurement was the same as described above, except that the slant of the adapting stimulus was 0°. An inspection of 0° slant was not expected to induce SAE (Bergman & Gibson, 1959; Balch et al., 1977). The 12 or eight sessions, each requiring about 10 min, were performed in a random order with a rest period of at least 10 min between consecutive sessions. A session was aborted and tried again when subjects reported that the change of tilt by 180° occurred quite often.

3. Results

The magnitude of SAE was obtained by subtracting the baseline slant from the slant measured under each condition. For the group data, the mean baseline slant was 1.5° (SE = 1.0). The group mean magnitudes of SAE are plotted in Fig. 5 as a function of the tilt difference between the adapting and test stimuli. The SAE measured with 0° tilt difference (= 15.5) was significantly different from 0° ($t(317) = 11.9$, $P < 0.01$, two-tailed t-test). However, SAE was not significant

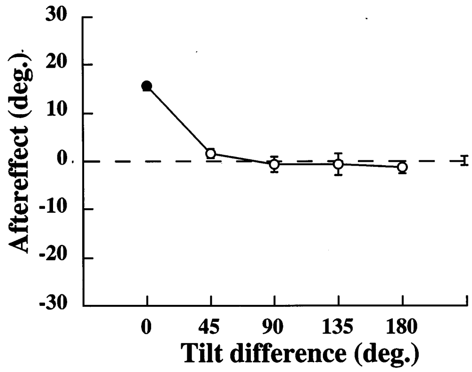

Fig. 5. The mean magnitude of slant aftereffect (SAE) is plotted as a function of tilt difference between the adapting and the test stimuli. The results are averaged through all subjects and conditions using different tilts of the test stimulus. The magnitudes of SAE are obtained by subtracting the mean baseline slant (= 1.5°) from the mean slant measured under each condition. Only the SAE measured with 0° tilt difference was significantly different from the mean baseline slant (two-tailed t-test, $P < 0.01$) and is indicated by the filled circle. The error bar represents ± 1 SE. The error bar shown to the right of the SAEs is ± 1 SE of base line slant.

when the tilt difference was not 0°. These results indicate that the structure from motion display effectively induces SAE, but that the hypothetical slant detector does not function independently of surface tilt.

The data from each subject show the same tendency under each test-tilt condition (Fig. 6). The points where significant SAE was obtained (5% significance level, two-tailed t-test) are indicated by filled symbols. As shown in Fig. 6, maximal SAEs were obtained when the tilt difference was zero for all subjects. The magnitude of SAE was highest at 0° tilt difference regardless of the tilt of the test stimulus. This suggests that tilt difference was the main factor affecting SAE magnitude.

As subjects viewed the test stimulus for an average of 30 s, presentation of the test stimulus could also have induced SAE. However, adaptation to the test stimulus is negligible because similar effects, if there are any, should also have affected the baseline values, and the magnitude of SAE shown in Figs. 5 and 6 was obtained by subtracting the baseline slant from the slant measured under each experimental condition.

The slant aftereffect we obtained in our experiment might be accounted for by the aftereffects of the two-dimensional features of the stimulus images as Balch et al. (1977) have pointed out. To investigate this possibility, we measured SAE with the stimuli generated under orthographic projection. In this supplementary experiment, the tilt of the adapting stimulus was either 90 or 270°, and that of the test stimulus was 90° (measurements for baseline slant were not conducted). Since orthographic projection was used, the two-dimensional features of the adapting stimuli differing in tilt by 180° are statistically the same except for the direction of the needle. Nevertheless, the subjective 0° slants judged after adapting phases with 90 and 270° were different (Fig. 7). Subject JS (one of the authors) and MS (who was unaware of the purpose of the study) showed similar results ($t(18) = 2.83$, $P < 0.05$ for JS and $t(18) = 8.58$, $P < 0.0001$ for MS. a two-tailed t-test). This fact implies that the observed aftereffect was influenced by perceived three-dimensional surface orientation, and not two-dimensional features projected onto the retina.

4. Discussion

Although slant and tilt are mathematically independent dimensions, our results suggest that slant is not processed independently of tilt (at least under the conditions of our experiment). The group mean SAE was significantly greater than zero only when the tilt of the adapting stimulus was the same as the tilt of the test stimulus. The results for each subject also indicated a similar tendency.

Surface orientation can be represented mathematically in many ways. For example, a description of a unit normal vector can serve as the representation of surface orientation because an oriented surface has a unique unit normal vector. Gradient space (Woodham, 1981; Horn, 1986) is another way to represent surface orientation. In gradient space, surface orientation is uniquely described by two gradients of depth in orthogonal directions. Ordinal structure, proposed by Todd and Reichel (1989), can be considered as a less quantitative representation of surface orientation based on the gradient of depth. In this representation, only the signs (+ , 0, or −) of gradients of depth in arbitrary directions at a point on the perceived surface are represented.

Although the slant–tilt representation and gradient space are mathematically equivalent, Stevens (1983a) claimed that the slant–tilt representation can more appropriately describe human performance in the judgment of surface orientation than gradient space. The fact that the slant–tilt representation has been employed by many of the previous studies is consistent with his idea. In our study, however, the magnitude of SAE was shown to depend on the tilt difference between the adapting and the test stimuli. The result suggests that slant is not processed independently of tilt in the visual system at least in the case of structure from motion, although slant and tilt are mathematically independent dimensions.

In general, adaptations and aftereffects can be explained in terms of changes in response characteristics of the specific mechanisms that are responsible for the property being perceived (e.g. Coltheart, 1971; Frisby, 1979; Wandell, 1995). SAE has also been related to changes in the response characteristics of hypothetical slant detectors (Coltheart, 1971; Balch et al., 1977). In the following discussion, the slant detector is simply considered as a mechanism that can represent a whole range of slants without assuming any specific implementation.

Under the assumption that slant and tilt are processed independently (Stevens, 1983a), a pair of slant and tilt detectors is sufficient to unambiguously represent surface orientations at each point in the visual field. Fig. 8 schematically shows these surface orientation detectors and their response to the adapting and the test stimuli. In the left half of Fig. 8, orientations of the adapting and the test stimuli are shown. When an adapting stimulus with 60° slant and 90° tilt is observed (Fig. 8A), the slant detector indicates 60° slant and the tilt detector indicates 90° tilt (if the orientation is perceived accurately). Fig. 8B shows the response of the slant and the tilt detectors for a test stimulus with 15° slant and 90° tilt. The slant detector indicates a 15° slant, but will underestimate it after adaptation. When the tilt of the adapting stimulus is 180° (Fig. 8C), the tilt detector responds differently, but the response of the slant detector should not be affected. If such detectors are operating, neither magnitude of SAE should be affected by any manipulation of tilt. The present results, however, challenge this idea. Since the magnitude of SAE was affected by the tilt difference between the adapting and the test stimuli, these results indicate that different slant detectors are activated by surfaces with different tilts.

Fig. 9 shows another type of surface orientation detector which can explain our experimental results. This type of surface orientation detector consists of multiple slant detectors and a single tilt detector. Each slant detector is assumed to respond to a slant of a surface only when the surface has a specific tilt. Thus, the slant detectors also have a selectivity to tilt. When an adapting stimulus with 60° slant and 90° tilt is

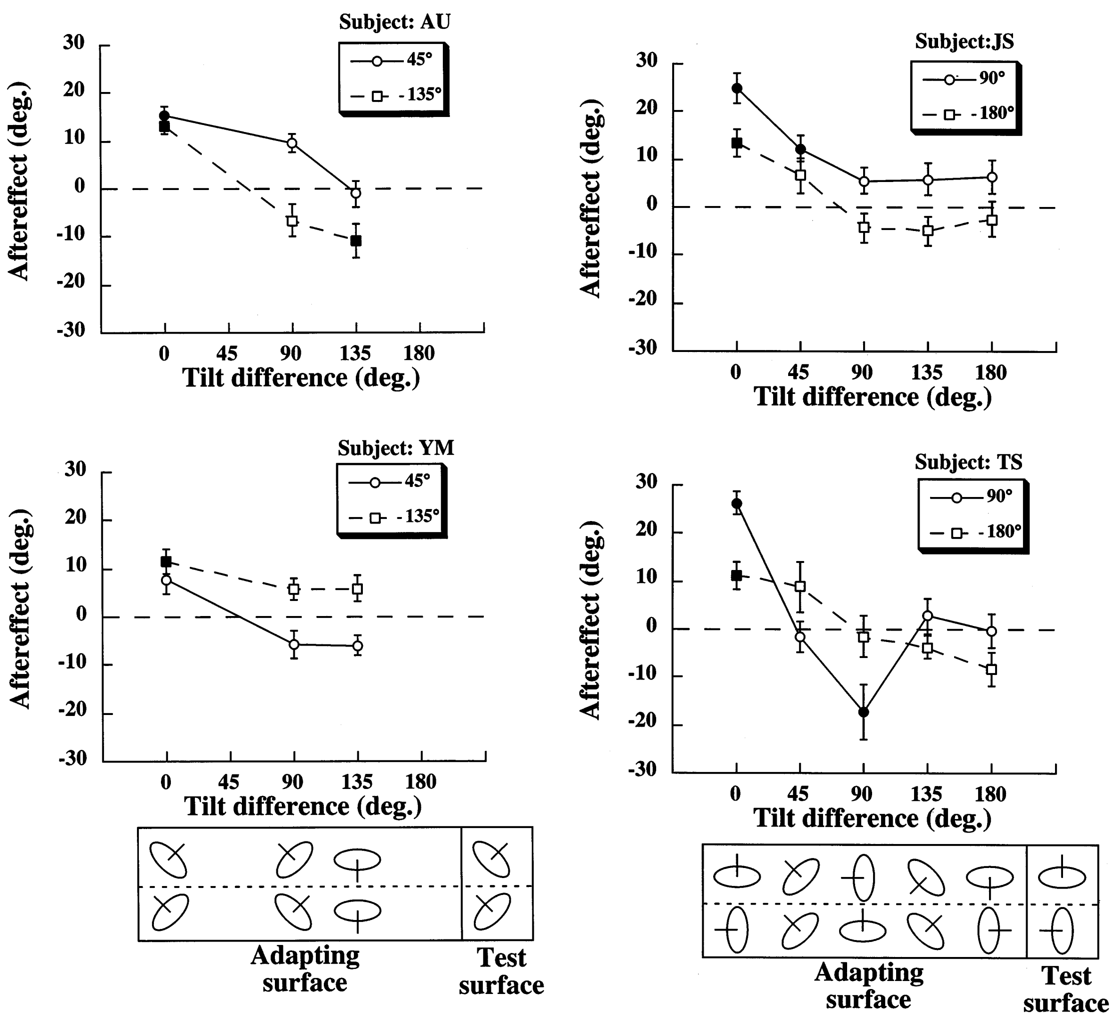

Fig. 6. The mean magnitude of slant aftereffect (SAE) for each subject is plotted as a function of tilt difference between the adapting and the test stimuli. The points that differ significantly from the mean baseline slant at a level of 5% (two-tailed t-test) are plotted with the filled symbols. The error bar represents ± 1 SE. The legend shows the corresponding tilt of the test stimulus. The tilts of the test and the adapting stimuli are also shown using images of oriented disks.

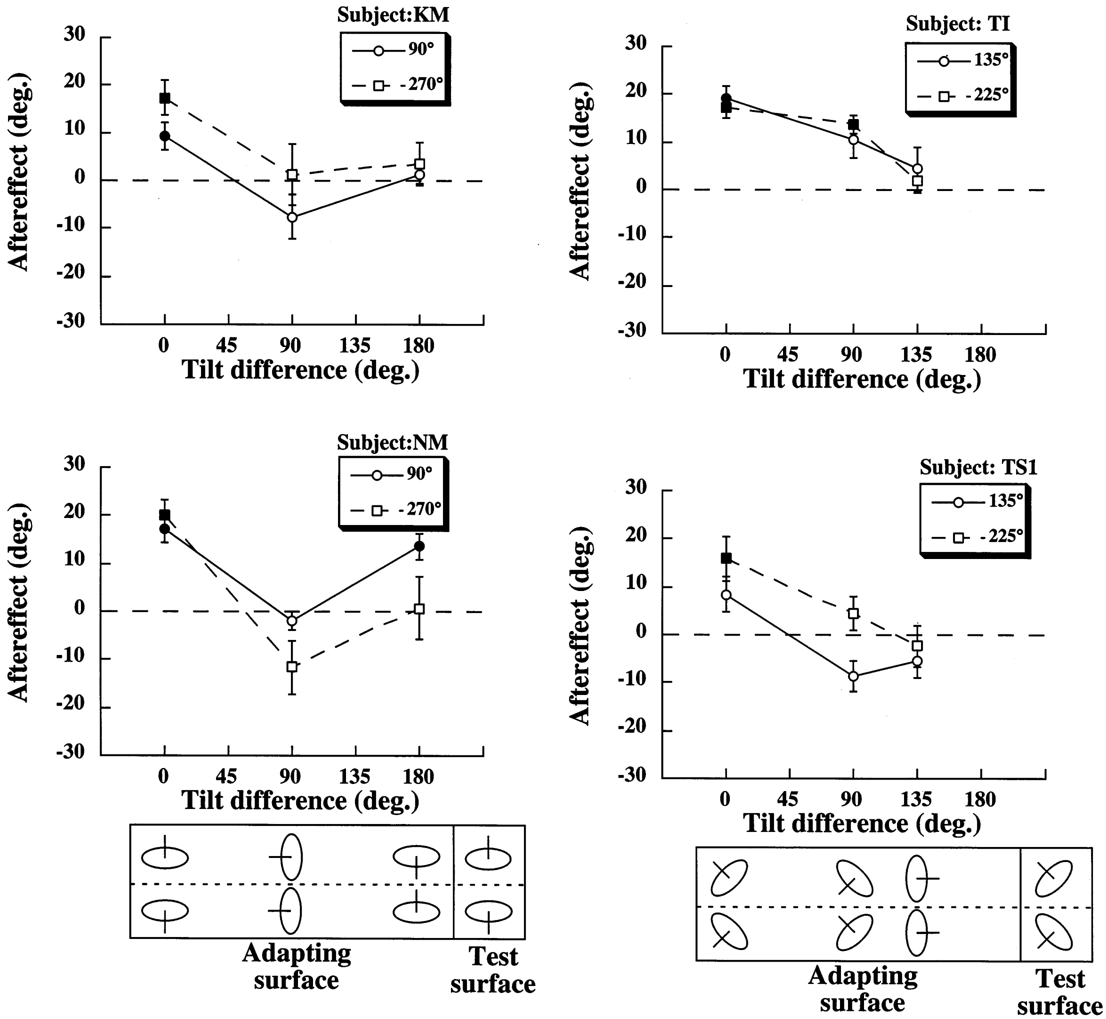

Fig. 6. (*Continued*)

presented (Fig. 9A), only the slant detector specialized for 90° tilt responds, and the adaptation occurs in this slant detector. Fig. 9B shows the responses of these detectors for the test stimulus with 90° tilt and 15° slant. Although the slant detector may indicate 15° slant before adaptation, the slant will be underestimated after adaptation to the adapting stimulus with 90° tilt, since the slant detector responsible for the perceived slant is the same. However, if the adapting stimulus with 180° tilt is observed during the adapting phase, adaptation occurs at the slant detector for 180° tilt surface (Fig. 9C). Thus, this adaptation will not affect the perceived slant of the test stimulus with 90° tilt. Therefore, as observed in our experiment, this type of detector induces SAE that is dependent on the tilt difference between the adapting and test stimuli. Note that even if the tilt detector does not exist, the tilt of a surface can be indicated by the response of these slant detectors. Thus, detectors tuned only for tilts are not needed to indicate a surface orientation uniquely. However, whether such tilt detectors actually exist in our visual system is beyond the scope of this study.

The results of this study suggest that a neuron which has a sensitivity to slant (if it exists) must also have a sensitivity to tilt. Sugihara, Murakami, Komatsu, Shenoy and Andersen (1998) recorded responses from macaque MSTd neurons when the stimuli similar to

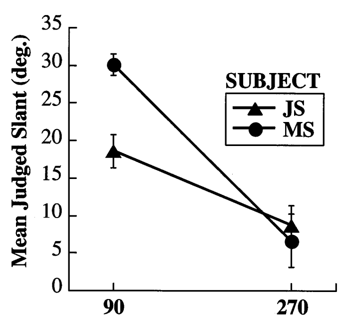

Fig. 7. Mean subjective 0° slant obtained from the stimuli generated by orthographic projection. Tilt of the test stimulus was 90°, and those for adapting stimuli were either 90 or 270°. Thus, tilt-differences of 0 and 180° were investigated. Error bar indicates standard errors.

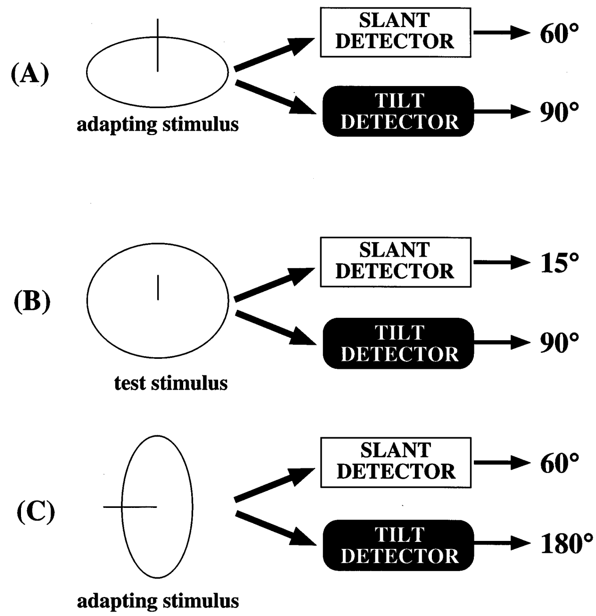

Fig. 8. A schematic representation of the responses of a set of detector for surface orientation. In this detector, one slant detector and one tilt detector are paired and their responses indicate a unique surface orientation. Each response corresponds to a stimulus surface orientation shown to the left of this figure by using images of slanted disks.

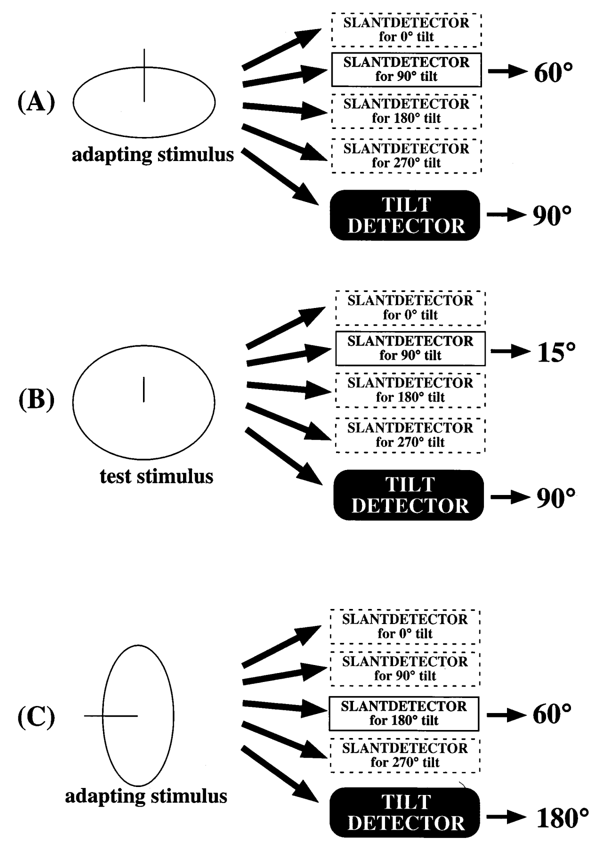

Fig. 9. A surface orientation detector consists of one tilt detector and multiple slant detectors. Each slant detector also has a sensitivity to tilt, and indicates slant of a surface with a specific tilt.

those used in our experiment were presented. They reported that neurons exist whose response changed systematically according to the change in stimulus slant, and that most of these neurons were also selective to tilt. Thus, if these neurons can be interpreted as slant detectors, Sugihara et al.'s (1998) report is consistent with the surface orientation detectors depicted in Fig. 9.

The visual system has to measure the optical flow in the retinal image to estimate slant (and also tilt) from the stimuli used in our experiment. Although the adapting slant was fixed at 60°, the overall optical flow changed depending on the stimulus tilt. Thus, it may be possible that the observed tilt-dependency of SAE reflected the tilt-dependency of optical flow. If this is the case, the tilt-dependency of SAE might be a cue-specific phenomenon. Thus, whether the tilt-dependency of SAE can also be observed from stimuli including cues other than optical flow, e.g. shading and texture gradient, is still an open question.

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