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N90-22959

OPTICAL, GRAVITATIONAL, AND KINESTHETIC DETERMINANTS OF JUDGED EYE LEVEL

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SUMMARY

Subjects judged eye level, defined in three distinct ways relative to three distinct reference planes: 1) a gravitational horizontal, giving the "gravitationally referenced eye level" (GREL); 2) a visible surface, giving the "surface-referenced eye level" (SREL); and 3) a plane fixed with respect to the head, giving the "head-referenced eye level" (HREL). The information available for these judgments was varied by having the subjects view an illuminated target that could be placed in a box which: 1) was pitched at various angles, 2) was illuminated or kept in darkness, 3) was moved to different positions along the subject's head-to-foot body axis, and 4) was viewed with the subjects upright or reclining. Our results showed: 1) judgments of GREL made in the dark were 2.5° lower than in the light, with a significantly greater variability; 2) judged GREL was shifted approximately half of the way toward SREL when these two eye levels did not coincide; 3) judged SREL was shifted about 12% of the way toward HREL when these two eye levels did not coincide; 4) judged HREL was shifted about half way toward SREL when these two eye levels did not coincide and when the subject was upright (when the subject was reclining, HREL was shifted approximately 90% toward SREL); 5) the variability of the judged HREL in the dark was nearly twice as great with the subject reclining than with the subject upright. These results indicate that gravity is an important source of information for judgment of eye level. In the absence of information concerning the direction of gravity, the ability to judge HREL is extremely poor. A visible environment does not seem to afford precise information as to judgments of direction, but it probably does afford significant information as to the stability of these judgments.

INTRODUCTION

A normal video display conveys fairly accurate information about exocentric directions among displayed visual objects (see Ellis, this volume), but not about egocentric directions, particularly those relative to eye level. This information is important to the observer in the natural environment, and can be used to advantage, especially in the case of a head-mounted display. The concern of the present paper is the mechanism underlying judgments of eye level, and the interactions of vision, gravitation, and bodily senses in these judgments.

There are at least three distinct meanings for visual eye level, all of which are important for the present analysis. Each meaning has associated with it a distinct reference plane with respect to which eye level can be specified. If a given reference plane passes through both the eye and a visual target, the target is said to be at that particular eye level. The three types of eye level are shown in figure 1, and described in table 1.

The Target/Head (T/H) system is responsible for the determination of the direction of a target relative to the head, or head-referenced eye level (HREL). This system presumably uses extra-retinal (e.g., kinesthetic or proprioceptive) eye position information (Matin, 1976). The Target/Gravity (T/G) system is responsible for the determination of the direction of a target relative to gravity, the gravitationally referenced eye level (GREL). It is composed of T/H and a Head/Gravity (H/G) system. The latter system presumably operates on the basis of vestibular (primarily otolithic) and postural information (Graybiel, 1973). The Target/Surface (T/S) system is responsible for determining the direction of a target relative to a visible surface, the surface-referenced eye level (SREL). In order to judge the direction of a target relative to the SREL, an observer must use optical information about the orientation of the surface; no extra-retinal, vestibular, or other proprioceptive information is necessary. The optical information involved might be in the form of depth cues which allow the observer to compare eye-to-surface distance with target-to-surface distance, or it might be in a form which allows a "direct" determination of SREL from optical information without recourse to judgments of distance (Gibson, 1950; Purdy, 1958; Sedgwick, 1980). Thus, in principle, T/S can be completely independent of T/H and T/G.

If an observer is standing on a level ground plane in a normal, illuminated, terrestrial environment, with head erect, all three eye levels (HREL, GREL, and SREL) coincide, and determination of any one automatically leads to determination of the other two. It is thus impossible, in that environment, to determine the relative contributions of the three physiological systems described. To do that, some means of separating them is necessary. Various methods to accomplish this separation were used in the following experiments.

EXPERIMENT I: THE EFFECT OF ILLUMINATION ON JUDGMENT OF GREL

Introduction and Method

Our experimental paradigm consisted simply in having the subject adjust a point of light to eye level, defined in one of the three ways above. First, we ask, "What contribution does optical information make to judgments of GREL?" To answer this question we simply turned off the lights. This eliminated optical information regarding orientation to the ground plane and all other environmental surfaces, and presumably eliminated information to the T/S system. The subject was seated in a dental chair which he or she could raise and lower hydraulically. (This technique minimized the possibility of the subject simply setting the target to the same visible point in each trial.) The task was to adjust the height of the chair so that the subject's eyes were "level" with a small target. (All three types of eye level are coincident in this situation.) A total of 80 trials occurred for each of 10 subjects.

Results

Constant errors (which indicate accuracy) and standard deviations (which indicate precision) were calculated individually for each subject. The averages over all subjects are shown in table 2. The differences between light and dark are significant ($p < 0.01$ by ANOVA).

DISCUSSION

The finding of higher constant error in the dark means that a small target appears to be about 2.5° higher in the dark than in the light. Others (MacDougall, 1903; Sandstrom, 1951) have found similar results. We have no satisfactory explanation for this effect.

The finding that eye level judgments are more variable in the dark is not surprising, nor is it easily explained. Three distinct hypotheses seem possible; the first two assume that T/S provides more accurate and precise directional information than T/G; the third makes no such assumption. The three hypotheses are

1. The "suppression" hypothesis assumes T/G is simply suppressed when T/S is available. If T/S is more precise than T/G, this suppression will result in improved precision.

2. The "weighted average" hypothesis assumes that the variability of the final judgment is a weighted average of the variabilities of T/G and T/S.

3. The "stability" hypothesis assumes that the function of optical information is to minimize the drift of directional judgments made by means of nonoptical information. Thus, no directional information per se is necessary from T/S, and no assumptions are made about its precision.

The following experiments are intended to help decide among these three hypotheses.

EXPERIMENT 2: THE EFFECT OF PITCHED SURROUNDINGS ON GREL

Introduction

Another way to study the interaction of the eye-level systems is to put them into "conflict." This effect has been extensively investigated in the roll dimension with the now classical "rod-and-frame" paradigm (Witkin and Asch, 1948).

Method

A modification of the "pitchbox" method (Kleinhans, 1970) was used. Each of 12 subjects looked into a Styrofoam box, 30 cm wide by 45 cm high by 60 cm deep. The box was open at one end, and could be pitched 10° up or down (fig. 2).

Illumination was very dim (0.5 cd/m^2) to minimize visibility of surface features, but the inside edges of the box could be seen clearly. The apparatus allowed the pitchbox to be displaced linearly up or down as well as to be changed in pitch orientation. The subject could indicate eye level by adjusting the vertical position of a small target (produced by a laser beam).

In this experiment, the subject was instructed to set the target to the point in the pitchbox that was at his or her GREL. A 2x2x3x2 design with replication was used. The experiment consisted of four within-subject factors: (1) viewing condition (dark vs. light), (2) pitchbox position (high vs. low: 6 cm apart), (3) pitchbox angle (10° up, level, or 10° down), and (4) laser starting position (up vs. down). Each factor combination was presented twice, yielding a total of 48 trials per subject.

RESULTS AND DISCUSSION

Box Pitch

Mean error of judged GREL is plotted in figure 3 as a function of orientation, position, and illumination of the pitchbox. It is clear that a strong effect of orientation on GREL exists in the light condition, but not in the dark. This can be described as a shift of judged GREL in the direction of true SREL. The magnitude of this shift is indicated by the slope of the judgment function. A total change in pitch (i.e., of SREL) of 20° produced a shift in GREL of 11.1° in the light, but only 1.5° in the dark. We will consider the slope of 0.55° (in the light) to be a measure of the strength of the effect of the visual environment. This effect is comparable in magnitude to that found by Matin and Fox (1986), and by Matin, Fox, and Doktorsky (1987). The simple fact of compromise between SREL and GREL means that T/G is not totally suppressed, even while T/S is operating, and is strong evidence against the suppression hypothesis.

Box Height

The effect of box height is clearly evident in the figure. The linear shift of the pitchbox of 6 cm (5.5° of visual angle) produced a 1.47 cm (1.35°) shift in GREL. This is comparable in magnitude to a similar linear displacement effect found by Kleinhans (1970). It may be due to the Dietzel-Roelofs effect (Howard, 1982, p. 302), where the apparent straight ahead is displaced toward the center of an asymmetrical visual display. Another possible explanation is a tendency for subjects to set eye level toward the same optically determined point on each successive trial. Whatever the cause of this effect, it may account for as much as 40% of the orientation effect, since with our apparatus, a change in orientation also produced a displacement of the visual scene.

Variability

It might be expected that conflict between two systems would greatly increase variability. For example, each system could contribute a component equal to its own variability, and there would be an additional component caused by variability in combining the systems. Figure 4 shows within-subject standard deviations calculated separately for each of the three orientations, in the light and the dark.

Here it can be seen that variability of judgment in the dark is higher than in the light; however, it is not affected by orientation. There is no more variability when the systems are in conflict (at ±10°) than when they are not (when the pitchbox is level, at 0°). This finding indicates that the weighting of the systems is very stable over a series of trials for each subject.

EXPERIMENT 3. THE EFFECT OF GRAVITY ON SREL JUDGMENTS

Introduction and Method

To observe the operation of T/S, we instructed the subject to align his or her line of sight with the floor of the movable pitchbox, thus judging the SREL. Just as we "turned off" T/S by extinguishing the light, we can turn off T/G by orienting the subject so that gravity does not abet the task. Each of 12 subjects judged SREL, both with upright posture, when they could presumably use gravitational information and T/G, and reclining on the left side, where gravity and T/G were of no use. (The T/H system presumably continued to operate in both conditions.) In the upright condition the method was identical to that of Experiment 2, except that the instructions were to find SREL rather than GREL. In the reclining condition the entire apparatus (shown in fig. 2) was rotated 90°.

As in Experiment 2, the pitchbox was set in two different positions displaced 6 cm along the subject's longitudinal body axis (Z axis).

Results and Discussion

Results are plotted in figures 5 and 6. ANOVA showed significant effects of box pitch and box height.

Box Pitch

There is a clear shift of SREL judgments in the direction of HREL in both the upright and reclining conditions. The slope is 0.15, much less than the 0.55 found in Experiment 2. (Note that, while Experiment 2 showed an effect of optical variables on a nonoptical judgment, the present experiment found an effect of nonoptical variables on an optical judgment.) The fact that the slope is essentially the same for both upright and reclining body orientations implies that T/H rather than T/G is producing the bias we obtained. This result is similar to that of Mittlestaedt (1983).

Box Height

The effect of the 6-cm box displacement was a shift of 2.47 cm (2.26°) in the upright and 3.5 cm (3.21°) in the reclining condition. The size of this effect implies that the subjects did not effectively use the optical orientation information available to them. Instead, they seem to have had a strong tendency to set the target near the same location on the back of the box with each trial.

Variability

Standard deviations for SREL judgments are shown in figure 7.

SREL judgments made with the subject upright showed greater within-subject variability than those made with the subject reclining. This observation may be taken to imply that gravity does not enhance the precision of SREL judgments under upright conditions.

EXPERIMENT 4: THE EFFECT OF GRAVITY AND PITCHED SURROUNDINGS ON HREL JUDGMENTS

Introduction and Method

To observe the influence of T/S on T/H, we instructed the subject to set his or her eyes "straight ahead" and place the target at the fixation point, thus judging HREL. In the upright condition the method was identical to that of Experiment 2, except that the instructions were to find HREL rather than GREL. The reclining condition arrangement was identical to that of Experiment 3.

Results and Discussion

Results are plotted in figures 8 and 9. ANOVA showed significant effects of orientation and box height.

Box Pitch

There is a clear shift of HREL judgments in the direction of SREL in both the upright and reclining conditions. The slope for the judgments of HREL with upright posture in the light is 0.45, about the same magnitude as was observed in Experiment 2. We thought that this effect could be due to a confusion of instructions when HREL and GREL were coincident, and we expected a much weaker effect in the reclining conditions, when GREL was absent. In fact, however, a much stronger effect was found (slope = 0.89). This can be explained in terms of Mittlestaedt's (1986) vector combination model. In the upright condition, both T/G and T/H indicate a more or less horizontal eye level, and T/S would be combined with both of these. In the reclining condition T/S combines with only T/H. The result in the reclining condition is thus closer to T/S.

Variability

It can be seen in figure 10 that, for upright posture, the variabilities of HREL and GREL judgments are very similar, both in the dark and in the light. For reclining posture, however, HREL variability is twice as great in the dark as in the light. This result indicates that the presence of gravitational information has a stabilizing effect on HREL judgments.

CONCLUSIONS

1. Increased precision in the light. We present evidence against both the suppression and the weighted average hypotheses. Only the stability hypothesis is not contradicted by these data. This hypothesis could be tested directly by using a random dot field as a visual environment. Such a field would have no direction information, so any improvement in precision of GREL would be by means of stability information.

2. Box displacement effect. This may be a significant factor in the orientation effect. It could be controlled in a future experiment by rotating the pitchbox around the center of its back, rather than around the subject's eye.

The large size of this effect when judging SREL indicates that ability to judge orientation of the line of sight in the pitch dimension relative to a surface on the basis of purely optical information is poor under the conditions of this experiment.

3. Head relative information. Perhaps our most surprising result was the almost complete "visual capture" of HREL judgments in the light while the subject was reclining on his or her side in Experiment 4, and the corresponding high variability of these judgments in the dark. Both of these results indicate very low ability to use T/H to judge eye level in the absence of gravity information. In more practical terms, this result indicates that judgment of the pitch of the observer's head (and by implication, the rest of his or her body) relative to a surface is much less precise, and subject to a much higher degree of visual capture, when gravity is not present to aid this judgment.

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TABLE 1. TYPES OF EYE LEVEL

Symbol	Type	Physiological system	Reference plane
HREL	Head-referenced eye level	Target/head (T/H)	Arbitrary plane tied to head
GREL	Gravity-referenced eye level	Target/gravity (T/G) (T/G = T/H + H/G)	Gravitational horizontal
SREL	Surface-referenced eye level	Target/Surface (T/S)	Ground surface or other visible plane surface

TABLE 2. MEANS AND STANDARD DEVIATIONS (DEG) FOR ERROR IN EYE-LEVEL JUDGMENTS IN LIGHT AND DARK, Average of 10 subjects (Stoper and Cohen, 1986)

	Light	Dark
Constant error (mean)	0.29	2.79
Variable error (standard deviation)	1.03	1.72

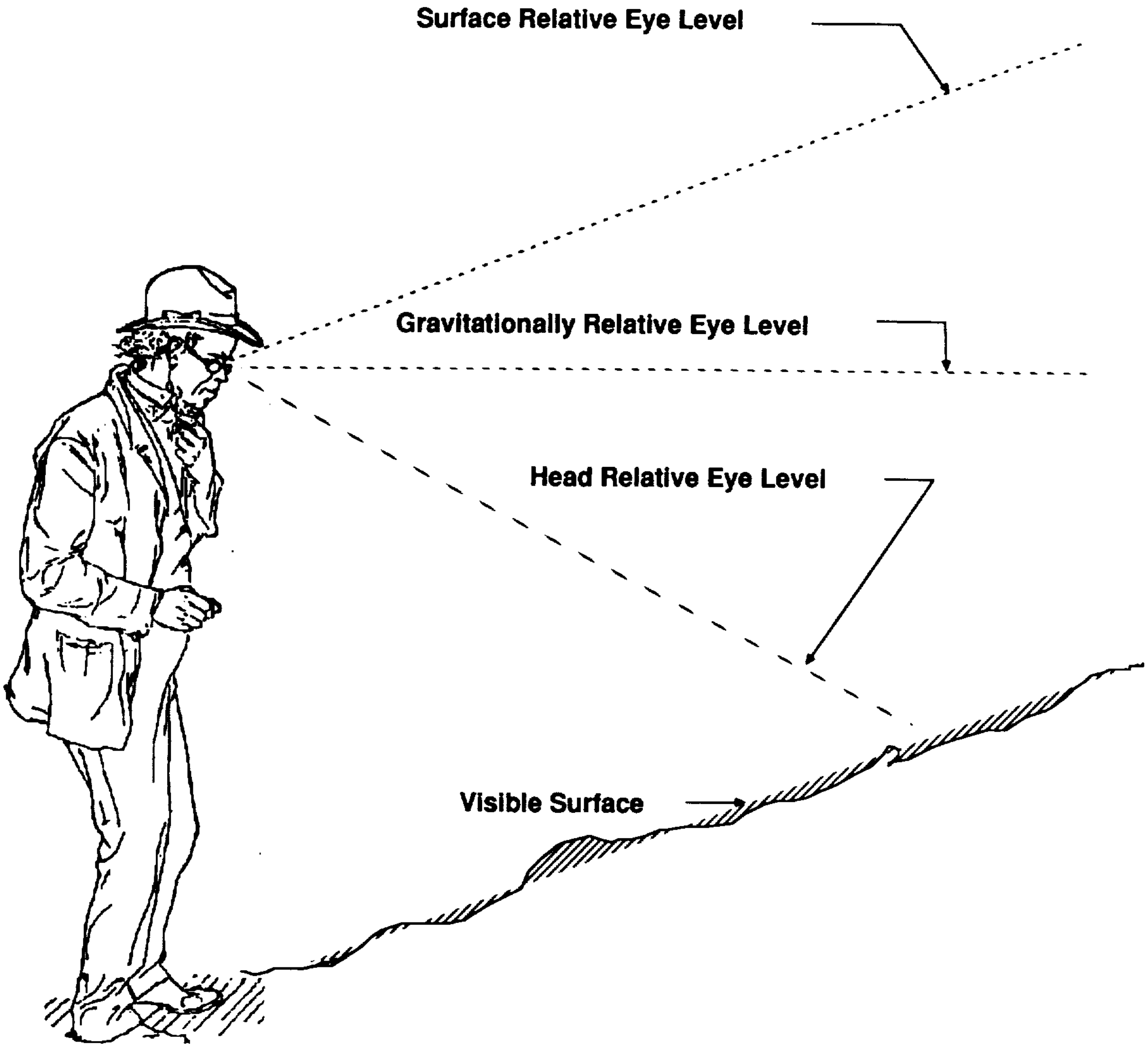

Figure 1.– Three types of eye level in normal terrestrial environment. See table 1 for description.

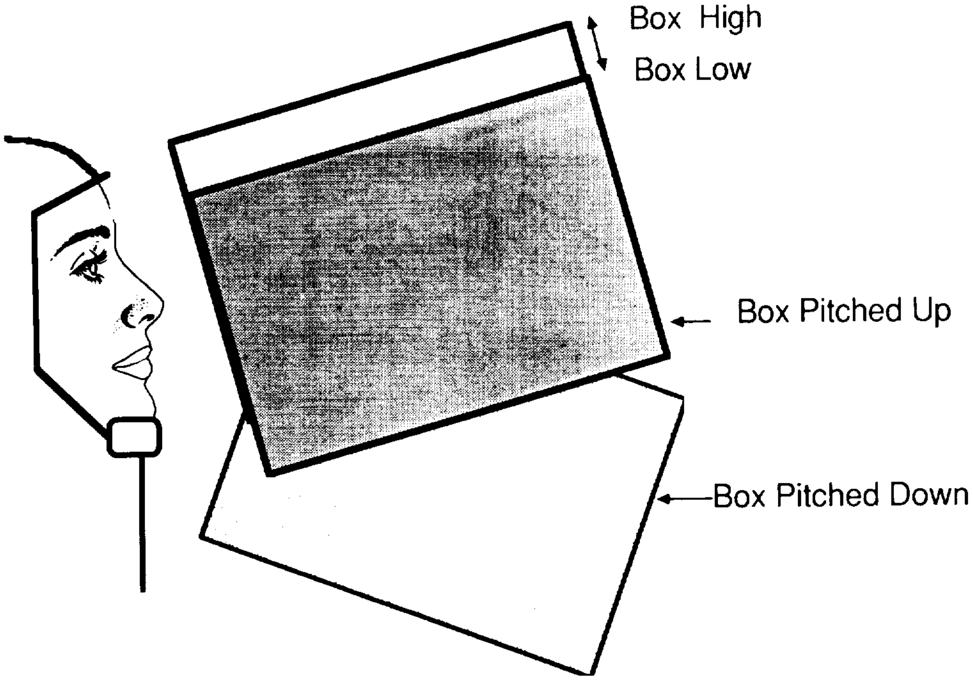

Figure 2.– Orientations and positions of the pitchbox.

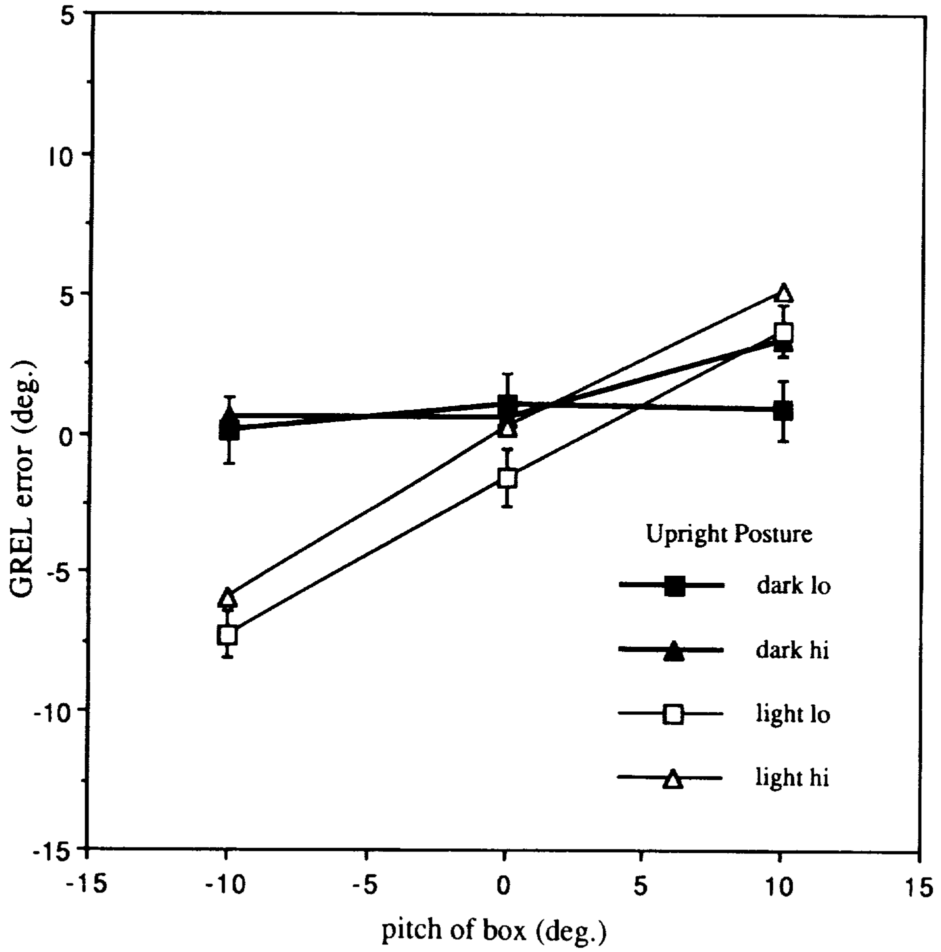

Figure 3.– Mean error in judgment of gravitationally relative eye level (GREL) of 12 subjects as a function of orientation, position, and illumination of the pitchbox. Pitch of +10° means the pitchbox was pitched up. Error bars represent the standard error of the mean (between subjects).

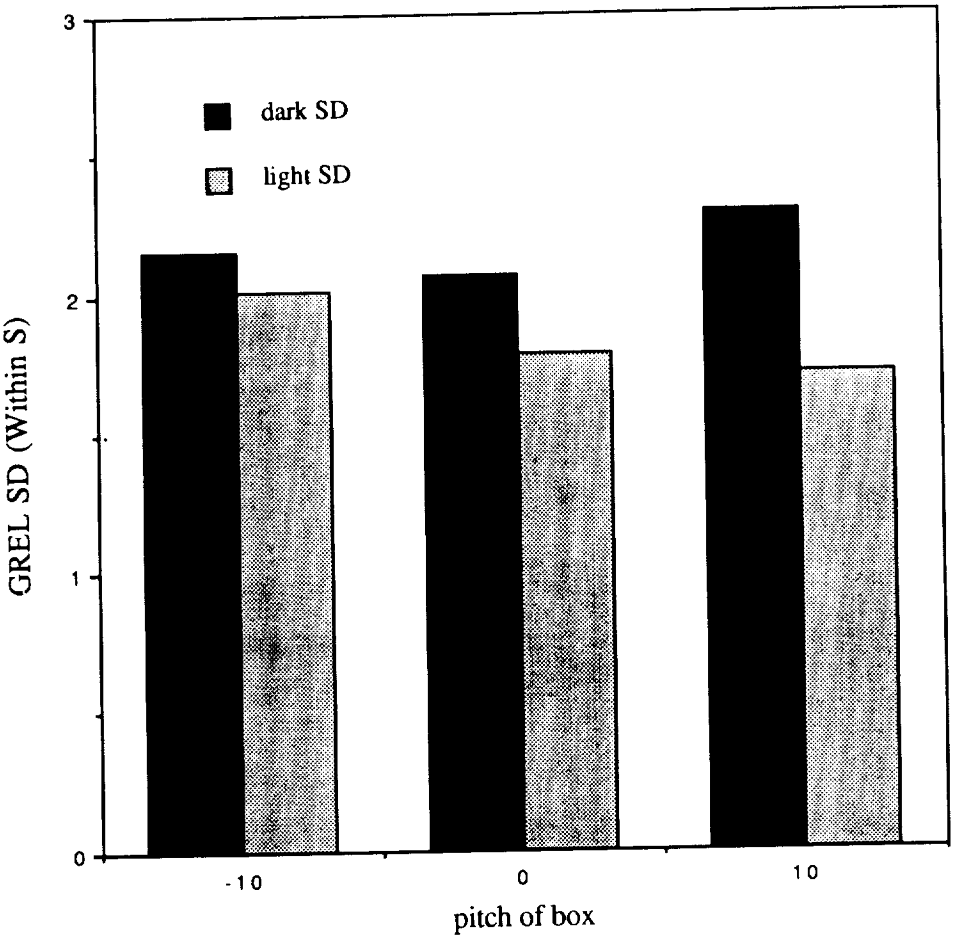

Figure 4.– Standard deviations (within subjects) of GREL judgments of 12 subjects for each of three orientations, in the light and in the dark.

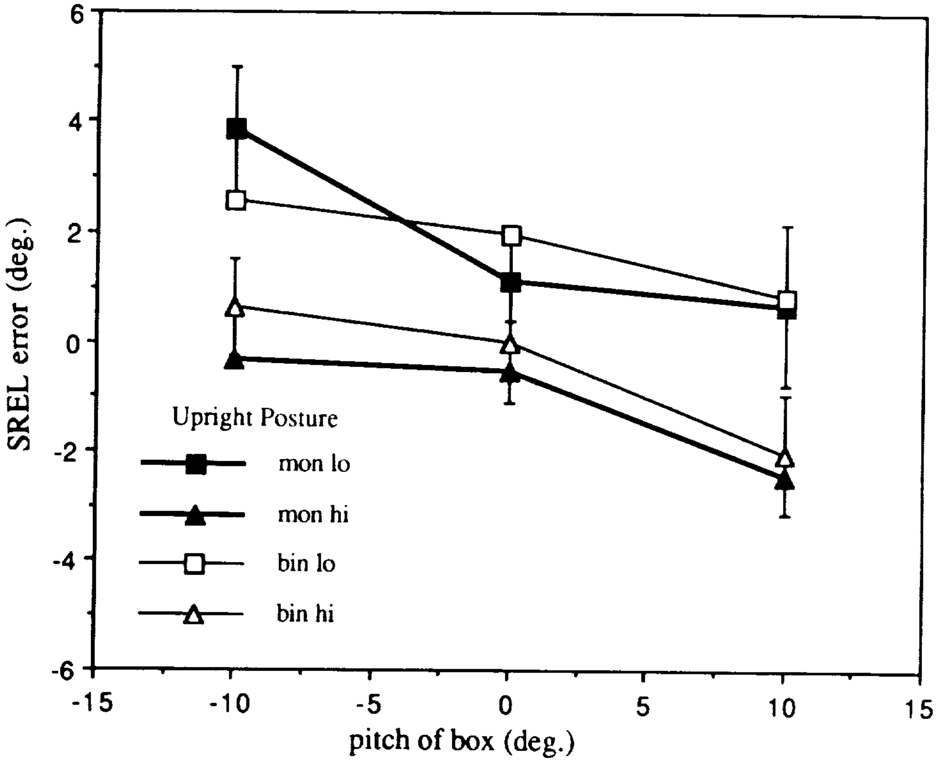

Figure 5.– Mean error in judgment of surface-relative eye level (SREL) of 12 subjects as a function of orientation, position, and illumination of the pitchbox; judgments made with upright posture. Error bars represent the standard error of the mean (between subjects).

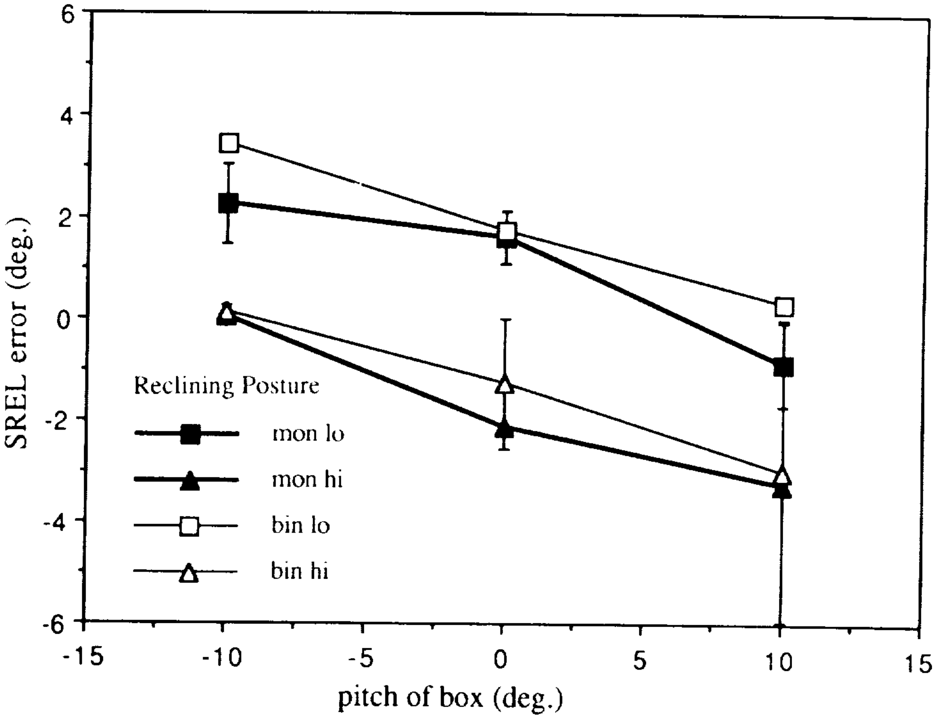

Figure 6.– Mean error in judgment of SREL of 12 subjects; judgments made with reclining posture.

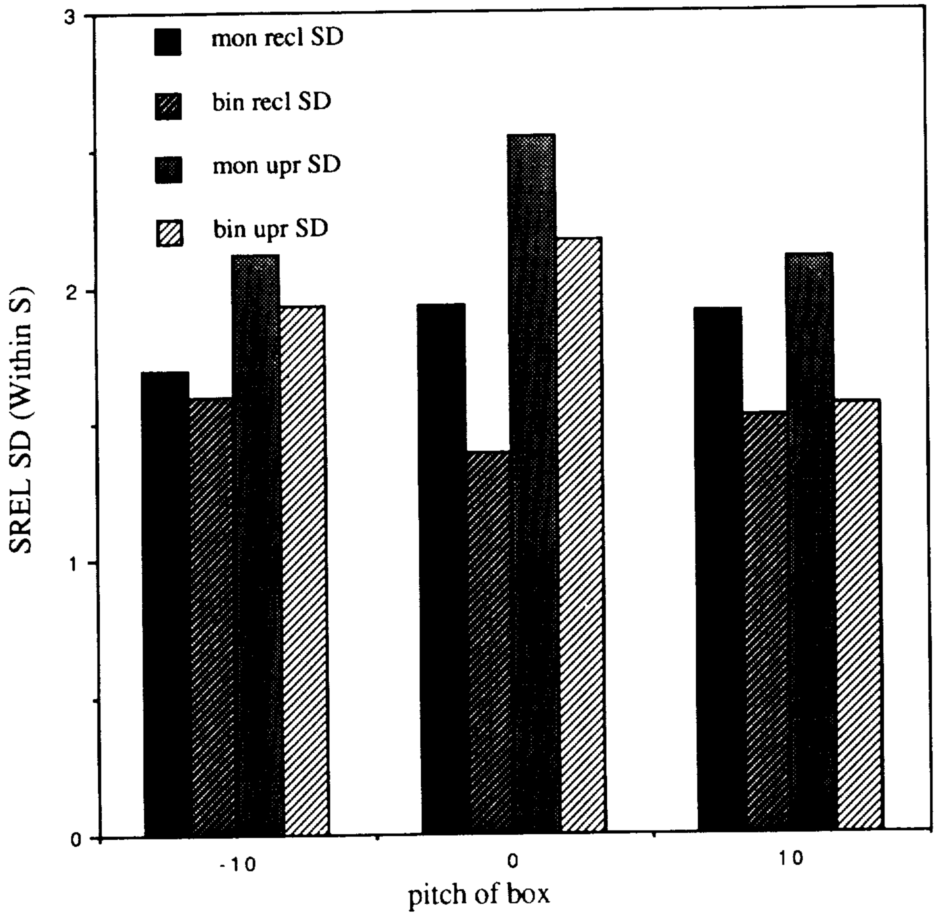

Figure 7.– Standard deviations (within subjects) of SREL judgments of 12 subjects for each of three orientations, in the light and in the dark.

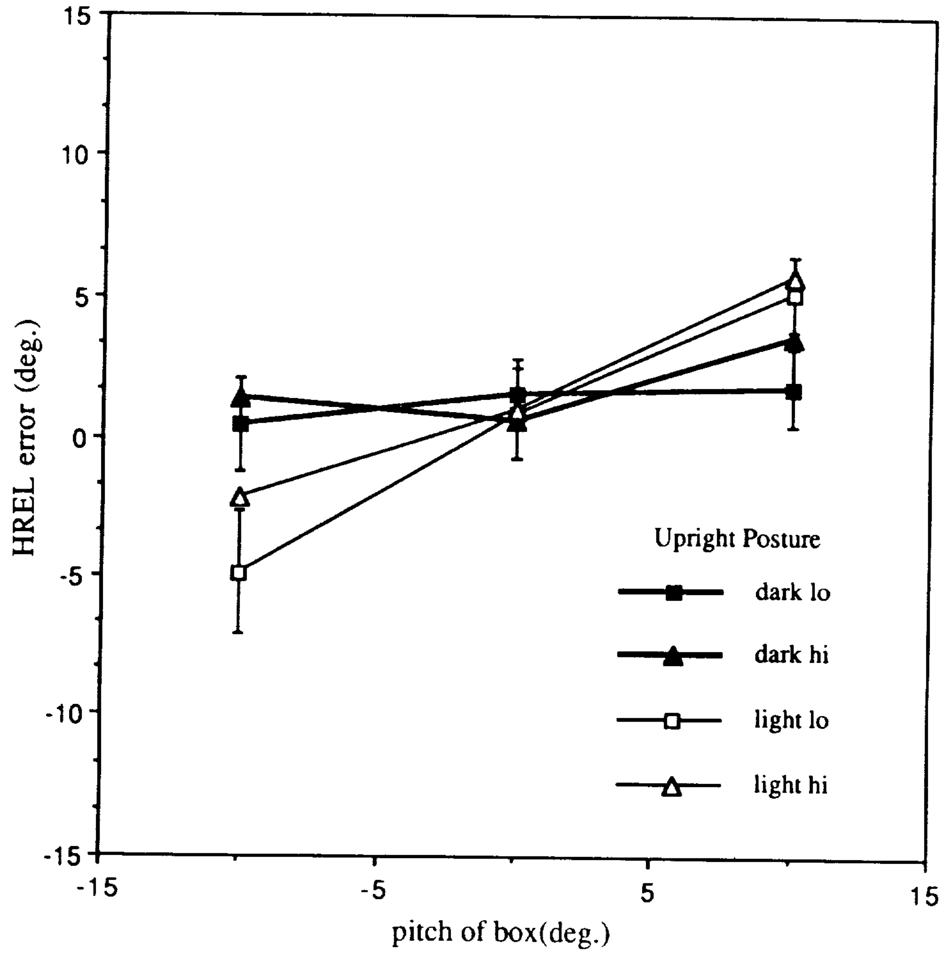

Figure 8.– Mean error in judgment of head-relative eye level (HREL) of 12 subjects as a function of orientation, position, and illumination of the pitchbox; judgments made with upright posture. Error bars represent the standard error of the mean (between subjects).

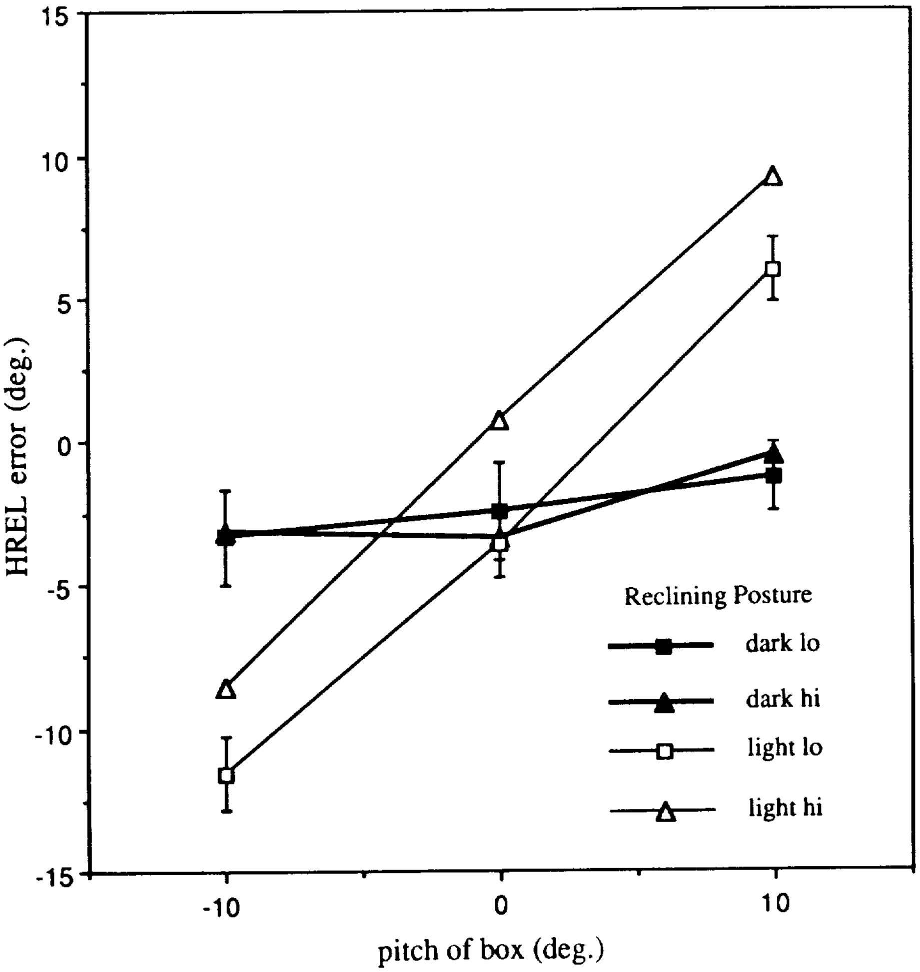

Figure 9.– Mean error in judgment of HREL of 12 subjects; judgments made with reclining posture.

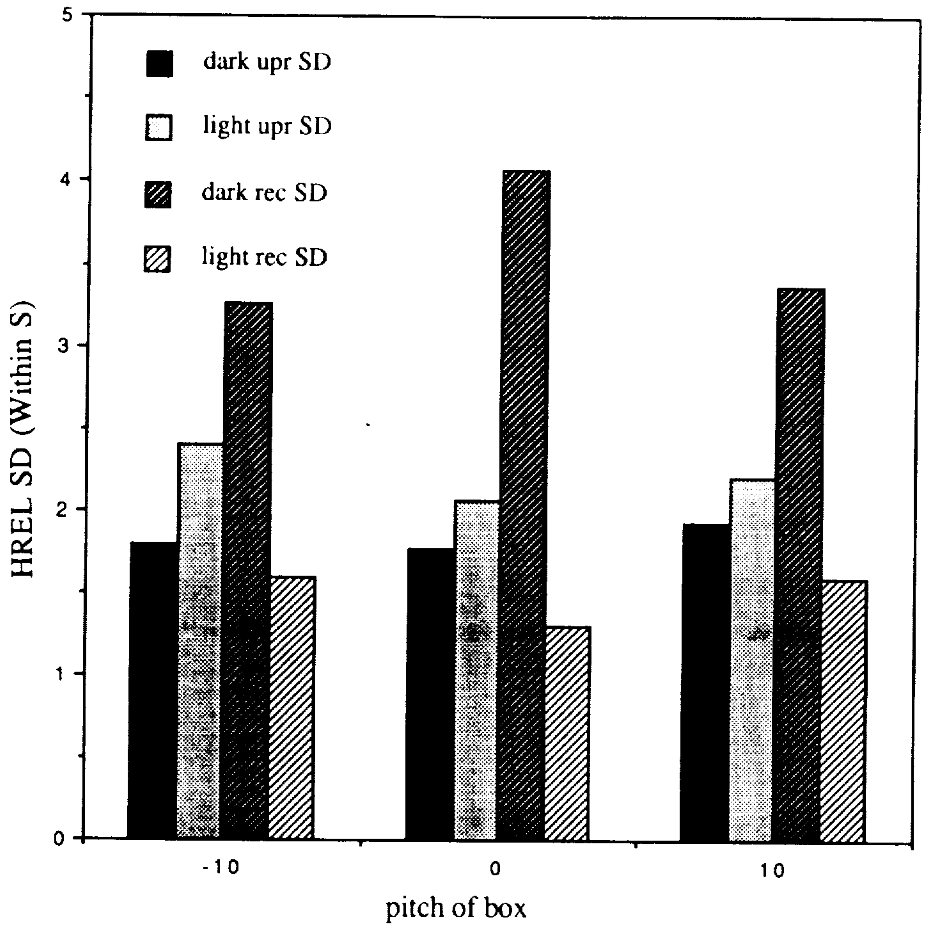

Figure 10.– Standard deviations (within subjects) of HREL judgments of 12 subjects for each of three orientations, in the light and in the dark.