Effects of gravitational and optical stimulation on the perception of target elevation

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To examine the combined effects of gravitational and optical stimulation on perceived target elevation, we independently altered gravitational-inertial force and both the orientation and the structure of a background visual array. While being exposed to 1.0, 1.5, or 2.0 G_z in the human centrifuge at NASA Ames Research Center, observers attempted to set a target to the apparent horizon. The target was viewed against the far wall of a box that was pitched at various angles. The box was brightly illuminated, had only its interior edges dimly illuminated, or was kept dark. Observers lowered their target settings as G_z was increased; this effect was weakened when the box was illuminated. Also, when the box was visible, settings were displaced in the same direction as that in which the box was pitched. We attribute our results to the combined influence of otolith-oculomotor mechanisms that underlie the elevator illusion and visual-oculomotor mechanisms (optostatic responses) that underlie the perceptual effects of viewing pitched visual arrays.

For well over a century, it has generally been agreed that the perceived location of a visual target depends on both retinal and extraretinal information (Bell, 1823; Helmholtz, 1866/1962; Hering, 1879/1942; Wade, 1978). Retinal information is derived from the image of the target on the retina, its location on the retina, and the shapes and locations of images of other objects in the visual field. Extraretinal information is derived from the orientation of the eyes, relative to the head, and from the orientation of the head, relative to an external frame of reference (e.g., gravity). When the relationship between an observer and the gravitational frame of reference is altered, as occurs when an observer is tilted with respect to gravity, or when the magnitude of the gravitational-inertial force (GIF) is increased or decreased, the apparent locations of objects are usually altered as well.

Two illusions, the oculogravic illusion and the elevator illusion, involve errors in the perceived elevation of a vi-

sual target when the target is being viewed by an observer exposed to altered GIFs (Cohen, 1973; Graybiel, 1952; Schöne, 1963; Whiteside, Graybiel, & Niven, 1965). The oculogravic illusion occurs when an observer is exposed to a change in both the direction and the magnitude of the GIF; the observer experiences not only a change in the apparent location of an isolated visual target, but a change in the apparent orientation of the surrounding visual array as well. The elevator illusion occurs when an observer is exposed to a change in the magnitude, but *not* the direction, of the GIF; an isolated visual target will appear to be above its true location when it is viewed in hypergravity and to be below its true location when it is viewed in hypogravity. The elevator illusion is greatly attenuated (and possibly even eliminated) when the target is viewed in the presence of a structured visual array (DiZio, Li, Lackner, & Matin, 1997; Schöne, 1963); however, specific quantitative data regarding the degree of attenuation, as a function of optical structure, has not previously been reported. The elevator illusion has been attributed to changes in oculomotor control that result from atypical stimulation of the otolith organs when they are exposed to altered gravitational-inertial conditions (Cohen, 1973, 1992, 1996).

Altered gravitational-inertial conditions are not the only means by which changes in the apparent locations of visual targets can be brought about; changes in the orientation of the visual background against which a target is viewed can have similar effects. For example, when a

This work was funded by NASA Grant UPN 199-16-12-08 to M.M.C. We thank Abigail Bautista, Greg Breit, Jon Griffith, Dan Gundo, and Gerald Mulenburg for their superb technical support in conducting these studies. We are also grateful to Ralph Pelligra and Donald Peeler for their careful and professional medical monitoring of the observers in the human-rated centrifuge. Finally, we acknowledge the many helpful comments and suggestions on earlier drafts of this paper that were provided by Sheldon Ebenholtz, Larry Guzy, Leland Stone, and David Tomko. Correspondence should be addressed to M. M. Cohen, NASA Ames Research Center, Mail Stop 262-2, Moffett Field, CA 94035-1000 (e-mail: mmcohen@mail.arc.nasa.gov).

background optical array is not aligned with the observer's body, as occurs when the array is pitched (i.e., rotated upward or downward about an observer's left-right body axis), it can produce dramatic illusory changes in the apparent elevation, or height, of a visual target. The array can comprise a small box (Cohen, Ebenholtz, & Linder, 1995; Kleinhans, 1970; Stoper & Cohen, 1989, 1991), an entire room (Cohen et al., 1995; Matin & Fox, 1989), or even individual tilted lines (DiZio et al., 1997; Matin & Li, 1992, 1994).

To evaluate the relative contributions of retinal and extraretinal information on the ability to localize a visual target, we systematically altered (1) the orientation of the optical array, (2) the structure of the array, and (3) the intensity of the GIF. The observers were exposed to various intensities of G_z while they looked into a pitchbox that was set at various orientations with different optical structures. In repeated trials, our observers adjusted the position of a target so that it appeared to be at their horizon.¹

METHOD

Observers

Eighteen individuals, 15 male and 3 female, served as observers in this experiment; they ranged in age from 31 to 60 years (median age was 37.5 years). Sixteen observers were naive as to the purpose of the study and were paid for their participation. Two observers were fully aware of the purpose of the experiment and were not paid—one was an author of this paper (M.M.C.), and the other was the Medical Services Officer at the Ames Research Center (R.P.). Prior to serving as observers, all individuals were required to undergo and pass a thorough medical examination at an independent medical facility. They each read and signed a document indicating informed consent; they were screened for tolerance to acceleration on the centrifuge and had to demonstrate their ability to withstand without difficulty more than 5 min of continuous exposure to 2.0 G_z . All had 20/30 vision or better, either uncorrected or corrected by eyeglasses or contact lenses.

Apparatus

As illustrated in Figures 1 and 2, each observer was seated on a freely swinging chair that faced radially outward from the center of the darkened gondola in the human-rated centrifuge at Ames Research Center. The distance from the axis of rotation of the centrifuge arm to the pivot point on the chair was approximately 7.62 m. For each observer, the chair was balanced so that GIF would be increased only along the z (head to foot) body axis. A triaxial accelerometer, mounted on the chair at the level of the observer's ears, was used to verify that changes in the GIF were restricted to the z body axis. Throughout the experiment, a closed circuit infrared video system allowed both the experimenter and the medical monitor to view the observer in the centrifuge.

A tightly fitting helmet, rigidly attached to the chair, stabilized the position of the observer's head so that the bridge of the observer's nose was centered with respect to the pitchbox. While the observer was comfortably seated upright in the chair, the height of the seat was adjusted such that the observer's eyes were positioned at the same height as the pivot axis of the pitchbox, which measured $30.5 \times 30.5 \times 45.7$ cm in depth, width, and height, respectively.

The pivot axis ran horizontally through the center of the rear surface of the box; the distance from the bridge of the observer's nose to the pivot axis was 53.5 cm. White graph paper covered all interior

walls of the box; the paper was marked at intervals of $\frac{1}{8}$ in. (3.175 mm) with green lines that were aligned with the interior edges.

The box was fitted with eight electroluminescent strips, each about 6.3 mm wide, that defined all eight interior edges; thus, four of the illuminated edges defined the rectangular distal surface, and four protruded from the corners of the surface toward the observer, along the outer edges of the floor and ceiling of the box. The four edges closest to the observer at the open end of the box were not illuminated. The electroluminescent strips were the sole source of illumination.

When viewed at the rear of the box, the vertical lines subtended about 45° visual angle from top to bottom and were laterally separated by approximately 31°. Along the center of the rear wall, a light-emitting diode (LED) was mounted in a track that ran from the top to the bottom of the box. An electric motor, operated by either the observer or the experimenter, was used to adjust the vertical position of the LED in its track. Another motor, operated only by the experimenter, was used to set the pitch orientation of the box.

Experimental Design

The experiment consisted of 27 test conditions that were derived by combining three conditions of optical structure with three orientations of the pitchbox and three intensities of GIF. The optical structure conditions were the following: (1) The box was brightly illuminated, and all interior details, as well as the LED target, were fully visible; (2) the box was dimly illuminated by the electroluminescent strips that defined its interior edges (the observers reported that only the strips and the LED target were visible); and (3) the box was dark, except for illumination of the LED target itself. The three orientations of the pitchbox were the following: (1) The box was pitched upward 20° (i.e., top toward the observer); (2) the box was level; and (3) the box was pitched downward 20°. The three intensities of

Figure 1. The observer, seated upright at 1.0 G_z , viewing a target at eye level on the far wall of the pitchbox. The pitchbox is shown in three orientations: +20° (top of far wall rotated toward the observer), 0° (pitchbox level), and -20° (top of far wall rotated away from the observer). The toggle switch on the armrest controlled the elevation of the target inside the pitchbox.

Figure 2. The observer, seated upright at $2.0 G_z$, viewing a target at eye level on the far wall of the pitchbox in three orientations: $+20^\circ$, 0° , and -20° .

the GIF were the following: (1) The centrifuge motor was engaged, and the centrifuge arm was rotated at 3.00 revolutions per minute, which provided $1.0029 G_z$ (nominally, $1.0 G_z$) at the observer's head; (2) the centrifuge was rotated at 11.46 revolutions per minute, providing $1.5 G_z$ at the observer's head; and (3) the centrifuge was rotated at 14.26 revolutions per minute, providing $2.0 G_z$ at the head.

The experimental conditions of optical structure and pitchbox orientation were counterbalanced across the 18 observers. Six of the observers were exposed to the fully illuminated box in their first session; 6 were exposed to the box defined by the luminescent strips in their first session; and 6 were exposed to the darkened box in their first session. Within each condition of optical structure, the orientation of the box was set according to the sequence -20° , 0° , $+20^\circ$, $+20^\circ$, 0° , -20° for 3 of the observers, and according to the sequence $+20^\circ$, 0° , -20° , -20° , 0° , $+20^\circ$ for the other 3 observers. The sequence of G_z within each session was determined according to a Latin-square design. At the beginning of each session, the centrifuge was totally dark, and G_z was increased along a 30-sec haversine until the experimentally required value of G_z was reached.

Data Collection

The experimental data were fed from the centrifuge gondola via slip rings to an IBM 386 personal computer; a Labtech notebook program was used to collect, store, and provide on-line processing of the data. Subsequent statistical analyses were conducted off line.

Data collection was not initiated until approximately 1 min after the centrifuge had achieved the desired steady-state G_z . On alternating trials, the experimenter set the target either near the top or near the bottom of the pitchbox. The observers used a toggle switch to adjust the position of the target so that it would appear to be at their horizon. After positioning the target, they pressed a button that automatically registered the location of the target. The experimenter repositioned the target, and the observers again attempted to place it at their horizon. The experimenter then set the box at a new orientation, and the same procedure was repeated until four settings at

apparent eye level were obtained for each observer at each of the three pitchbox orientations. All viewing was binocular. Whenever the experimenter adjusted the position of the target or the orientation of the box, the observers were instructed to close their eyes; compliance was verified via the closed circuit video monitor.

The centrifuge was brought to a stop in a descending G_z haversine curve; the observers then rested until they and the medical monitor agreed to continue the session. The centrifuge was again rotated, and the same procedure was repeated for each level of G_z . At least 24 h elapsed between individual sessions.

RESULTS AND DISCUSSION

The results are summarized in Table 1 and in Figures 3 and 4. As verified by analysis of variance (ANOVA) and regression analyses, the observers set the targets progressively lower as the magnitude of G_z was increased [$F(2,34) = 47.23, p < .001$]. Thus, a target that remained at true eye level would appear to be more elevated with each increase in G_z . Similarly, the settings of the target varied with changes in the orientation of the pitchbox in which the target was viewed; the settings were biased in the same direction as that in which the box was pitched [$F(2,34) = 122.13, p < .001$]. Thus, a target at true eye level appeared to be higher when the box was pitched downward and lower when the box was pitched upward. The optical structure of the pitchbox also influenced settings of the target. Overall, settings made in the dark tended to be lower than those made when the pitchbox was dimly illuminated by the electroluminescent strips or when its interior was fully illuminated [$F(2,34) = 19.32$,

Table 1
Effects of Optical Structure, Pitchbox Orientation,
and G_z on Setting a Target to Apparent Eye Level
(Mean Elevation $\pm$ Standard Error For 18 Observers)

Orientation	1.0 G_z	1.5 G_z	2.0 G_z
Pitchbox Fully Illuminated			
-20°	-10.0° $\pm$ 1.4°	-12.1° $\pm$ 1.8°	-14.1° $\pm$ 1.8°
0°	-1.0° $\pm$ 0.9°	-2.1° $\pm$ 1.1°	-3.2° $\pm$ 1.2°
+20°	+8.0° $\pm$ 1.5°	+6.4° $\pm$ 1.7°	+4.3° $\pm$ 2.0°
Pitchbox Defined By Electroluminescent Strips			
-20°	-9.9° $\pm$ 1.5°	-12.9° $\pm$ 1.3°	-14.3° $\pm$ 1.5°
0°	-0.5° $\pm$ 0.7°	-2.9° $\pm$ 0.8°	-4.2° $\pm$ 1.1°
+20°	+8.7° $\pm$ 1.6°	+5.4° $\pm$ 1.7°	+3.5° $\pm$ 2.0°
Pitchbox Dark			
-20°	-3.0° $\pm$ 1.1°	-8.6° $\pm$ 1.2°	-11.7° $\pm$ 1.5°
0°	-1.8° $\pm$ 1.1°	-7.8° $\pm$ 1.3°	-11.9° $\pm$ 1.5°
+20°	-0.9° $\pm$ 1.2°	-6.9° $\pm$ 1.3°	-10.3° $\pm$ 1.6°

$p < .001$]. Furthermore, the effects of optical structure significantly interacted with the effects of both G_z [$F(4,68) = 12.51, p < .001$] and pitchbox orientation [$F(4,68) = 65.78, p < .001$].

As revealed by separate ANOVAs and by regression analyses of the data obtained from each of the three conditions of optical structure, the effects of increased G_z depended strongly on how, or whether, the pitchbox was illuminated. These effects are summarized in Table 2. When the pitchbox was dark, the apparent elevation of the target changed at a mean rate of 9.41° per G_z [$F(2,34) = 34.46, p < .001$]. When the electroluminescent strips dimly il-

luminated the box, the effect was reduced to 4.44° per G_z [$F(2,34) = 32.56, p < .001$], a reduction of 53%. When the box was fully illuminated, the effect was reduced to 3.30° per G_z [$F(2,34) = 17.48, p < .001$], a reduction of 65%. Despite the assertion made by Schöne (1963) that this effect of increased G_z does not occur with a well-structured optical array, it was not eliminated, but merely attenuated, even in the presence of the fully illuminated pitchbox.

In the dark, the orientation of the pitchbox had an extremely small, but nonetheless statistically significant influence [$F(2,34) = 11.72, p < .001$] on settings of the target, with a mean slope of 0.04° per degree of box pitch. We believe that this small effect could possibly have resulted from the path followed by the LED in its track on the far wall of the box. As demonstrated by Matin and Li (1994), even a single pitched line can influence the apparent elevation of a visual target; in the present study, the sequential positions of the LED on the far wall of the box traced out such a pitched line. It is also possible that the LED alone might have provided sufficient illumination for the observers to be affected by changes in the orientation of the pitchbox, even when the box itself was not intentionally illuminated.

The orientation of the pitchbox influenced settings of the target much more strongly when the box was fully illuminated [$F(2,34) = 110.30, p < .001$] and when it was dimly illuminated by the electroluminescent strips [$F(2,34) = 95.91, p < .001$] than when the box was dark. For both of the former conditions, the slope was virtually the same, between 0.45° and 0.46° per degree of box pitch

Figure 3. The effects of GIF at 1.0, 1.5, and 2.0 G_z for various orientations of the pitchbox when the full box was visible, when only the strips were visible, or when the box was dark. Open circles are settings to eye level at a pitchbox orientation of 20°. Triangles are setting values at 0°, and diamonds are setting values at -20°. Error bars show the mean standard errors across subjects for each of the orientations of the pitchbox.

Figure 4. The effects of pitchbox orientation at -20° , 0° , and $+20^\circ$, when the full box was visible, when only the strips were visible, or when the box was dark. Open circles represent target settings at $1.0 G_z$, triangles represent setting values at $1.5 G_z$, and diamonds represent setting values at $2.0 G_z$. Error bars show the mean standard errors across subjects for each of the G_z values.

(see Table 3). This finding, which is consistent with the results reported by Matin and Li (1992), suggests that the visual stimulation caused by the pitch orientation of the box provided a 45%–46% bias in setting the elevation of the target when it was viewed against the illuminated box as a background.

Although the apparent elevation of the target clearly was affected by the orientation of the pitchbox, the influence of pitchbox orientation (i.e., the rate of change in target settings per degree of box pitch) was not significantly altered by the magnitude of G_z [$F(4,68) = 0.96$, $p > .05$] across the range of conditions examined here. This finding is in close agreement with the observations reported by DiZio et al. (1997), but stands in sharp contrast to the results reported by Chelette, Li, Esken, and Matin (1995), who showed a diminishing influence of pitch orientation as the GIF was increased to $4.0 G_z$ in increments of $1.0 G_z$. In the present study, when the pitchbox was partially or fully illuminated, the rate of change in target settings resulting from orientation of the box was essentially the same at 1.0 , 1.5 , and $2.0 G_z$, between 0.45° and

0.46° per degree of box pitch. The bases for the divergence of the present results and those of DiZio et al. from the results reported by Chelette et al. are uncertain, although differences in stimulus condition and display might offer plausible explanations.

The study by Chelette et al. (1995) had observers monocularly view extremely dim pairs of pitched lines that were well into the peripheral field of vision, $\pm 25^\circ$ from the observer's midline; this should be contrasted with the eccentricity of about $\pm 15.5^\circ$ used in the present study. It is well established that bloodflow to the peripheral retina is progressively compromised and the sensitivity of the peripheral retina is reduced as the intensity of GIF is increased (Christy, 1961; Duane, 1953). Thus, the decreasing effectiveness of the pitched lines on apparent target elevation with the increasing GIF that was reported by Chelette et al. might have simply been because the increased GIF diminished the observer's ability to detect the dim lines in the peripheral field, and not because of any intrinsic interaction between the effects of retinal pitch and the magnitude of the GIF. That no effect of increased GIF was obtained by DiZio et al. (1997) with stimuli similar to those used by Chelette et al. might have been due to the relatively small increase in GIF, from 1.0 to $1.5 G_z$, in the DiZio study.

Matin and Fox (1989) have suggested that visually perceived eye level (VPEL) is determined by linearly additive influences of the pitch of the visual field and of gravity. Their model, which is similar to that proposed by Stoper and Cohen (1989, 1991), assumes that there are two independent sources of influence. One source is the visual array based on retinal information (V), and the

Table 2
Effects of G_z With Various Optical Structures and
Pitchbox Orientations (Mean $\pm$ Standard
Error of Slope for 18 Observers)

Orientation	Full Box	Strip Box	Dark Box
-20°	-4.08 ± 0.07	-4.47 ± 0.94	-8.75 ± 1.47
0°	-2.15 ± 0.03	-3.66 ± 0.62	-10.06 ± 1.14
$+20^\circ$	-3.69 ± 0.24	-5.19 ± 0.81	-9.41 ± 1.41
Mean	-3.30 ± 0.05	-4.44 ± 0.79	-9.41 ± 1.34

Note—Slope values are degrees of change in target elevation per G_z .

Table 3
Effects of Pitchbox Orientation With
Various Optical Structures and Values of G_z
(Mean + Standard Error of Slope for 18 Observers)

G_z	Full Box	Strip Box	Dark Box
1.0	$0.45 \pm <0.01$	$0.46 \pm <0.01$	$0.05 \pm <0.01$
1.5	0.46 ± 0.02	0.46 ± 0.03	$0.04 \pm <0.01$
2.0	0.46 ± 0.05	0.45 ± 0.04	0.04 ± 0.02
Mean	0.46 ± 0.02	0.46 ± 0.02	0.04 ± 0.01

Note—Slope values are degrees of change in target elevation per degree of box pitch.

other is a body-referenced mechanism that is based on nonretinal (mostly somesthetic and vestibular) information (B). The model may be summarized as follows:

$$VPEL = k_v(V) + k_b(B).$$

The relative weightings of V and B are given by the terms k_v and k_b , respectively, where $k_v + k_b = 1$. Previous studies in our laboratory and elsewhere have typically reported values of k_v in the range of .35–.65 when a well-structured pitched visual array is viewed by an upright observer in a normal terrestrial (1.0 G_z) environment. According to Matin and Fox, when an observer views a single target in the dark, $k_v = 0$ and $k_b = 1$.

Our model asserts that both mechanisms influence the direction of gaze when the observer attempts to direct his eyes to a specific location in external space. Thus, when the observer believes that his/her direction of gaze is directed to the horizon, there is actually a systematic deviation from this gaze direction that can be determined (1) by the orientation of the visual array on the retina (Cohen et al., 1995), (2) by nonretinal information (e.g., by vestibular stimulation; Cohen, 1996), or (3) by both (Cohen, 1999).

In the present study, we have preserved, under all G_z conditions, the same fixed orientations of the visual display relative to the observer (i.e., +20°, 0°, and –20°). The direction of the GIF was unchanged, whereas its magnitude was increased. Our experimental data have shown k_v to be approximately 0.45°–0.46° per degree of box pitch, a value that was virtually identical at 1.0, 1.5, and 2.0 G_z , whenever the pitchbox was illuminated. Thus, for the present data, according to the model, k_b , the weighting of the body-based, or nonretinal, influences, can be given by $(1 - k_v)$, which equals about 0.54. If the weighting values k_v and k_b remain constant under all G_z conditions, and if the influences of V and B are independent of one another, the following numerical values apply for our pitchbox when it provided a well-structured visual array:

$$VPEL = .46(V) + .54(B)$$

where V is information concerning the pitch orientation of the visual array, and B is information regarding the pitch orientation of the body. This general formulation applies whenever the structure of the visual array is such that it provides information regarding its own orienta-

tion. Changes in intensity of the GIF that are not accompanied by changes in its direction have no effect on the relative weightings.

When the pitchbox was dark, the settings of target elevation changed at a rate of $-9.41\%/G_z$, considerably more than when the pitchbox was visible. The interaction between pitchbox orientation and G_z magnitude is particularly interesting. For example, consider a pitchbox in which the far wall is parallel to the GIF (i.e., 0° box pitch). Simply because it is visible, the box reduces the influence of increased G_z on apparent target elevation. However, if the box is pitched upward, thus causing a target at objective eye level to appear below its true position, the orientation of the pitchbox will counteract the effects of increased G_z , which, alone, would cause the target to appear above its true position. Similarly, if the box is pitched downward, thus causing a target at true eye level to appear above its objective position, the orientation of the pitchbox can work in the same direction as the effects of increased G_z , which, alone, would cause the target to appear above its true position. Thus, a structured optical array can not only attenuate the effects of increased G_z , since it diminishes the elevator illusion, but it can also produce an additional, independent influence, depending on the array's orientation with respect to gravity.

These two effects are probably due to different underlying physiological mechanisms. As demonstrated by Cohen (1996), the elevator illusion is related to otolith-oculomotor responses, which cause the eyes to be driven downward during exposure to increased G_z . The attenuation of the elevator illusion appears to be due to visual suppression of the otolith-oculomotor signals that results from the viewing of a structured visual array (Cohen, 1999). In contrast, the biasing effects of the pitched visual array are probably due to an optostatic response (Crone, 1975) that occurs when observers view such a visual stimulus. As demonstrated by Cohen et al. (1995), when a pitched visual array is viewed, the eyes of the observer deviate in the same direction as that in which the array is pitched. This optostatic effect appears to be superimposed on any otolith-oculomotor drive that results from gravitational stimulation and that could be attenuated in the presence of the visual array.

Thus, our experiment raises some interesting and potentially very important theoretical and operational questions. For example, is it possible to provide sufficient optical structure that would eliminate the elevator illusion entirely? Will larger magnitudes of G_z overcome the stabilizing effects of optical structure when optical structure is not lost because of reduced peripheral retinal sensitivity? Can these results be of help in designing practical antidisorientation displays for use in hypergravity environments? Answers to these questions must await additional research.

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NOTE

1. The terms *horizon* and *eye level* are used interchangeably in this paper. Both terms refer to a plane that passes through the center of an observer's eyes and that is orthogonal to the net GIF acting on the observer. For a person who is standing erect on a horizontal floor, the horizon and eye level are both given by the height of the observer's eyes above the floor. In the context of this experiment, the observer was instructed to place the target so that it appeared to lie in the plane that was orthogonal to the GIF and would pass through the center of the observer's eyes when the observer's gaze was perceived to be orthogonal to the GIF.

(Manuscript received October 26, 1999;
revision accepted for publication April 7, 2000.)