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# Postural Stability and Stereo-Ambiguity in Man-Designed Visual Environments

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*Abstract*—**Our modern rectilinear visual environment contains visual stimuli for which evolution has not had time to optimally shape visual processing. One such stimulus, periodic stripes, is known to lead to visual depth ambiguity. In this paper we show that postural instability, as measured by the variance of fore and aft sway, is increased by viewing such stimuli. This instability may be the precursor of falls. Designers must evaluate the visual impressions conveyed by their systems in order to avoid postural instability due to visual ambiguity.**

## I Introduction

We have been investigating effects of stereoambiguous visual stimuli, and in particular, of the stimulus provided by an escalator tread In a prior paper [1] we showed that such stimuli cause subjective disorientation and we hypothesized that the cause lay in the "wallpaper illusion " We offered the conjecture that such disorientation is a manifestation of a chain of events that can, albeit rarely, culminate in a fall Briefly, the stereoambiguous stimulus gives rise to false fusion, a stable but inappropriate angle of visual convergence This leads both to disorientation and to postural instability, the latter possibly leading to a fall The main focus in this paper is measurements of postural stability in the presence of a stereoambiguous stimulus We show here, for the first time, the existence of several elements of the theoretical chain of events a) inappropriate binocular convergence consistent with false fusion and the wallpaper illusion, b) heightened postural instability, and c) correlation between subjective disorientation and postural instability

### *Background*

Many take for granted that humans can stand upright on two legs with "correct posture " But the orientation of the human body with respect to gravity is an active skill involving years of learning and coordination of dozens of muscles, of our vestibular nervous system, and of our sense of sight [2]. As with other human skills, the standard of perfect posture is rarely, if ever, achieved The residual minimum level of random activity is called postural sway [3], [4] Under some circumstances postural sway can be increased to the point where we "lose our balance" and fall [5], [6]

### *Role of Vision in Postural Stability*

Lee and Lishman [6] (and others [7], [8]) have demonstrated that posture can be manipulated in the laboratory by controlling the visual stimuli They created a moveable room which could be viewed from a stationary platform The observer was not informed that the room was suspended from above and could be controlled to swing or oscillate left–right with respect to his frame of reference, with chosen amplitudes and frequencies Despite the constancy of the gravitational cues, the observer's postural center of gravity was observed to vary with the same frequency as the swinging room As the amplitude of the sway of the swing was increased, the amplitude of the observer's postural sway increased to the level that subjects occasionally lost their balance Clearly visual cues are afforded great importance in the maintenance of posture, and may even supercede the sensing of gravity [7]

Normally, as we move about the world, we need not worry about swinging rooms or other artificial manipulations of the visual environment However, as visual patterns in our environment have become increasingly rectilinear (lines and edges), we have been confronted with visual stimuli that increase the demands upon our capacity for interpretation The central question asked here is can an interaction of the visual system with certain visual patterns modify our postural stability?

### *Visual Patterns and Stereo-Ambiguity*

Visual space can be thought to have three dimensions up–down, left–right, and fore–aft It is in the latter dimension, mediated in part by the perception of depth (stereopsis), where ambiguities can potentially cause changes in postural stability

In some cases, stereo-ambiguity arises with visual stimuli occurring in common everyday situations One example of this is the "wallpaper" illusion The "wallpaper" illusion was first described by Meyer [9] about a

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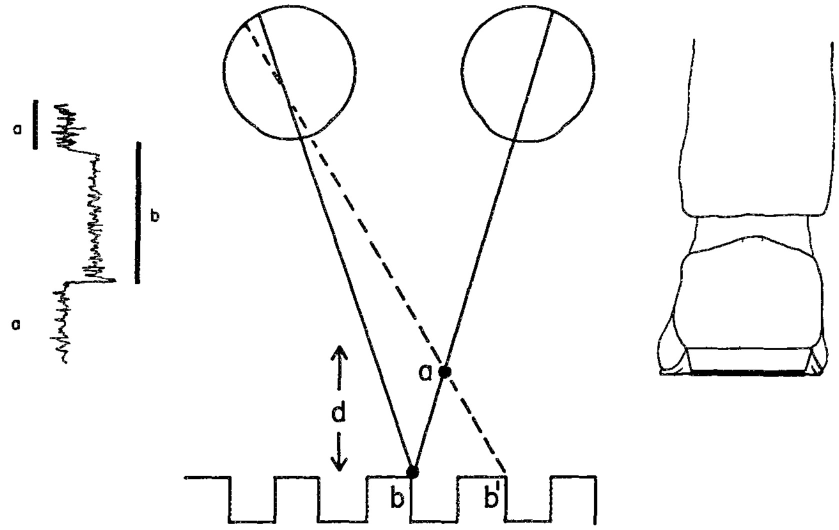


Fig 1 Schematic representation of eye misalignment while viewing a periodic target If the observer fixates point *b* with both eyes, the angle between them is appropriate to the distance of the object from the observer If the observer fuses adjacent similar features, such as the cleat corners shown at *b* and *b'*, the eyes adopt the wrong angle of convergence for the distance of the object This state is termed "false fusion " In this case, disparities of points on the object lead to a sensation that it is closer Inset binocular eyemovements of an observer viewing a striped pattern The difference of the two eye position signals estimates the binocular convergence of the subject The right-most deflection (*b*) shows a 4 s period during which the observer fixates a small fixation target at 2 m Prior and following deflections (*a*) occurred when the fixation was removed to 1 m in front of the target plane and then entirely withdrawn The subject could only see a large striped pattern during this time His subjective report was of a wallpaper-like illusion The stable difference signal indicates in inapprppriate angle of convergence for the distance of the target

century and a half ago It occurs when a person with normal binocular vision views a pattern that is periodic in the horizontal meridian of the visual field. When viewing such a pattern, the two eyes may adopt an angle of convergence that is inappropriate to the actual distance of the object, but which, because of the periodicity of the object, allows fusion to take place If this occurs, the object may appear to be substantially closer to (or farther from) the viewer than it really is, binocular and monocular depth cues are not in accord, and disorientation is commonly reported

This is illustrated by the diagram in Fig 1 If the two eyes fixate a common point *b*, then the images to both eyes will be fused in the brain into single unitary perceptual "image " Under these conditions a normal percept should result because the angle of convergence of the two eyes is appropriate to the distance of the object. If, on the other hand, the left eye fixates *b* and the right eye fixates *b'*, there is fusion with an inappropriate angle of convergence This is termed "false fusion" [10] The falsely fused object appears to lie in a plane passing through point *a* [10] which is closer to the eyes in this example This latter perception competes with and sometimes dominates other visual cues to the actual distance of the object

When there is a conflict in sensory information available from the different sensory modalities, disorientation can result It seemed to us likely that such disorientation may be related to postural instability [1], [2], but so far a direct link has not been established

*Escalator as an Ambiguous Stereo Stimulus*

False fusion engendered by wallpaper is not likely to be hazardous to the viewer However, escalator tread plates also have the repeating periodic pattern intrinsic to the "wallpaper" illusion The escalator is of considerable importance in this context since, unlike wallpaper, near which falls are relatively uncommon, it is an altitude-translating device encountered by most urban pedestrians, which is the site of thousands of debilitating falls annually [1]

The visual stimuli available to an escalator rider consist centrally of the moving surface, called the treads These are flanked by featureless, reflective, buff-polished stainless steel skirts The tread surface consists of alternating cleats and grooves about 1 5 and 5 mm wide, respectively The cleats are usually highly polished while the grooves are painted black, giving the tread a luminance profile that is periodic [12] For an observer of average height viewing the tread, this repeating pattern has a spatial frequency of about 6 cycles per degree of visual angle This spatial frequency is very close to the peak spatial frequency of the contrast sensitivity function of the human visual system [11], [12] The contrast of the tread is measured [12] to be about 0 995, which is higher than that of most other visual patterns in the visual environment, which typically measure far less than 0 90 Hence, the tread presents a highly visible visual pattern to the viewer

The purpose of the present study is to establish some additional links among the various sensory and motor system behaviors discussed above First it was necessary to establish that the stereo-ambiguity of repeating visual patterns causes observable inappropriate convergence, as described above, for this has not heretofore been shown Second, we sought to establish whether the postural system is affected by visual stimuli that cause both inappropriate convergence and the associated "false fusion" both in the laboratory and in the field Finally, we looked for evidence linking postural effects to the disorientation previously shown to occur with false fusion [1]

## II Methods

### A Eye Position Measurements of an Observer Viewing Stimuli with Stereo-Ambiguity

We first sought to establish objective evidence of inappropriate convergence during periods of erroneous depth perception, for without such evidence the theory linking stereoambiguous stimuli to falls would have no basis. Binocular eye movements of an observer viewing a vertically striped pattern were measured with a Stanford Research Institute (Model IV) Eyetracker The Eyetracker monitors the position of reflected (Purkinje) images from the optical surfaces of the eye (cornea and the lens, front and back surfaces) formed from an infrared light source [13] The image positions, which are converted into voltage signals, indicate the rotational angle of the two eyes The difference of these is formed to give a signal proportional to the angle of binocular convergence of the subject The voltage signals were sampled at a rate of 500 Hz (12 bit precision) and displayed on a chart recorder

The subject was positioned in the Eyetracker by clamping the mouth around a bite bar fitted with dental impression compound. The target was a vertically striped 50° wide by 30° high black-on-white pattern, and was viewed at 2 m distance Each period of the striped pattern subtended 0 25° The luminance of the background was 10 cd/m$^2$ and the contrast of the striped pattern was about 90%.

The observer was instructed to fixate the end of a pointer, held alternately in the plane of the target or up to 1 m in front of it In this way the subject was encouraged to alternately fixate the target plane or in front of it. He was asked to indicate when he experienced false fusion Example eye movement recordings are shown in the inset of Fig 1, which shows a voltage amplitude recording corresponding to difference of the two eyes' positions as function of time The epochs labeled *a* occur when the subject was asked to fixate the pointer held briefly 1 m in front of the target plane after which the target was immediately removed During *b* the two eyes accurately fixate the target The entire sample lasts about eight seconds. Calibration of the voltage signal confirmed that the subject was fixating almost 1 m in front of the true objective plane that contained the striped pattern In addition, verbal report indicated that false fusion, and the wallpaper illusion, occurred during that period From this it may be inferred that inappropriate convergence of the eyes can be elicited from such repeating patterns, and the resulting sensory fusion is supportable by such repeating patterns

### B Posturographic Measurements

*1) Subjects* Nine subjects were selected from the University student population and ranged in age 20-30 years for the laboratory test Three additional student subjects were utilized in the field test All subjects had normal visual acuity and stereoacuity

*2) Visual Stimuli for the Laboratory Study* The visual stimuli were back-projected upon a translucent glass plate that subtended 40° × 60° using a Kodak Carousel projector Lenses (subject's correction plus 2 5D) and prisms were placed before the eyes in a trial frame so that the subjects' eyes were at physiological rest (unconverged and unaccommodated, the visual state when viewing a target at optical infinity) The experimental pattern consisted of a high contrast set of vertical stripes of 1 23 cycles per deg, a pattern known to elicit the wallpaper illusion because of its periodic nature The control pattern was identical to the experimental pattern, except for the addition of five superimposed black letter patterns whose presence was intended to prevent false fusion. In viewing the control pattern, misalignment of the superimposed letters in the two eyes would have given rise to diplopia [14], or double images, which would be readily perceivable by normal subjects Each letter was approximately 17° square The stimuli were viewed in a darkened room, and viewing distance was 40 cm

*3) Visual Stimuli for the Field Test.* We used two otherwise identical escalators owned and maintained by the Bay Area Rapid Transit District (BART). The treads of one of these had been painted as follows: first, white paint was used to lower the cleat-groove contrast Next, a black pattern consisting of nonperiodic elements including the BART logo at the center, was applied. During our tests, both escalators were unoccupied and stationary, and were viewed while standing on the sway transducer positioned on the bottom platform

*4) Postural Sway Measurement:* The postural sway of each subject was transduced as follows a 40 × 40 cm steel platform was supported by two orthogonal cantilevered steel torsion bars. Strain gauges mounted on these measured the deformations of the torsion bars as the subjects' center of gravity changed position Signals were amplified and displayed on a Tektronix 564B oscilloscope equipped with a bridge amplifier, and then were digitized (12 bit precision) and statistical calculations were performed The sampling rate was 50 Hz

*5) Procedures.* Subjects were positioned upon the sway platform and were instructed to stand upright and to attempt to remain motionless. Subjects were instructed to look at the center of the stimulus pattern, in order to minimize edge cues Nine 1 min trials were run on each subject with striped and control patterns alternated.

We analyzed the spectra of measured signals with both test and control patterns in two of the subjects Fig 2 shows examples of such spectra obtained using chart sam-

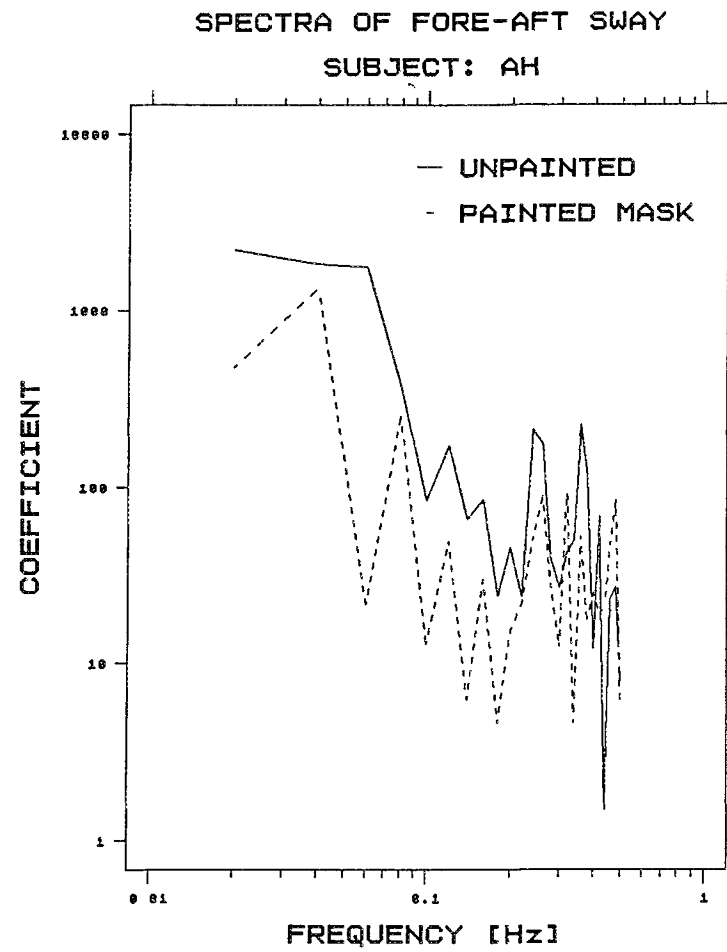


Fig 2 Spectra of fore and aft sway Spectra were estimated from samples obtained during the field test These samples gathered at 1 s intervals Ordinate is the amplitude coefficient Abscissa is the frequency specified hertz There is a great deal of variability from sample to sample These examples are typical of several other samples examined Generally, the spectrum peaks at lowest frequencies and stimulus effects are to increase power This provides a rationale for using postural variance to quantify stimulus effects

ples entered into a statistical data analysis package (Statgraphics Ver 2 6, Statistical Graphics Co ) The postural signal exhibits most power at frequencies below 0 1 Hz This is consistent with earlier results of Scott and Dzendolet [15] The only consistent difference between signals measured during the two viewing conditions is that power increases in the test condition (unpainted escalator)

Hence, following Dornan *et al* [7], we chose to estimate the mean squared deviation from the mean position of the center of gravity as the dependent measurement of postural sway This statistic is chi-square distributed, but was approximated by the Gaussian distribution, for statistical testing, since the number of samples was large

### C Measurement of Subjective Disorientation

This study was conducted in the field Subjects were 21 normally sighted students Test and control escalators (see Section II-B 2) above) were each observed for a 30 s period with order randomized After viewing was complete subjects were asked to retrospectively identify which of the two escalators was "more disorienting" and whether such a judgment was easy or not

## III Results

### Postural Stability

The results of the laboratory posturographic measurements are summarized in Table I where they are expressed as the variance of the voltage signal Our interest was in the effect of the visual stimulus on the variance of posture towards and away from the target The table shows that the striped pattern, without the superimposed control targets, increases the variance of the fore-aft sway, which is predicted by our hypothesis of stereo-ambiguity Six of nine subjects showed individual effects in the predicted direction, although the effects were generally less than a factor of two The pooled results from all subjects show a statistically significant increase in postural instability when viewing the test (stripes only) pattern This constitutes the first demonstration that a static visual stimulus can engender increased sway

Table II shows the results of an experiment which relates stereo-ambiguity to a nonlaboratory stimulus, the escalator Subjects viewed stationary escalator treads, with the typical 6 cycle/deg viewing surface, in the field One

TABLE I
POSTUROGRAPHY MEASUREMENTS OF CHANGES IN THE OBSERVER'S CENTER OF GRAVITY WHILE VIEWING EXPERIMENTAL AND CONTROL PATTERN POSTURE VARIABILITY EXPRESSED AS MEAN SQUARED DEVIATION FROM THE MEAN (VARIANCE)

| Subject | Pattern Experimental (Vertical Stripes) | Control (Vertical Stripes with Letters) |
|---|---|---|
| D F | 983 | 1455 |
| L X | 1619 | 1848 |
| J E | 1403 | 889 |
| L B | 708 | 799 |
| D D | 1596 | 831 |
| R K | 1439 | 1385 |
| J L | 1308 | 603 |
| J W | 4114 | 1468 |
| A H | 1548 | 973 |
| Pooled Variances | 1413 | 1137 |
| 3 Sigma Confidence | (1384, 1445) | (1114, 1163) |
| Intervals | $N = 18000$ | $N = 18000$ |

TABLE II
POSTUROGRAPHY FOR THREE SUBJECTS VIEWING TREATED AND UNTREATED ESCALATOR

| | Unpainted (Normal) | Painted (Treated) |
|---|---|---|
| Pooled Variance (scaled) | 1 21 | 0 65 |
| 3 Sigma Confidence | (1 07, 1 35) | (0 59 0 71) |
| Intervals | $N = 1002$ | $N = 687$ |

set of treads was standard appearance, while the other had been treated with a superimposed painted pattern designed to minimize the stereo-ambiguity. Example spectra for these two viewing conditions are shown in Fig 2 described above The results of the field test show that less sway variance was measured, by about a factor of two for the pooled data, for the painted escalator, e g , when the visual target's tendency to lead to the wallpaper illusion was minimized This result is also statistically significant.

### *Subjective Judgements*

An early finding in this series of investigations showed that disorientation experienced by escalator riders could be attributed to stereo-ambiguity [1] We sought in this study to determine whether the extent of disorientation reported by observers could be related to the amount of stereo-ambiguity presented by escalator treads We asked 21 unaware subjects to view the first step of two different stationary escalators from the bottom platform The steps of one escalator were painted with a high contrast pattern (described above) that was intended to prevent the wallpaper illusion The other escalator was untreated and was thus typical in appearance, although it did exhibit the usual scratches, mars and foreign substance spots After viewing the steps of the treated and untreated escalator, the subjects were asked to judge whether the treated escalator step was more or less "disorienting" than the untreated escalator step For this subjective judgement of treated and untreated escalators, 17 out of the 21 subjects judged the painted escalator step to be less disorienting than the unpainted step Of the 17 subjects who reported the comparison "easy" to make, 15 judged the painted step to be less disorienting These are statistically significant results ($p < 0.003$ and $p < 0.001$, respectively, binomial test) which show that masking the ambiguous features of the tread pattern, while not materially reducing its visibility, reduces the disorientation reported by subjects Subjective disorientation and postural stability are thus linked, and we suggest that the link is due to a common dependence upon the existence of stereo-ambiguity in the visual stimulus

## IV Discussion

Lee and Lishman [6] have shown that the external modification of the visual impression of the world in a left-to-right direction can cause a compensatory left–right sway in the posture It has also been shown that closing one's eyes increases the amplitude of postural sway [6], [7] which attests to the importance of vision in maintaining upright stable posture Our research extends these findings by showing that a fore–aft modification of postural variance can be caused by an appropriate manipulation of the stereo-depth cues in visual space

Plainly, there are complex interactions amongst the visual sensory system and two related motor systems, those of binocular convergence and postural control Fig 3 summarizes relations amongst these entities as they relate to the narrow problem addressed here Visual stimulation impinges on two eyes Responses lead to the generation of binocular convergence control signals Manifestations of these signals are measurable as the angle of convergence ($A$), which can be erroneous for stereoambiguous stimuli, and, if so, which define the state termed "false fusion " When false fusion occurs, the central apparatus for computing depth is faced with discordant input, with monocular cues and binocular cues at odds as to the actual distance to the stimulus These lead to two responses, both measurable. first, subjective disorientation occurs, and second postural instability increases We speculate that increased instability may be the precursor of falls

Our assessment of subjective reports of disorientation and its relationship to stereo-ambiguity runs counter to the usual reasons advanced to explain disorientation and falls on escalators Height has been suggested as a cause and so has escalator motion Our subjective test provides evidence that it is the striped pattern of the treads per se, and neither escalator movement (it was stationary) nor viewing from a height (it was viewed from the bottom platform) causes the disorientation reported by our subjects

The problem of periodicity in visual targets is not restricted to escalators Stairs, steps, carpets, and tile-flooring can create the same type of visual ambiguity Visually ambiguous patterns should be avoided in designs for any walking surface In the case of the escalator this is of particular importance since the surface is moving, which may tend to aggravate the effects of postural instability

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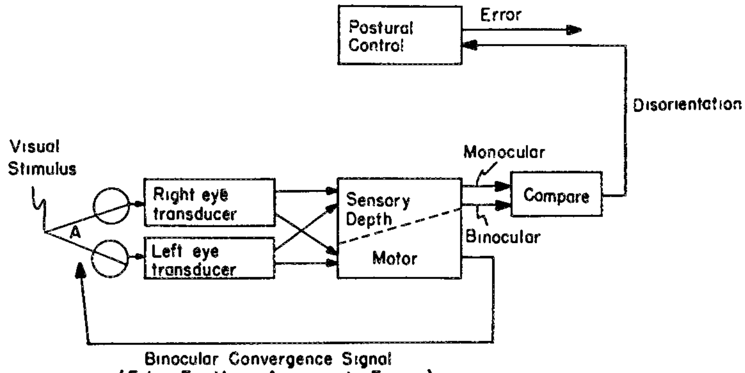


Fig 3 Hypothesized relationships between binocular convergence signal, false fusion, disorientation, and postural instability

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