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STUDIES OF THE INTERACTIONS BETWEEN VESTIBULAR FUNCTION AND TACTUAL ORIENTATION DISPLAY SYSTEMS

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When humans experience conditions in which internal vestibular cues to movement or spatial location are challenged or contradicted by external visual information, the result can be spatial disorientation, often leading to motion sickness. Spatial disorientation can occur in any situation in which the individual is passively moved in the environment, but is most common in automotive, aircraft, or undersea travel. Significantly, the incidence of motion sickness in space travel is great: The majority of individuals in Shuttle operations suffer from the syndrome. Even after the space-sickness-producing influences of spatial disorientation dissipate, usually within several days, there are other situations in which, because of the absence of reliable or familiar vestibular cues, individuals in space still experience disorientation, resulting in a reliance on the already preoccupied sense of vision.

One possible technique to minimize the deleterious effects of spatial disorientation might be to present attitude information (including orientation, direction, and motion) through another less-used sensory modality - the sense of touch. Data from experiences with deaf and blind persons indicate that this channel can provide useful communication and mobility information on a real-time basis. More recently, technologies have developed to present effective attitude information to pilots in situations in which dangerously ambiguous and conflicting visual and vestibular sensations occur.

This summer's project at NASA-Johnson Space Center will evaluate the influence of motion-based spatial disorientation on the perception of tactual stimuli representing veridical position and orientation information, presented by new dynamic vibrotactile array display technologies. In addition, the possibility will be explored that tactile presentations of motion and direction from this alternative modality might be useful in mitigating or alleviating spatial disorientation produced by multi-axis rotatory systems, monitored by physiological recording techniques developed at JSC.

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Final Report
NASA/ASEE Summer Faculty Fellowship Program - 1996
Johnson Space Center

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Date Submitted:	August 2, 1996
Contract Number:	NAG 9-867

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ABSTRACT

When humans experience conditions in which internal vestibular cues to movement or spatial location are challenged or contradicted by external visual information, the result can be spatial disorientation, often leading to motion sickness. Spatial disorientation can occur in any situation in which the individual is passively moved in the environment, but is most common in automotive, aircraft, or undersea travel. Significantly, the incidence of motion sickness in space travel is great: The majority of individuals in Shuttle operations suffer from the syndrome. Even after the space-sickness-producing influences of spatial disorientation dissipate, usually within several days, there are other situations in which, because of the absence of reliable or familiar vestibular cues, individuals in space still experience disorientation, resulting in a reliance on the already preoccupied sense of vision.

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PHYSICAL LIMITS OF VIBROTACTILE SALTATION ON TWO BODY SITES: VOLAR THIGH AND LOWER ABDOMEN

INTRODUCTION The utility of tactile stimulation to provide for an alternative communication channel has been demonstrated when other sensory modalities were occluded, as in cases of deafness or blindness, or overloaded. Tactile patterns can also be used to provide information for spatial orientation, including direction, orientation, velocity, or attitude of the user in 3-dimensional space. These have been demonstrated by pilots maneuvering their aircraft using tactile displays in the complete absence of visual cues. One mode in which such patterns can be generated is to sequentially activate a line of tactors: The resulting sensation will be a moving point or a line drawn on the skin. An alternative to activating every tactor in a series would be to use the phenomenon of sensory saltation that requires as few as two physical sites to provide the sensation of many (e.g. 3-7) energized sites. In order to optimize the display, it would be important to know if the physical separation between the two sites has a limit, beyond which the illusion breaks down. Although a minimal form of the illusion has been explored on sites such as the fingertip, palm, forearm, and abdomen with punctate stimuli, this study extended these data to those sites to be used with tactile displays under construction, with stimulus patterns intended to generate the vector sensations useful for spatial orientation.

Sensory saltation was discovered by F. A. Geldard and C. E. Sherrick (1972) while they were examining a class of spatio-temporal phenomena (specifically the Tau and Kappa effects). These are all perceptual illusions in which judgments of either the spatial or temporal parameters among stimuli are influenced by the levels of the other parameter. Although the majority of these phenomena have been described in the sense of touch, Geldard extended his studies to show that sensory saltation could be demonstrated in the other spatial senses, of vision and audition (Geldard, 1975, 1976, 1977). The original description of the illusion implied motion by including the notion that it mimicked a "rabbit jumping up the forearm" (Geldard, 1975). There are a number of ways in which the sensation of motion like this might be generated on a sensory surface. Simply stimulating each of a linear array of lights or taps, *seriatim*, can produce the impression of one of these moving across the sensory field if the timing, spacing, and intensity are appropriate. A general pictorial representation of this mode may be seen in **Figure 1**, in which elements in the array of stimulators, represented in (**A**), are driven in the manner shown in (**B**) to produce the sensation represented in (**E**). The mode of pattern generation called sensory saltation is also described in **Figure** 1, in (C) and (D).

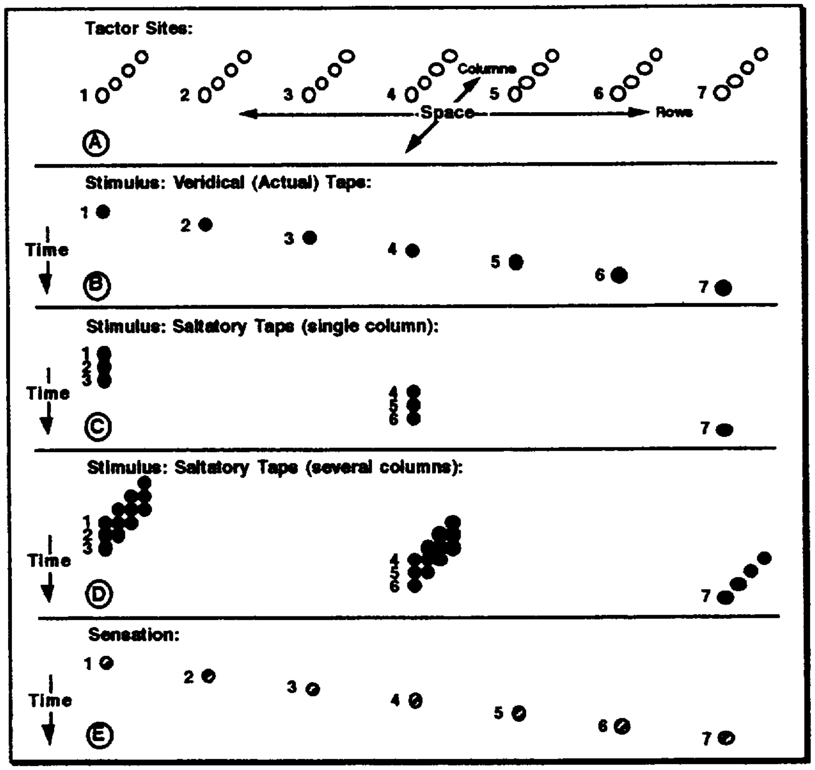

Figure 1. - Saltatory phenomena -spatial and temporal descriptions.

The essence of saltation is a mislocalization of one event, in space, as a consequence of presentation of another immediately following event. Although phenomena such as the Phi effect, and auditory localization are well-known, and illustrate the interdependence of space and time to produce specific emergent experiences in perception, saltation is unique in that the range of times over which it operates is larger than that controlling most other illusions, and the experience is one of mislocalization of specific events. For example, some types of auditory localization depend on critical temporal differences between events on the order of 160-200 μsec (Evans, 1982). In auditory saltation, however, clicks generated by speakers distributed across the acoustic field, will be mislocalized with inter-stimulus intervals ranging from 20-250 msec. This is the same range of time delays that produce visual and tactile saltation.

Tactile saltation consists of a series of taps at one site that are mislocalized in a linear manner owing to the presence of one or more taps at a nearby second locus, presented temporally close to the last tap at the first locus (e.g., Cholewiak, 1976, Geldard, 1982; Geldard & Sherrick, 1983). Consequently, a series of taps at only a few sites (such as in

(C) in **Figure** 1) can appear to distribute themselves over an entire spatial extent (represented by the sensations in (E)). Note that four of the sensations are displaced spatially from their sites of generation. The advantage of saltation is that finely defined lines can be generated with many fewer veridical stimulus loci than are felt. Specifically, a well-defined finely dotted line made up of, e.g., seven or more individual taps can be produced with only two or three contactors, using the appropriate spatiotemporal parameters for the saltatory illusion. This trading relationship between space and time can generate finer detail then apparently possible, given the resolving power of the skin. One model of tactile pattern perception likens the skin to blurred vision (Loomis, 1990), in which it is hypothesized that the skin cannot resolve stimuli located close together because it acts like a low-pass filter for spatial detail. A pattern produced by saltation, however, is quite vivid and immediately apparent to subjects without extensive training or instruction. The manner in which apparent spatial frequency is thus increased by altering temporal frequency may be useful in attempts to generate accurate geometric features or flowing sensations on tactile displays. Furthermore, because of the ability to generate a spatially-distributed display with fewer generators than perceived sites, such a mode of presentation can be used in a fault tree. For example, if a line is normally generated by a series of seven taps produced by a line of seven stimulators, the saltatory mode can be invoked if intermediate stimulators fail. Using this mode and its specific spatio-temporal parameters, the same sensation of seven distributed taps (as in **(B)**, above) could be produced by presenting the stimuli with only three tactors distributed over the same space with the equivalent temporal sequence of events (three at the first, three at the fourth, and a single one at the seventh , shown in (C) in **Figure** 1). Indeed, the sensations are indistinguishable on a number of quantitative and qualitative bases over a large range of temporal burst durations and interstimulus intervals (Cholewiak, 1996).

The temporal parameters of saltation have been well-explored by Geldard and his associates. However, the parameter that has not been as well evaluated with the multiple-tap saltatory generator is the appropriate physical separation (spacing) among tactors. The literature indicates that there is a physical limitation to the separation, but those studies were conducted with a minimal form of the phenomenon, using only two taps (Geldard, 1982; Geldard & Sherrick, 1983, 1986). In these cases, Geldard used the apparent displacement of a single tap to the skin produced by a pair of tactors whose physical separation was varied in several directions around a central point on the finger, palm, forearm, upper chest, or ventral thigh. Indeed there are limitations in distance whose magnitude depend on the site being stimulated. Furthermore, asymmetries exist that are consistent with the possibility that the underlying neuroanatomical substrate is correlated with cortical receptive fields (see. esp., Geldard & Sherrick, 1983).

The two-tap version of saltation used in these previous studies is a particularly precise, but ephemeral version, certainly much less robust than those using several taps at each locus. The present study explores the spatial limits for saltation using forms of saltation and two body sites that might be practically used for orientation/ mobility displays. The saltatory modes involve multiple stimuli, and the body sites are the ventral thigh and the lower quadrant of the back. The specific question to be addressed concerns the influence of spatial separation between adjacent active tactors necessary for the perception of a continuous string of events across the space defined by the elements.

APPARATUS AND PROCEDURE A vibrotactile array consisting of seven enclosed piezoceramic beam benders (illustrated in **Figure 2, right**) was used to generate the stimuli. The contactors, attached to the benders as shown in **Figure 2, left**, were 7 mm in diameter. Each element was attached to the fabric substrate with Velcro™ so as to allow variable spacing, and was driven with a burst of 250 Hz sinusoidal vibration, with the timing and sequencing of the patterns controlled through the parallel port of a computer. In these initial studies, the bursts of vibration were always c. 40 msec long, as were the interburst intervals. Consequently, a 4-1 pattern involved 4 40-msec bursts of vibration at one locus, separated with an interburst interval of 40 msec, followed after a 40-msec delay with the final 40-msec burst at the terminal location.

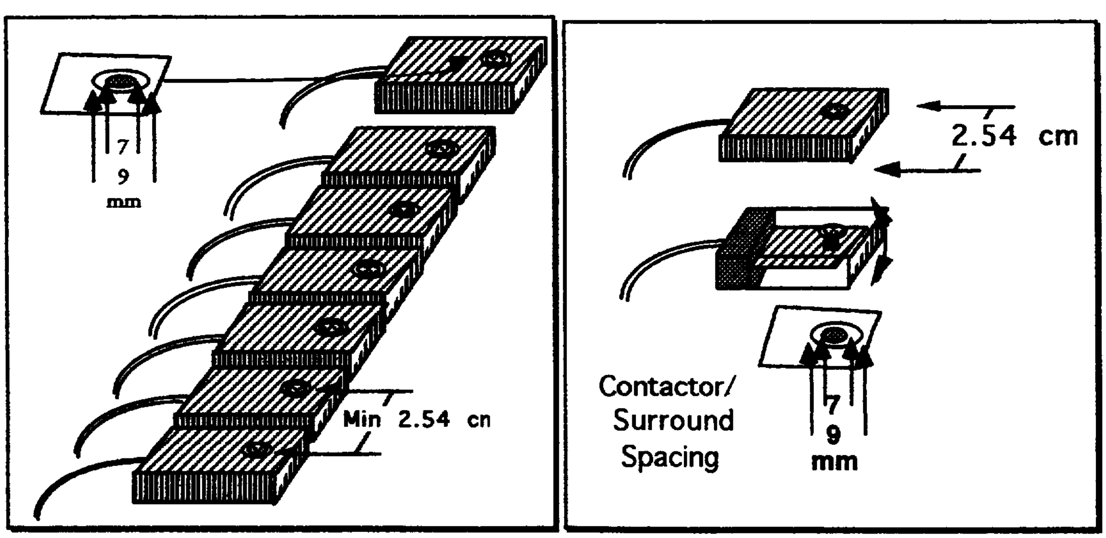

Figure 2. Linear tactile array (L) and individual tactors (R).

The array was either placed along the ventral surface of the left thigh or vertically along the left lower quadrant of the back of the seated participant touching the person through a fabric of "t-shirt" weight, and were held against the body with an elastic Velcro™ wrap.

The perceived intensity of an individual burst of vibration was estimated to be c. 20 dB re sensation level, although owing to local variation in sensitivity (see, e.g., Weinstein, 1968), there was a noticeable variation from site to site. To insure that all tactors touched the skin properly, prior to each testing session an "alignment" series was presented in which participants were required to indicate whether they felt each tactor activated individually with a brief weaker stimulus. If any tactors were not felt, the array was refit and the alignment series retested.

Testing involved the method of limits, in which the separation between the active contactors was functionally increased over successive trials. On each trial, the participant had to respond with a Yes/No keypress whether s/he felt a continuous pattern of individual taps running from the initial site to the terminal site. In cases in which the extent was not complete, a criterion was set that required displacement that covered at least 50% of the interstimulus space. A typical session involved four blocks of 42 trials (7 presentations of each of 6 physical separations, for example). Presentations were blocked by direction (proximo-distal (p-d) or disto-proximal (d-p) along the body's surface), and, in the case of the 4/6 and 1 presentations, by burst number. Consequently, a typical session might have a 6-1 d-p block, a 6-1 p-d block, and 4-1 d-p and p-d blocks of trials. See next section for descriptions of the tested patterns. Subjects wore headphones to mask ambient environmental noise.

STIMULUS PATTERNS: Two different saltatory generation modes are explored: In one version, (3-3-1) a saltatory image will be generated with the 7-element linear vibrotactile array in the manner described above in **Figure 1 (C)** - three bursts at the first and second active loci, with a single final burst of vibration at the terminal locus. The active loci on the 7-tactor array were functionally shifted to be adjacent (tactors 3, 4, & 5), one tactor apart (tactors 2,4, & 6), or two tactors apart (1, 4, & 7). The spacing of the elements on the array was adjustable, so three levels of tactor separation were implemented: 3 cm, 4 cm, or 5 cm. Consequently, a wide range of physical separations were available, depending on the functional and physical separations, ranging from 3 to 30 cm. In practice, the full range could not be used owing to restrictions on the distances available on the body sites explored. The data indicate that this was not the limiting factor. The second mode tested (4-1 or 6-1) involved a number of bursts generated at the first locus (either 4 or 6 bursts, in separate blocks of trials), while only a single burst is presented at the second location, either adjacent or separated from the first by one or more quiet tactors (up to a limit of 5 quiet ones). In these cases, tactors were only separated by 3 cm, providing a range of functional separations from 3 to 18 cm.

PARTICIPANTS: Three members of the laboratory staff, including the P.I., served as participants in these studies. As indicated in the proposal, experienced, trained observers are more important in studies of this type. Each person served in each condition, typically for as many as 2 or even 3 or more blocks of trials.

RESULTS: Responses for each condition of mode and spacing were averaged across direction, with standard errors calculated to indicated variability. The number of observations/ condition ranged from a minimum of 112 to as many as 238. The results for these sessions are shown in **Figure 3** as the probability that a spatiotemporal pattern will produce a clear perception of mislocalization (i.e., that saltation occurred), as a function of the spacing between (4-1 or 6-1 pattern) or among (3-3-1 pattern) the active elements, with body site and stimulus mode as the parameters.

The data indicate that these stimuli will produce saltation more than 75% of the time using only two active contactors if the physical separation between tactors is less than 10 cm. This is true regardless of whether the back or the thigh is stimulated, and whether the pattern involves 4 or 6 stimuli occurring at the first site and only one at the second site. In the case of the 3-3-1 pattern mode, the data are less well ordered, but suggest that, on either body site, tactors might be placed as much as 12 cm apart and reliably produce saltation. Note that the functions shown in the **Figure** for the 3-3-1 modes consist of data collected in 3 separate blocks of trials (one with tactors separated by 3 cm giving effective distances of 3, 6, & 9 cm, one with tactors separated by 4 cm, producing distances of 4, 8, and 12 cm, and a third session with tactors separated by 5 cm, producing distances of 5, 10, and 15 cm.) It is possible that some of the noise in these functions results from changing criteria as the participant was tested in different sessions across the 3, 4 or 5 cm separations.

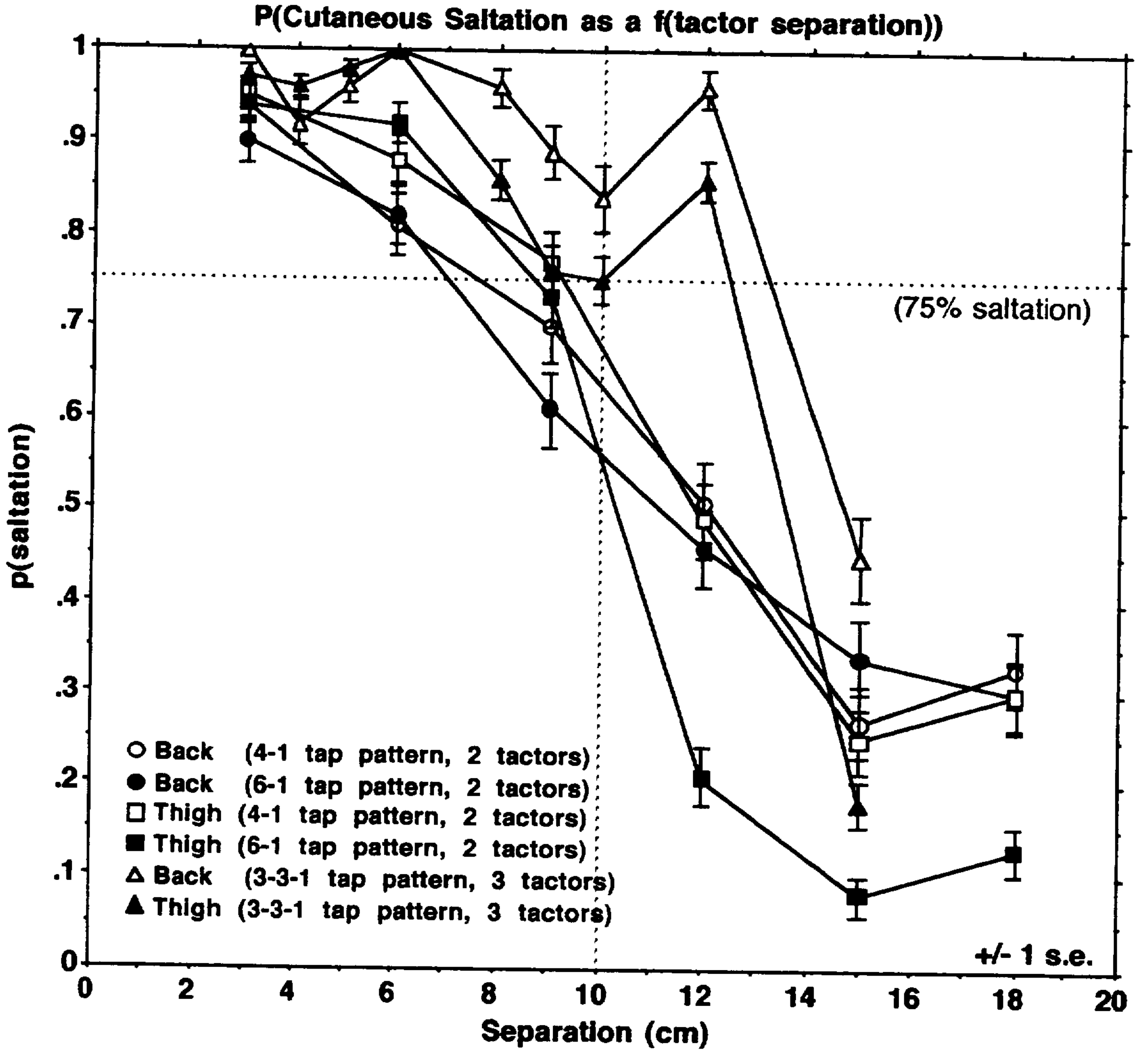

Figure 3. - Probability of saltation as a function of tactor separation.

<u>DISCUSSION AND CONCLUSIONS:</u> These data indicate that, in a tactile array to be placed on either the ventral thigh or the lower quadrant of the back, elements should be spaced at the most 10 cm apart to reliably obtain sensory saltation with these pattern generation modes. Interestingly, there is a correspondence between these results and those obtained by Geldard for the more-difficult-to-observe 2-1 "reduced" saltatory pattern on the thigh (Geldard, 1983). In this case, he also found that saltation failed if the tactors were separated by more than c. 10 cm, although there was an asymmetry in his results showing that longer separations were possible in the longitudinal direction (along the limb) than in the transverse direction (across the width of the thigh). He did not explore the back. The data collected in the present study suggest that saltatory areas, as generated by a number of different modes, may have equivalent spatial limits.

GROWTH OF THE PERCEIVED MAGNITUDE OF WHOLE BODY TILT USING THE METHOD OF ABSOLUTE MAGNITUDE ESTIMATION

RATIONALE: Having shown that good tactile movement could be produced with stimuli spaced c. 10 cm apart, this study was intended to collect baseline data regarding the perception of spatial disorientation - specifically tilt from vertical - prior to actually combining the tactile cue with the vestibular stimulus. A number of techniques have been used to evaluate individual's perception of whole body tilt, but the majority appear to involve a cross-modality matching of the magnitude of one sensory dimension (perceived whole-body tilt) to that of another sensory dimension (e.g., the location in space of an illuminated line). This project brings to bear the more-direct scaling method of absolute magnitude estimation, or, as Gescheider (1985) describes it, absolute scaling, to the problem of perceived body tilt. The potential advantage of this well-established technique is its independence from sensory interactions (see, e.g. Guedry, 1973; Stevens, 1975).

APPARATUS & PROCEDURE: For the vestibular task, observers were seated on a chair that could be tilted with respect to gravity. The chair could also be rotated, although there was no rotatory stimulus in this study. The rotator system was composed of a Contraves-Goertz Direct-Drive Rate Table (Model 824) mounted on a 1811-G19 Heavy Duty Pedestal. The rate table had a height of 42 in and diameter of 18 in, and could be tilted in the pedestal using a Duff-Norton Super-Pak MPA-6515-10/JB linear actuator. The chair, originally designed for the Microgravity and Vestibular Investigation (MVI) studies performed both as ground-based studies and on the Orbiter in space a number of years ago, had a 4-point restraint harness as well as a fixed helmet to secure the head during stimulation. When the observer was seated and restrained in the chair, a heavy black-fabric hood was drawn over the head and upper trunk to obscure any visual references to vertical. Each block of trials began with the chair in the zero degree tilt position. The constrained random series was begun once the subject was comfortable in the chair and the hood was properly positioned. Using a remotely controlled drive system, the experimenter moved the chair towards the first stimulus level, overshooting and returning in a number of steps to discourage the use of possible temporal cues resulting from the move from one stimulus position to the next. Once the stimulus position was reached, a ten-second settling period was imposed at the end of which the observer was directed to make an estimate (described next) of the magnitude of tilt. The next stimulus was always in the opposite direction. Consequently, the chair moved through zero degrees between each stimulus position. In between blocks, the chair was returned to the zero position, and a brief rest period was provided in which the subject could remove the hood. As is typical in magnitude estimation procedures, only two blocks were presented to preclude the possibility of the observers learning or categorizing the stimuli. Observers were not told that the same positions were to be presented in each block, nor were they told what the maximal extent of tilt that was possible with the apparatus. When all participants served in the roll-tilt series, the chair was rotated 90 deg in the pedestal, and they returned for the pitch-tilt series.

STIMULUS: The independent variable in this experiment was the degree of whole-body tilt: tilt angle: 5, 10, 15, 20, 25, and 30 deg, presented randomly. In one session, tilt was presented in two roll (side-to-side) directions (right or left), while in a second session, two pitch (front-to-back) tilt directions were presented. Each of the six degrees of tilt in the two directions (12 stimuli) were randomly presented twice per session in two separate blocks of trials. Observers gave their responses verbally.

MAGNITUDE ESTIMATION: After the procedure was briefly described to the participant, but prior to the main study reported here, a brief preliminary training series was conducted to explain and familiarize each person with the method of absolute magnitude estimation. This series required observers to make judgments of the magnitude of line lengths, which is a relatively easy task that appears to stabilize loudness scaling (Stevens, 1975; Zwislocki & Goodman, 1980; Zwislocki, 1983). Lines were presented in the brief training series by presenting a number of lines drawn on white paper to the observer, who gave their estimates verbally.

Observers were read these introductory remarks:

> Today we will do a magnitude estimation experiment. Because the magnitude estimation procedure is very sensitive to the actual words that are used in the instructions, I am going to read these to you.
>
> In this experiment, we would like to explore the ideas you have about the sizes of a number of things. Specifically, we would like to find out how intense various stimuli seem to you. In this first familiarization series, we will start with some lines of different lengths. First, I would like you to imagine a long line, . . . and a large number. Now imagine a short line, . . . and a small number. You can do this because you have ideas about the sizes of lines and numbers. I will now actually show you a series of lines. Your task will be to assign a number to every line in such a way that your impression of how large the number is matches your impression of long the line is. You may use any positive number that seems right to you- whole numbers, decimals, or fractions. Just assign a number to each line so that the size of the number matches your impression of the length of the line. Judge each stimulus as if it was presented in isolation. In other words, try not to compare it to the other stimuli that have been presented to you. If you feel that you must make a comparison, make

> it with all the lines and all the numbers that you have had experience with or can imagine. Just assign a number to each line so that your impression of the size of the number and your impression of the length of the line match in magnitude. Do you have any questions?

Stimuli were briefly shown to the observer and their responses recorded. Following the visual task, the next set of instructions were read to the observer:

> OK - that was a magnitude estimation procedure. Do you feel comfortable with it? Earlier I asked you to imagine a long line and a large number. You could do this because before we even started today you had ideas about what is big and small for lines and numbers. Now we will do the tilt experiment itself in which you will do several more blocks of magnitude estimation trials. In this case, we will ask you to focus on your perceptions of the magnitudes of numbers and of tilt positions in different orientations. Now, just as with the lines, I would like you to imagine a strong body tilt, . . . and a large number. Now imagine a weak body tilt, . . . and a small number. Again, you can do this because you have ideas about the sizes of numbers and the amounts of whole body tilt.
>
> In this experiment there will be two blocks of magnitude estimation trials. I will present a series to you, one at a time, with a brief break between blocks. In some of the trials the stimulus will be of a high amount of tilt, and in others it will be less. Your task will be to assign a number to every stimulus in such a way that your impression of the magnitude of the number size matches your impression of the magnitude of the amount of whole-body tilt. Use any positive number that seems right to you-whole numbers, decimals, or fractions. As before, judge each stimulus as if it was presented in isolation. In other words, do not try to compare it to the other stimuli that have been presented to you. Respond as quickly and spontaneously as you can. We will support your head by putting it into a helmet, will ask that you wear a hood to mask the visual vertical cues in the room, and will support you firmly in the tilt chair. Try to relax. Any questions?

Finally, the observer was seated in the tilt-chair system, restrained with the harness, had the helmet-hood placed down over the head, and the tilt series began as described above.

PARTICIPANTS: Ten members of the laboratory staff served as participants in this study. There were three females and seven males. None of the observers had participated in magnitude estimation studies previously, and only one had experienced whole-body tilt in which he was required to make estimates of his actual position in degrees from vertical. Each person served in all conditions

RESULTS: Because magnitude estimates have been shown to be logarithmically distributed, geometric means of the estimates from all of the observers were calculated and plotted as a function of actual tilt angle. The group data for the first condition (in which roll was the direction of tilt) can be seen in **Figure 4**. Plotted in the Figure are the estimates for tilt in the positive direction (+ = right), negative direction (- = left) and the average over the two directions. Also shown are bars indicating standard errors of the estimates. Although they were not statistically tested, the variability among the functions suggests that there were no significant differences among the functions. Also shown in the figure are the power functions fit to [logarithmic transforms of] these data by the method of least squares. Exponents of these functions are all greater than 1 - averaging 1.547 - and the regression coefficients indicate that these data are extremely well-fit by the functions.

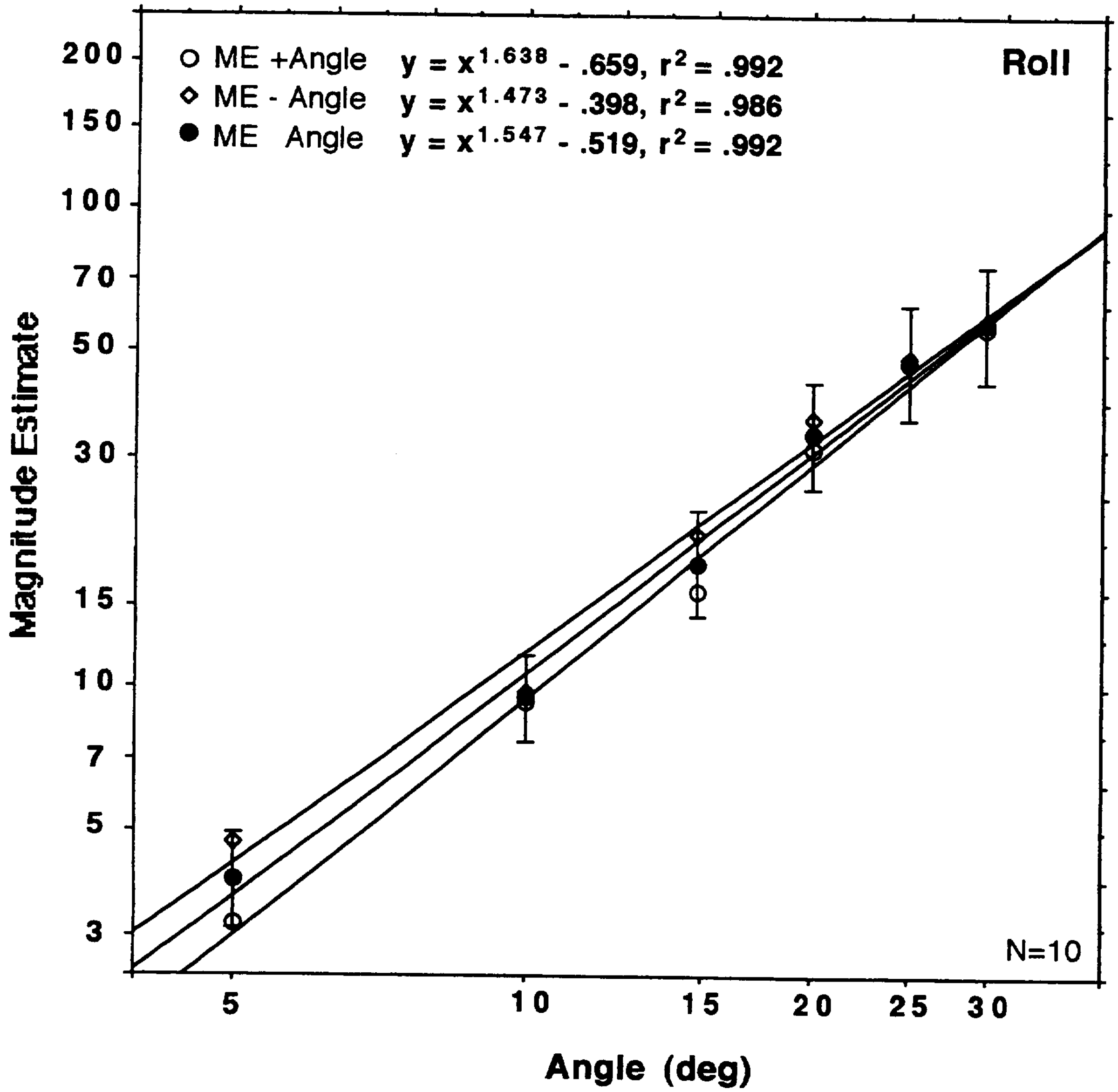

Figure 4. - Magnitude estimates of whole body roll as a function of degree of tilt.

In Figure 5 are plotted the data for estimates of whole body tilt in the pitch direction (to and fro). In this case, note that data are incomplete: only three of the above observers served in this study. The experiment was unexpectedly terminated owing to equipment failure. Error bars are not shown because of the small number of participants for whom data are shown. Nevertheless, points are well fit by the functions, indicated by the regression coefficients of the power functions fit to [logarithmic transforms of] these data by the method of least squares. As with roll tilt, exponents of these functions are all greater than 1 - averaging 1.255. Caution is advised regarding comparisons of these functions with **Figure** 4, because individual number usage of the missing observers could influence both the slopes and the intercepts of these functions. However, the function derived from the roll data for the same three subjects is shown in **Figure** 5, for comparison.

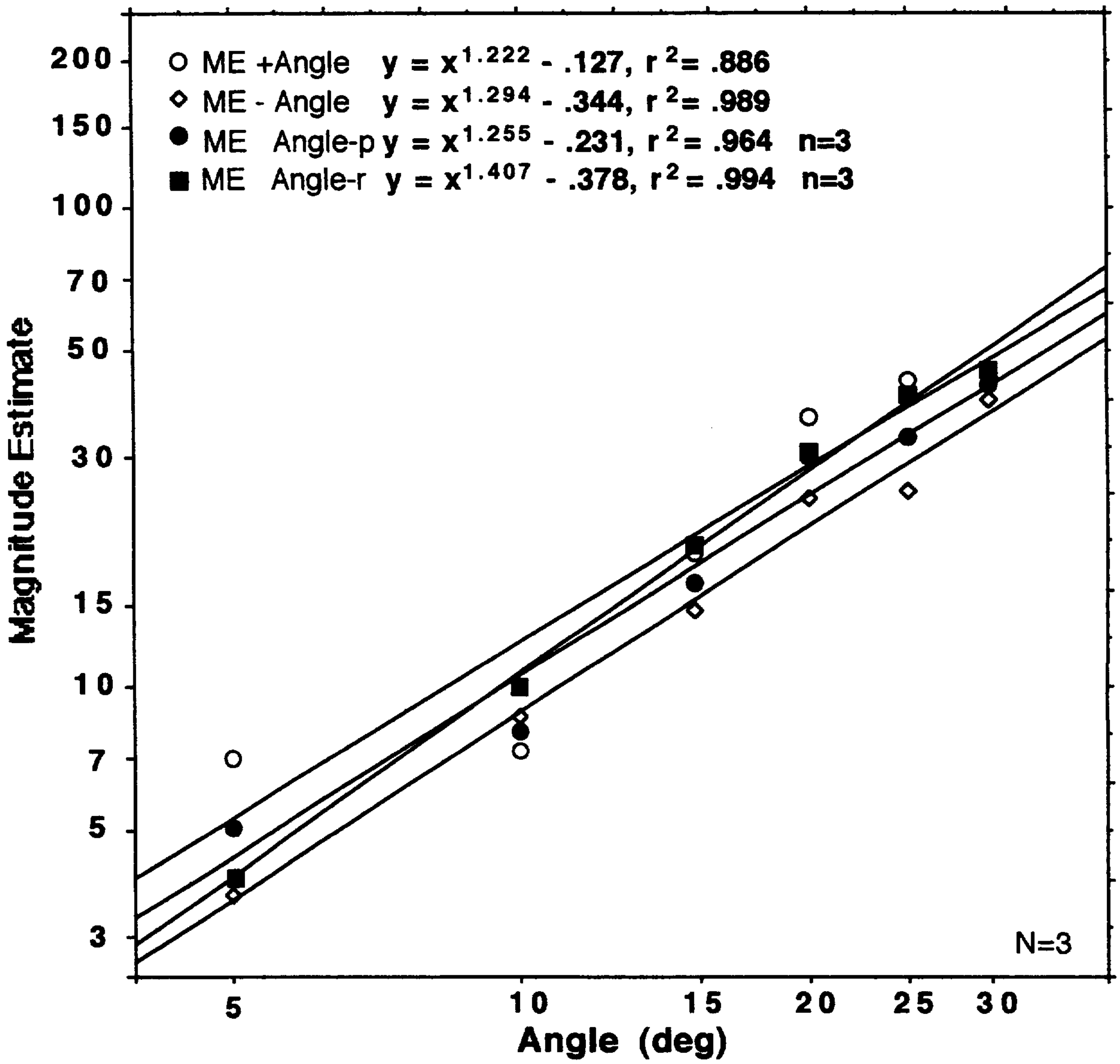

Figure 5. - Magnitude estimates of whole body pitch as a function of degree of tilt.

<u>CONCLUSIONS</u>: The functional relationships illustrate the expansive nature of the degree of roll (or pitch) and the amount of perceived tilt: people feel as though they are more tilted than the physical stimulus would suggest.

NOTE

The author would like to express his appreciation to Ms. Charmaine Mangram for her assistance and participation and Ms. Amy Wiseman for her patient and attentive extended participation as an observer in these studies. This research was conducted while the author was a NASA/ASEE Summer Faculty Fellow at the Space Biomedical Research Institute at the Johnson Space Center, Houston, TX.

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