1989

The Effects of display type and direction of movement in the visual control of heading

Stephanie Joy Hinz
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DOI: <https://doi.org/10.31979/etd.6fac-3usr>
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visual control of heading**

Hinz, Stephanie Joy, M.A.

San Jose State University, 1989

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The Effects of Display Type and Direction
of Movement
in the Visual Control of Heading

A Thesis

Presented To

The faculty of the Department of Psychology
San Jose State University

In Partial Fulfillment
of the Requirements for the Degree
Master of Arts

by

Stephanie Joy Hinz

May, 1989

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APPROVED FOR THE UNIVERSITY

**The Effects of Direction of Movement and Display Type in the
Visual Control of Heading**

**Stephanie Joy Hinz
San Jose State University**

VISUAL CONTROL OF HEADING

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ABSTRACT

The present study used the active control of heading to compare performance differences in locating and maintaining headings over two simulated environments. The type of display (wireframe grid and dot matrix) and required heading angle (0.0, 7.0, and 12.0 deg) were varied, and performance was recorded for ten male subjects. Heading during each flight was "randomly" disturbed using a sum of six sine waves. The subjects' task was to actively control heading angle errors during simulated "flight." Absolute mean heading angle errors (accuracy in locating the correct heading) and median adjusted root mean square error (ARMSE), a measure of heading variability, were derived from the raw data. Results showed that subjects were able to locate and maintain 0.0 deg headings with both displays better than the other required headings. Performance was better (lower angular errors) for the grid display than for the dot display at the smaller heading angles (7 deg). At larger heading angles (12 deg), however, performance was best for the dot display. The performance differences may be due to frame grid verses dot matrix display. These data have several important implications for the design of perspective displays that might be used for the control of flight.

ACKNOWLEDGEMENTS

I wish to express my sincere appreciation to the three members of my thesis committee, Dr. Kevin Jordan, Dr. C. Thomas Bennett, and Dr. Nancy Eldred for their guidance and numerous contributions to this research. Special thanks are also extended to Dr. Walter Johnson for his liberally devoted time and patience. Lastly, I would like to thank my husband, Richard Hinz, for his moral support throughout this endeavor. This project was made possible by the National Aeronautics and Space Administration through NASA Grant NCC 2-327 to San Jose State University. This experiment was conducted in the NASA-Ames Research Center Facilities.

The Effects of Direction of Movement and Display Type In the Visual Control of Heading

Investigations of the information used for controlling aircraft heading were conducted during World War II. The research centered on understanding how the perception of depth and distance were involved in aviation. A list of "cues" or "clues" which applied to the perception of depth and distance resulted from the research and gained wide acceptance. However, the experiments failed to clarify the problems related to how a pilot lands an aircraft since they were based on cues for depth perception. According to Gibson (1950), these cues cannot be used to predict the success or failure of a student pilot, nor do training programs to improve depth perception make it easier to fly.

Sources of Optical Flow Information

In 1950, Gibson proposed a "ground theory" of space perception to amend the problems with "air theories." Ground theory defines a pilot's space by the ground and the horizon whereas previous theories described it with respect to the air a pilot flies through. The basic idea was that visual space does not consist of just an object or array of objects in the air, but should be conceived of as a continuous surface or array of adjoining surfaces. Also, the spatial

characteristics of objects in the visual world are given by the background of the objects, and not by the objects themselves.

Gibson, Olum, and Rosenblatt (1955) proposed that the problem a pilot faced in landing situations was one of surface-space perception because a continuous surface is involved. They criticized the concept of motion parallax as an adequate explanation for motion perception. Motion parallax refers to the apparent change in position of an object resulting from a change in direction or position from which the object is viewed (See Appendix A for list of definitions). Gibson et al., (1955) state that motion parallax cannot fully explain the deformation of the environment when the observer is looking straight ahead and there is no lateral displacement of the eyes or the body during forward locomotion. Therefore, Gibson et al., (1955) developed the concept of motion perspective. Motion perspective provides a mathematical description of the two foci of radial inflow and outflow in the whole array at a moving point of observation (Gibson et al., 1955; see Figure 1). As a surface is approached, the scene radially expands from the point of intersection of the surface and the direction of travel. The center of the radial flow is referred to as the focus of expansion, and corresponds to the direction an observer is moving (Gibson

Figure 1.

Flow of the Optic Array During Locomotion.

Note. From *The Senses Considered as Perceptual Systems*,

p.161, by James J. Gibson, 1966, Boston: Houghton Mifflin Company,.

Copyright 1966 by James J. Gibson.

1950, 1966, 1979). According to Gibson (1950, 1958, 1966) the focus of expansion plays a major role in the guidance of locomotion.

Another source of information used in locomotion which is closely related to expansion patterns involves ground texture. Texture refers to the structure of a surface, which must reflect light in order to be perceived as a surface, instead of merely as an insubstantial area of color. Physical occurrences such as complete darkness and a clear sky do not reflect light, and therefore are not surfaces, and do not possess texture (Gibson, 1950). The elements that specify a textured surface appear to be spaced closer together as the surface extends into the distance. The gradient is used in the perception of depth and the spacing provides information about the distance of any point on the gradient. Texture gradients contain the traditional depth cues of linear perspective, and relative size and height, as well as additional information about distance. Gradients enable an observer to move in the environment without losing depth information.

A texture gradient that has been used frequently in flight simulation studies is a wire frame grid composed of two set of parallel lines orthogonal to each other (see Wolpert, Owen, & Warren, 1983; Wolpert, 1987; Johnson, Tsang, Bennett, & Phatak, in press). The lines that are perpendicular to the

direction of an observer's motion provide information regarding forward speed from optical edge rate (which is defined as the rate at which discontinuities, or texture boundaries cross a fixed reference point in the field of view; see Warren 1982), but offer no information useful for maintaining a heading angle (see Figure 2).

Heading angle refers to the direction one is moving, and is delineated by a velocity vector with respect to the nose of the craft. This can be compared to ground track heading which refers to following a specific path in order to reach a particular destination. In order to maintain one's heading angle, the ratio between forward and lateral velocities must remain constant. In other words, by maintaining a constant velocity vector with respect to the nose of the aircraft, heading angle is stable.

Heading angle and ground track heading also differ with respect to how tracking error is determined. Tracking error with respect to heading angle is defined by the difference between the direction the observer should have been heading, and where they were actually heading. For example, if the required heading angle was 15 degrees north and they were heading 20 degrees north, the heading angle error would be 5 degrees irrespective of any location on the ground. Heading angle only refers to the difference between the nose of the

Figure 2.

Horizontal Line Display.

aircraft and the velocity vector irrespective of final destination, whereas ground track heading refers to following a specific path to reach a particular destination.

Therefore, tracking error for course heading (or ground track) is a measure of how much an observer deviates from the specific path or course they were following to get to a particular destination. For example, if the task was to go from point A to point B, tracking error for ground track heading would be measured with respect to how far one was from the path.

The lines parallel to an observer's movement provide information about lateral speed from edge rate (the rate at which discontinuities cross a fixed reference point). These lateral optical changes can be used to maintain heading angle (see Figure 3). Neither the parallel nor the perpendicular lines optically specify a radial focus of expansion when they are presented alone. However, the points that make up the parallel lines do provide some expansion information. That is, the points that make up a line expand from one another, but this expansion is not radial (see Figure 4). The texture gradient of the wire frame grid mentioned above which contains both horizontal and meridian lines, provides information useful about forward speed, lateral speed, and the focus of expansion, all of which may be useful in guiding locomotion.

Figure 3.

Meridian Line Display.

Figure 4.

Expansion of a Line.

-----<-----<-----<-----<---X--->----->----->----->-----

X is the point being approached

Another texture gradient used in flight and motion simulation studies is a dot display which can provide the same optical flow information necessary for locomotion. Larish and Flach (in press) performed a study to examine the contribution of edge rate and global optical flow rate (defined as the velocity of forward motion scaled in altitude units) in the perception of egospeed. They used two viewing conditions (controlled and uncontrolled), and two display types. In the controlled viewing condition conflicting two-dimensional cues were reduced to enhance the perception of depth. It has been suggested (Andersen 1986) that the availability of relative depth information in the display may be critical in the perception of self-motion.

Two displays were used, a grid texture and dot texture. The grid display consisted of regularly spaced colored rectangles. The dot display was made up of white dots on a black field. The position of any given dot was variable, yet the average texture density was the same as that of the grid display. The subjects' task was to imagine they were traveling in an aircraft, and to rate how fast they were moving.

A 100-point bar graph display was used to estimate speed. The results of Larish and Flach's study showed that edge rate was more important than global optical flow in the verbal estimation of egospeed under all conditions. However,

performance improved using global optical flow rate for the controlled viewing conditions, which were designed to enhance depth cues by reducing conflicting two-dimensional cues. They also found a marginal effect of display type. Larish and Flach (in press) attribute the effect to the difference in the salience of edge rate information in the two displays. A strong effect for edge rate was found even with the dot display which had no consistent edges. This finding suggests that the availability of edge rate information is not simply derived from the salience of edges, but rather is a source of information available from generalized patterns of discontinuities. It appears that edges do not have to be well defined in a display to have an effect on the perception of egospeed.

Focus of Expansion

The literature pertaining to locomotion has been influenced by Gibson's theory that the focus of expansion plays a major role in guidance situations. Havron (1962) developed a model which described the apparent speeds of movement of ground objects during final approach and landing. With this model, Havron compared speeds of movement with perceptual thresholds to evaluate the effectiveness of different expansion patterns on a pilot's performance during final approach and landing. The analyses show that the area of no perceptible movement, or target area, is not just the point of impact, but is seen as an area,

the shape of which depends on such factors such as approach angle, speed, and distance. However, Havron (1962) pointed out that the results must be regarded as conjectural because arbitrary, and not empirical, thresholds for the perception of movement were used.

Johnston, White and Cummings (1973) also examined Gibson's hypothesis regarding the role of the focus of expansion in guidance situations. Subjects viewed a random pattern of white dots on a black background at five rates of expansion. The subjects' task was to imagine they were driving toward the dots and to indicate with a pointer the exact spot they were traveling to. The findings showed that the accuracy of detection of the focus of expansion increased as the rate of expansion increased. However, since the mean errors were large, 10 degrees, the author concluded that subjects could not detect the focus of radial outflow, and that the errors could be explained by the bias to point to the center of the screen. Johnston et al. (1973) explain that accuracy should increase as the rate of expansion increases because velocities of dots adjacent to the focus of expansion are comparably greater. At slower rates of expansion, subjects may find it difficult to locate the correct position and will more than likely respond to the point of initial fixation which is the center of the screen (Johnston et al., 1973). From these results, and those reported by Havron (1962), it

appears that at slower rates of expansion the precision necessary for identifying the focus of expansion is lacking.

Another possible explanation for the high error rate is that the dots did not grow as the planar surface moved toward the observer. Therefore, a crucial source of information in detecting movement was lacking, namely a magnification or increase in the size of objects as they are approached (Cutting, 1986).

Palmer (1968) and Ferrante (1979) investigated how well a pilot can detect the aim point during descent. In both experiments, the magnitude of the expansion ratio (which is the vehicle's distance from the aim point divided by its velocity) was manipulated. Ferrante (1979) also examined the effects of glide slope angle and texture pattern (random and uniform dot patterns). Subjects in both experiments viewed expanding dot patterns and were asked to move a pen (Ferrante, 1979) or a dot (Palmer, 1968) to the point on the screen which corresponded to the focus of expansion. Ferrante (1979) found higher angular deviations from the aim point with the uniform pattern than the random pattern, and no significant effect of glide slope. Both Palmer (1968) and Ferrante (1979) found an increase in aim point errors with an increase in expansion ratio; that is, accuracy increased as the aim point was approached. However, detection of the

aim point appears to be of marginal use until the last few thousand feet of an approach to landing.

Warren (1976) also investigated the role of the focus of expansion in the guidance of locomotion. Subjects viewed seven simulated scenes which corresponded to those that would be seen by an observer looking out of a front, side, or intermediate window of a moving vehicle. Motion picture displays of random dots and a slide condition (an experimental control) composed of equally spaced parallel lines were used to present the different scenes. These displays represented linear displacement of the observer over an endless flat plane. The field of view was such that only two of the seven simulated headings were in view. The subjects were asked to give their impression of self motion (egomotion) and to indicate with a pointer where they felt they would have been heading if they were actually moving. The results showed that neither the perspective slide presentation or movie condition was "psychologically privileged" over the other with respect to generating the experience of egomotion. Also, observers were able to perceive the direction they were heading regardless of whether or not the heading direction (focus of expansion) was in view on the display. The general findings support Gibson. The point

which the subjects indicated as their heading was a direct function of the optically specified heading of the egomotion flow pattern.

Llewellyn (1971), however, rejects Gibson's (1950, 1958, 1966) hypothesis regarding the focus of expansion. Subjects in Llewellyn's study were also asked to locate the focus of expansion using a light after viewing a fronto-parallel array of moving dots. The differences between the judged and correct positions of the focus of expansion were measured as linear deviations. Errors ranged up to 5.85 cm on a screen only 8.58 cm in diameter.

These results indicate that subjects could not accurately locate the focus of expansion. Therefore, Llewellyn proposed a target detection theory which stated that guidance situations requiring accuracy involve locomotion toward a target. Information for this guidance is provided by movement of the target, the presence and nature of any drift signaling the existence of a heading error, and the nature of the correction required. Llewellyn conducted several studies to determine if subjects were more accurate in detecting target drift or the location of the focus of expansion. Llewellyn (1962, 1971) found that accuracy of target drift cancellation was shown to vary with stimulus changes whereas accuracy involving the detection of the focus of expansion did not. Also, the level of precision was far superior for detection of target drift than that for detecting the

focus of expansion. Therefore, Llewellyn (1971) concluded that target drift is more useful in guidance situations than the focus of expansion.

Palmer (1968), Ferrante(1979), Warren (1976), and Llewellyn (1962, 1971) all used an identification task in which subjects had to point toward the focus of expansion. Warren, Morris, and Kalish (in press) state that the high levels of inaccuracy found in these studies may be due to the type of task. Therefore, they examined how well an observer could detect where they were heading using a discrimination task. Subjects viewed a random-dot planar surface in which dot density, forward velocity, and angle of approach were manipulated. The task was to judge whether they appeared to be heading to the left or right of a target line presented at the end of the trial after the motion had stopped. Performance decreased as dot density decreased, and increased with an increase in forward velocity. Heading accuracy remained within 1.2 degrees even at comparatively slow speeds and with as few as 10 dots. Warren et al. (in press) state the previous results in which heading errors were between 4.0 and 10.0 degrees may be due to the choice of response tasks and not other display parameters.

From the results presented thus far, it appears that people are unable to locate where they are moving with any consistent accuracy. However, this

cannot be the case, or runners, skiers, and other athletes would be in great danger. Cutting (1986) states that these types of activities require judgments accurate within 1 deg of visual angle, and that evidence which indicates poorer performance than this should be distrusted. Cutting (1986) explains that through differential motion parallax one can locate where they are moving in the environment. Differential motion parallax refers to the different optical flow patterns that are generated, depending on where an observer is fixating while moving.

When one is moving and looking in the same direction there is equal instantaneous displacement of elements on the left and right, this is similar to Gibson's focus of expansion. However, when looking off to the side, there is asymmetrical displacement of objects closer to and farther away from a fixated object. For example, when moving forward and looking to the left, objects further away from a fixated object appear to move more slowly and to the right (in the direction of motion), whereas those objects closer to the fixated object move more quickly and to the left (opposite the direction motion). There is a different set of parallaxes associated with every object the viewer may choose to fixate or look at while moving in the environment (Cutting, 1986).

To test the concept of differential motion parallax, Cutting (1986) performed a study in which observers were asked to determine if the simulated motion represented looking ahead, to the left, or to the right. The environment consisted of 12 vertical lines, 4 randomly placed on each of 3 parallel planes orthogonal to the direction of motion. All of the lines extended the full vertical height of the display in order to prevent the use of relative size information which could be used to determine the distance of each plane. The distance between the three planes was varied as were the beginning and ending gaze angles. The results showed that subjects were unable to determine the direction of simulated movement at better than chance level under conditions which gave little impression of depth (this was the case when the three planes were close together). However, for conditions in which depth could be discerned, accuracy was above chance level for trials with ending gaze angles as small as 5 deg. For the condition in which the planes were furthest apart, accuracy for judging was reliable for gaze angles less than 1 deg to the left, 0 deg ahead, and less than 1 deg to the right. Unlike the findings of previous research, one may infer that observers could accurately locate their direction of movement (Cutting, 1986).

Active Control

All of the studies mentioned thus far have used simulations of forward motion to determine how well the focus of expansion can be detected. Limitations of these studies are that the participants were passive, and detection and/or reaction times were used as measures of performance. When a participant can interact with, and is in control of, some part of an event, performance can be measured continuously. However, during a passive detection task, performance can be measured only after an event has occurred. Also, an interactive participant has the opportunity to use visual feedback, which is not necessarily perceived correctly, about their performance throughout the entire event, whereas this is not possible for a passive observer. Since the active participant has access to different information than the passive participant, perception of an event and performance may differ radically. Active performance may also lead to a different understanding of a perceptual process.

Grunwald and Merhav (1976) performed an investigation using interactive participants. They simulated heading changes during rectilinear and curvilinear flight. The subjects' task was to control their path of motion using different reference points in the field of view. The results showed that the closer the reference point was to the observer, the lower the lateral tracking error.

More recently Zaff and Owen (1987) manipulated global optical flow rate, initial edge rate, and initial fractional change of both variables (defined as the percentage of change from the initial condition) to determine what influence they have on a person's ability to detect and control changes in self motion. Prior to this, Tobias and Owen (1984) using a passive paradigm concluded that fractional rate of change in flow rate was a functional variable for detecting changes in the rate of self motion. A fractional variable contains information that is relevant to performance, and one to which the individual is attuned. Three levels of initial fractional change in speed, three levels of initial global optical flow rate, and six levels of initial edge rate were used to present the accelerating and decelerating events. The simulated motion was over a flat surface composed of earth colored rectangles at four different altitudes. Subjects were told that each trial would begin at the same speed and their task was to maintain a constant speed throughout the trial. Applying pressure to a force-sensing control in the appropriate direction would cancel the computer initiated change in speed.

The results revealed an effect for all three variables investigated, although each had a different influence at different stages of the trials. However, with respect to the overall accuracy of performance during the task it is apparent that all three variables had a substantial impact on acceleration control. Previous

studies using reactive methodology (where the subject reacts to a stimulus, but has no control over the stimulus) have successfully distinguished contextual variables from functional variables on the basis of the characteristic psychophysical functions that were produced. Zaff and Owen's (1987) study, which used an interactive paradigm, has demonstrated that optical information which was defined as a contextual variable, specifically edge rate, was mistakenly used as though it were functional, with detrimental effects to performance. Through interactive studies it may be possible to determine which variables affect perception in a manner that approximates the real world.

The Present Study

Studies such as the one performed by Zaff and Owen (1987) have provided an important step for furthering the use of an interactive paradigm for investigating simulated motion. Another major question in need of investigation along these lines is to determine the salience of the visual cues necessary for maintaining heading angle during an interactive simulation of movement over an environment. Larish and Flach (in press) found a marginal difference between grid and dot displays when examining the perception of egospeed, which they attributed to the difference in prominence of edge rate in the two displays. However, differences may be attributable to the detectibility of motion parallax

cues, which provide some useful information for maintaining heading angle. In order to use motion parallax cues for maintaining heading, there must be rigid motion and shape constancy (which refers to the perceptually correct transformation of texture elements) of the objects in the environment. That is, the objects being passed over must be in a fixed position so that the relative position change can be determined as displacement of the observer occurs. The intersections in the grid display may not be perceived as rigid or fixed locations on the ground, but as meridian lines sweeping over horizontal lines. If no fixed positions can be detected in the display, this may interfere with determining where one is heading. However, a dot display, laid out in a perspective correct manner, will provide rigid motion and shape constancy, and changes in position will remain geometrically accurate.

The purpose of the present study was to evaluate whether type of display (dot or wire frame) and direction of movement have an effect on a person's ability to maintain a specific heading angle. The questions addressed were: 1) Does the magnitude of the heading angle errors differ in the two displays? 2) Are some heading angles more difficult to maintain than others? 3) Does the magnitude of some heading angle errors differ as a function of display type and direction of movement?

Method

Subjects

Ten paid subjects were recruited from Bionetics Corporation at NASA/Ames Research Center. All subjects were: 1) right handed, 2) between the ages of 18 and 45, 3) normal or corrected to normal vision and hearing, and 4) not licensed pilots.

Task and apparatus

The subject's task was to maintain a predetermined heading angle with as little deviation as possible during a simulation of forward motion. A cathode ray tube (CRT) was used to present the visual simulation displaying a window measuring 31.75 cm wide and 40.64 cm high, through which the world was viewed. The window was placed 63.5 cm from the subject's eyes and subtended 28.5 visual deg horizontally. Geometrically this placement was at the correct distance as that for a forward looking vehicle window with the middle of the window at eyeheight. A cab developed at NASA/Ames Research Center, which seats one person and resembles the cockpit of an aircraft was used to represent a vehicle. The simulated visual motion was generated by an Evans and Sutherland Picture System 2 in combination with a DEC RSX 11 minicomputer. Heading angle error was sampled 10 times a second during the 103 s of manual

control by a PDP 11/70 computer. One of the graphical displays presented to the subject was a wire frame grid composed of two sets of parallel lines orthogonal to each other. The latitudes and meridians were spaced 5208 ft apart on the ground. The other display, consisting of dots was laid out such that the dots corresponded to the positions of the intersections presented in the grid display. Thus, the relative density of dots to intersections was equal.

During the task the subjects experienced lateral wind gusts which took them off their heading angle. The wind was implemented by using a sum of sine waves, which were fully described by 6 associated amplitudes, frequencies, and initial phase angles which provided a near random presentation of the noise. The subject was required to maintain the correct heading angle. A right-handed spring centered MSI joy-stick was used to regulate lateral movement which controlled a velocity plant. The amount of velocity applied was proportional to the amount of deflection. The stick gain was 7 ft/sec of velocity for each deg of stick deflection. Error was measured by the angular difference between the assigned heading angle and the actual heading angle the subject was on. A PDP 11/70 computer was used to maintain a constant simulated altitude of 1500 ft and a forward velocity of 1500 knots.

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Design

Two factors, heading angle and display type were manipulated in a five (heading angles) by two (display types) by three (replications) within subjects factorial design. Heading angle was manipulated by presenting the velocity vector (focus of expansion) at one of three visual angles for each trial, 0.0 , 7.0, or 12.0 deg, fully counterbalanced for left and right positions. Two displays, a wire frame grid, and a dot display were used to represent the surface texture elements. Subjects received training trials until their performance reached the criterion mentioned below with the following headings: 0.0, 8.0 and 11.0 (left and right samples included). The 30 experimental trials consisted of three replications of the five heading angles (0.0, 7.0, and 12.0 left and right samples) crossed with the two displays. Heading error was sampled 10 times a second during the manual period of each trial (103 s.). These raw scores were collapsed into 10 second epochs for each trial. Adjusted root mean square error (ARMSE) and mean error were computed for each epoch, and for each trial the median ARMSE and mean absolute error were calculated. The latter two were used for analysis. However, both signed and unsigned values for mean absolute heading angle error were calculated. The signed values were used to determine if there

was a left or right bias, whereas the unsigned values were representative of the subject's ability to locate the required heading angle.

Procedure

Prior to initiation of experimental trials, subjects were trained to the following criteria: Average performance (measured by ARMSE) over four trials for the 8.0 and 11.0 deg conditions, across both grids, was to be less than the ARMSE for the uncontrolled noise. This criterion was used to ensure that subjects were not just making random stick movements, or introducing more noise into the system than that derived from the lateral winds. The same criterion was used for the 0 deg condition with the exception that only two consecutive trials were necessary to meet the criteria. The training trials consisted of 0 deg, and paired combinations of 8.0 and 11.0 deg such that one of the paired combinations was presented for the dot display, and the other for the grid display.

Subjects were given written, as well as verbal, descriptions of the control task and how performance was measured (see Appendices B and C). During the first part of the instructions the subjects read the first half of the written description of the task. The second part was a detailed explanation of the difference between heading angle and ground track heading. Lastly, the

subjects finished reading the written instructions. Subjects were told their task was to maintain their heading angle, which corresponded to the direction the craft was moving with respect to the craft's nose. In order to perform this they had to maintain an angle between their heading angle (moving direction) and the center of the craft (pointing direction). The craft could not yaw; therefore, the center of the craft was always pointing in the same direction.

Maintaining a heading angle was then contrasted to following a ground track heading in which the task would be to end up at some destination. Subjects were told not to simply follow a path on the ground as this would be maintaining a ground track heading. Instead, they were to use the ground as a reference. If the wind blew them off course they were instructed not to go back to the pattern on the ground they were following, as this would be following a course heading, but to pick out a new pattern that corresponded to the heading angle they were to maintain. Again, it was emphasized that the task was not to stay on a line between the start and end points, but to maintain the heading angle, parallel to the ground track. All subjects were shown at least one 50 s automated trial in which the vehicle was lowered to an altitude of 1000 ft and a forward velocity was increased to 3555 kts/hr with the dot display, to aid in detecting a pattern. If necessary this procedure was repeated until the subject

felt they had found a pattern to use. This procedure was repeated for the grid display. Subjects were told to watch the ground below them during the "AUTO" period, for any dynamic graphical pattern that might aid them in maintaining their heading angle. The strategy used to sustain heading angle was developed by each subject individually; none was offered by the experimenter.

During training, each trial consisted of an "AUTO" period, which was controlled by the computer, immediately followed by a manual period, which the subject controlled. The duration of the "AUTO" period was 10 s with the exception that a longer period was given if the subject requested one. However, trials with longer "AUTO" periods were not used to meet the training criterion as a shorter manual period effected the ARMSE score, which was used to determine if the subject met the criterion. During the "AUTO" period, the subject's task was to find the pattern they would use to maintain the heading angle for that trial. After 10 s, the word "AUTO" disappeared from the right-hand corner of the screen, and the 103 second period of manual control began.

Subjects were informed that they would be exposed to lateral wind gusts that would take them off of the heading angle. In order to control the heading of the craft, they were told to move the joy- stick the same direction the visual scene moved. Therefore if the visual scene appeared to be moving off course to the

right, they were to deflect the joy-stick to the right. This information should not be confused with giving the subject a strategy, as it merely provides the necessary information for controlling the craft. An example of offering a strategy would be to instruct the subject to follow a particular set of lines, or intersections to maintain a heading. The difference lies in that the former only provides general instructions, where the latter offers a strategy for maintaining a visual heading angle.

Once the criterion was met, subjects were given a five minute break after which the experiment began. The 30 experimental trials consisted of 3 replications of the 5 headings crossed within the 2 displays. The duration of the trials was 113 s consisting of a 10 second "AUTO" period and 103 s of manual control. The experiment was broken down into 3 sessions, each one containing 10 trials which included one sample of each possible combinations of headings and displays. After every four trials a two minute break was given, and at the end of each session a five to ten minute break was given depending on the subjects wishes. Heading angle and display type were randomly presented across all trials. Altitude and forward velocity were held constant throughout all trials.

Results

Heading angle error was measured 10 times a sec for 103 s. These raw scores were divided into 10 second epochs for each trial, with the last 3 s of each trial disregarded. Ten second epochs were chosen as this interval provided, on the average, ten negative to positive changes in heading angle error. Mean error and adjusted root mean square error (ARMSE) were computed for each epoch, and for each trial the mean absolute error and median ARMSE were derived. The means and standard deviations of the signed and unsigned mean absolute error scores for heading angle with the grid and dots displays are presented in Tables 1,2,3 and 4. In Tables 5 and 6 are the means and standard deviations for ARMSE heading angle error for heading angle with the grid and dot displays. Tests for homogeneity of variance can be found in Tables 7 and 8.

Two (display type) by five (heading angle) by three (replications) by ten (subjects) analyses of variance were performed for the dependent variables mean absolute heading angle error (signed and unsigned) and ARMSE heading angle error. The subjects' factor was treated as a random variable. The results of the three analyses of variance are shown in Tables 9 , 10, and 11.

Table 1

Dot Display: Mean Heading Angle Error and Standard Deviations for

Signed Mean Absolute Heading Angle Error in Degrees for 10 Subjects

		Replications		
		1	2	3
<u>Heading Angle (degrees)</u>		<hr/>		
0.0	<u>M</u>	0.043073	0.108099	0.063013
	<u>SD</u>	0.246538	0.269120	0.222811
7.0	<u>M</u>	0.114281	0.996951	0.319868
	<u>SD</u>	0.680904	0.156896	0.609102
-7.0	<u>M</u>	0.310186	0.309702	0.074242
	<u>SD</u>	0.664010	0.855604	0.125612
12.0	<u>M</u>	0.407914	0.294154	0.398449
	<u>SD</u>	0.644315	0.481376	0.574784
-12.0	<u>M</u>	0.414669	0.367570	0.287402
	<u>SD</u>	0.380505	0.418057	0.494303

Note. These are absolute means.

Table 2

Grid Display: Mean Heading Angle Error and Standard Deviations for

Signed Mean Absolute Heading Angle Error in Degrees for 10 Subjects

		Replications		
		1	2	3
<u>Heading Angle (degrees)</u>		<hr/>		
0.0	<u>M</u>	0.005187	0.024509	0.009357
	<u>SD</u>	0.164150	0.154434	0.100992
7.0	<u>M</u>	0.297713	0.296618	0.726596
	<u>SD</u>	1.474439	1.376658	1.250918
-7.0	<u>M</u>	0.107760	0.125356	0.292601
	<u>SD</u>	1.123041	1.347830	1.068789
12.0	<u>M</u>	0.118005	0.006402	0.111219
	<u>SD</u>	1.201731	1.033816	0.786032
-12.0	<u>M</u>	0.869915	0.319388	0.739560
	<u>SD</u>	1.090939	0.985045	1.124349

Note. These are absolute means.

Table 3

Dot Display: Mean Heading Angle Error and Standard Deviations in
Degrees for Unsigned Mean Absolute Heading Angle Error for 10 Subjects

		Replications		
		1	2	3
<u>Heading Angle (Degrees)</u>		<hr/>		
0.0	<u>M</u>	.151329	.172937	.148935
	<u>SD</u>	.193385	.228427	.171494
7.0	<u>M</u>	.592899	.568238	.462964
	<u>SD</u>	.786024	.467485	.400257
-7.0	<u>M</u>	.611466	.701536	.987511
	<u>SD</u>	.363854	.540180	.707414
12.0	<u>M</u>	.581028	.485680	.612379
	<u>SD</u>	.474257	.256455	.300172
-12.0	<u>M</u>	.505503	.489944	.474088
	<u>SD</u>	.227846	.241194	.293905

Note. These are absolute means.

Table 4

Grid Display: Mean Heading Angle Error and Standard Deviations in
Degrees for Unsigned Mean Absolute Heading Angle Error for 10 Subjects

		Replications		
		1	2	3
<u>Heading Angle (degrees)</u>		<hr/>		
0.0	M	.093575	.098567	.07475
	SD	.31324	.117142	.063931
7.0	M	1.158963	.921014	1.21293
	SD	.883184	1.024904	.718840
-7.0	M	.856892	.986240	.874661
	SD	.676961	.867964	.622417
12.0	M	.874589	.846898	.651535
	SD	.780854	.521433	.399908
-12.0	M	1.138401	.736694	.989378
	SD	.768786	.693280	.885578

Note. These are absolute means.

Table 5

Dot Display: Mean Heading Angle Error and Standard Deviations in Degrees
for ARMSE Heading Angle Error for 10 Subjects

		Replications		
		1	2	3
<u>Heading Angle (degrees)</u>		<hr/>		
0.0	<u>M</u>	3.04646	3.01648	2.93040
	<u>SD</u>	0.29717	0.31567	0.26809
7.0	<u>M</u>	3.073642	3.24681	3.08403
	<u>SD</u>	0.28807	0.21830	0.24682
-7.0	<u>M</u>	3.10695	3.15473	3.15679
	<u>SD</u>	0.29707	0.36051	0.26516
12.0	<u>M</u>	3.10532	2.940354	3.02438
	<u>SD</u>	0.20332	0.19455	0.19114
-12.0	<u>M</u>	3.00215	3.05381	2.99399
	<u>SD</u>	0.11813	0.27010	0.29712

Note. These are absolute means.

Table 6

Grid Display: Mean Heading Angle Error and Standard Deviations in Degrees
for ARMSE Heading Angle Error for 10 Subjects

		Replications		
		1	2	3
<u>Heading Angle (degrees)</u>		<hr/>		
0.0	<u>M</u>	2.90207	2.86253	2.87151
	<u>SD</u>	0.27881	0.20368	0.16314
7.0	<u>M</u>	2.98359	3.03569	3.07513
	<u>SD</u>	0.18070	0.23113	0.18586
-7.0	<u>M</u>	2.98172	3.04912	3.04080
	<u>SD</u>	0.24161	0.20083	0.25449
12.0	<u>M</u>	2.99357	3.06391	3.11596
	<u>SD</u>	0.22234	0.20696	0.25259
-12.0	<u>M</u>	3.08998	3.14818	3.12067
	<u>SD</u>	0.28796	0.18330	0.31783

Note. These are absolute means.

Table 7

Summary of Test for Homogeneity of Variance Using Signed MeanAbsolute Heading Angle Error as the Dependent Variable

Source	<i>df</i>	Number of Variances	<i>F</i> _{max}
Display (A)	149	2	1.560**
Heading (B)	59	5	5.488**
Replication (C)	99	3	1.099**
A X B	29	10	9.677**
A X C	49	6	1.849
B X C	19	15	7.202*
A X B X C	9	30	14.600**

p* < .05*p* < .01

Table 8

Summary of Test for Homogeneity of Variance Using ARMSE HeadingAngle Error as the Dependent Variable

Source	<i>df</i>	Number of Variances	<i>F_{max}</i>
Display (A)	149	2	1.109**
Heading (B)	59	5	1.269
Replication (C)	99	3	1.043**
A X B	29	10	1.522
A X C	49	6	1.849
B X C	19	15	1.491
A X B X C	9	30	3.052

* $p < .05$ ** $p < .01$

Table 9

Summary of Analysis of Variance Using Signed Mean Absolute Heading AngleError as the Dependent Variable

Source	<i>df</i>	<i>MS</i>	<i>Error</i>	<i>F</i>
Display (A)	1	147.49	A X D	3.826
Heading (B)	4	461.73	B X D	2.090
Replication (C)	2	72.50	C X D	0.529
Subjects (D)	9	481.26	-----	-----
A X B	4	16.30	A X B X D	0.894
A X C	2	48.22	A X C X D	1.421
B X C	8	41.31	B X C X D	0.897
A X B X C	8	22.67	A X B X C X D	0.830

* $p < .05$ ** $p < .01$

Table 10

Summary of Analysis of Variance Using Unsigned Mean Absolute HeadingAngle Error as the Dependent Variable

Source	<i>df</i>	<i>MS</i>	<i>Error</i>	<i>F</i>
Display (A)	1	525.00	A X D	11.003**
Heading (B)	4	518.45	B X D	7.512***
Replication	2	9.126	A X C	.4080
Subjects	9	1211.39	-----	-----
A X B	4	94.95	A X B X D	3.015*
A X C	2	9.64	A X C X D	.3940
B X C	8	11.59	B X C X D	.5530
A X B X C	8	17.03	A X B X C X D	1.0410

* $p < .05$ ** $p < .01$ *** $p < .001$

Table 11

Summary of Analysis of Variance Using Unsigned ARMSE HeadingAngle Error as the Dependent Variable

Source	<i>df</i>	<i>MS</i>	<i>Error</i>	<i>F</i>
Display (A)	1	12.07	A X D	1.057
Heading (B)	4	22.07	B X D	2.835*
Replication (C)	2	2.05	C X D	0.544
Subjects (D)	9	43.25	-----	-----
A X B	4	15.73	A X B X D	4.199**
A X C	2	4.573	A X C X D	1.769
B X C	8	3.302	B X C X D	0.754
A X B X C	8	2.596	A X B X C X D	0.593

* $p < .05$ ** $p < .01$

TESTS FOR HOMOGENEITY OF VARIANCE

Mean Absolute Heading Angle Error Findings

Location Error. The test for homogeneity of variance was significant for the main effect of display type, [$F_{max} (2, 149) = 1.560, p < .05$]; the main effect of heading angle, [$F_{max} (5, 59) = 5.488, p < 0.05$]; the main effect of replication [$F_{max} (3, 99) = 1.099, p < .05$]; the two way interaction for Display Type X Heading Angle, [$F_{max} (10, 29) = 9.667, p < .05$]; the two way interaction for Heading Angle X Replication, [$F_{max} (15, 19) = 7.202, p < .05$]; and the three way interaction between Display Type X Heading Angle X Replication, [$F_{max} (30, 9) = 14.60, p < .05$]. A complete summary of the homogeneity of variance results for mean absolute heading angle error can be found in Table 7. A correlation was performed between the absolute means and standard deviations (coefficient of variation) for all factorial variables to determine the source of significance, $r = .33318$. A critical-ratio z-test was performed to determine if this correlation was significant, the results show that $z = 1.794, p > .05$. From this it was determined that the source of significance for homogeneity of variance was probably not due to a linear relationship between treatment effect and variance. This indicates that as the size of the heading angle errors increased, the variance did not necessarily increase proportionately across heading locations.

Median ARMSE Heading Angle Error Findings.

Maintenance Error. The test for homogeneity of variance was significant for the main effect of display type [$F_{max}(2, 150) = 1.1099, p < .05$] and the main effect of replication [$F_{max}(3, 99) = 1.043, p < .05$]. A complete summary of the homogeneity of variance results for ARMSE heading angle error can be found in Table 8. A correlation was performed between the absolute means and standard deviations (coefficient of variation) for all factorial variables to determine the source of significance, $r = .270$. A critical-ratio z-test was also performed to determine if this correlation was significant, the results show that $z = 1.450, p > .05$. From this it was determined that the source of significance for homogeneity of variance was probably not logarithmic, nor due to a linear relationship between treatment effects and variance.

ANALYSIS OF VARIANCE AND POST HOC FINDINGS

Mean Absolute Heading Angle Error Findings

Both signed and unsigned values for mean absolute heading angle error were used for analysis purposes. The signed values show whether there is a left or right bias, whereas the unsigned values are representative of the subject's ability to locate the required heading angle. The results from the analysis of variance for the signed values showed no significant difference between the

mean absolute heading angle error for any of the main effects, two-way interactions, or three-way interactions (see Table 9). However, the results for the analysis of variance for the unsigned values did show a main effects for heading angle [$F(4,36) = 11.00$, $p < .05$] and display type [$F(1,9) = 7.51$, $p < .05$] as well as a significant two-way interaction for heading angle and display type [$F(4,36) = 3.00$, $p < .05$] (See Table 10).

The results from the Duncan tests for main effect of heading using the unsigned values show that 0.0 deg is significantly different from the other four heading angles (see Table 12). There were no significant differences found between the 12.0 deg left and right heading angles, nor between the 7.0 deg left and right angles. Duncan tests for the interaction of display type and heading angle for the unsigned values showed significant differences in performance between the grid and dot displays for 0.0 deg, 7.0 deg right, 7 deg left, 12.0 deg right, and 12.0 deg left. As can be seen in Table 13 the unsigned mean absolute heading angle error for the grid display was smallest for 0.0 deg, whereas performance was better with the dot than grid display for 7.0 deg left and right, and 12.0 deg left and right.

Table 12

Duncan Multiple Range Test for Heading Angle Using Unsigned MeanHeading Angle Error as the Dependent Variable

Heading Angle (Degrees)				
0.0	12.0	-12.0	7.0	-7.0
<hr/>				
Unsigned Mean Absolute Heading Angle Error in Degrees				
.1234	.6753	.7223	.8195	.8363
<hr/>				
<hr/>				

Any two means **not underscored** by the same line **are significantly** different (e.g., .1234 and .6753 are significantly different).

Any two means **underscored** by the same line **are not significantly** different (e.g., .8363 and .8195 are not different).

Table 13

Duncan Multiple Range Test for Heading Angle and Display Type Using Unsigned Mean Absolute Heading Angle Error in Degrees as the Dependent Variable

		Heading Angle (Degrees)							
G	D	D	D	D	D	G	G	G	G
0.0	0.0	-12.0	7.0	12.0	-7.0	12.0	-7.0	-12.0	7.0
Unsigned Mean Absolute Heading Angle Error									
.0889	.1577	.4898	.5413	.5596	.7660	.7910	.9060	.9548	1.097

Any two means not underscored by the same line are significantly different (e.g., 1.097 and .9548 are different).

Any two means underscored by the same line are not significantly different (e.g., .9548 and .9060 are not different)

Note . D=Dot and G= Grid

Median ARMSE Heading Angle Findings

Effect of display type (Dot vs Grid). The analysis of variance (see Table 11) showed no significant main effect for the display type, $F(1, 9) = 10.057, p > .05$. In fact, the magnitude of the differences between the means was so small (dot display mean equal to 3.06, grid display mean equal to 3.02) that no further analysis was deemed appropriate.

Effect for heading angle. The analysis of variance revealed a significant difference for ARMSE heading angle error for the main effect of heading angle [$F(4, 36) = 2.835, p < .05$] (see Table 11). In order to determine which heading angles were significantly different from one another, Duncan's multiple-range tests were performed. The only significant differences were between 0.0 deg and the other four heading angles (left and right samples of 7.0 and 12.0 deg; see Table 14). No significant differences were found between 7.0 deg left and 7.0 deg right, nor 12.0 deg left and 12.0 deg right (see Figure 5).

Effect of replication. As was expected, no significant difference was found between ARMSE heading angle error for the main effect of replication, [$F(2, 18) = 0.554, p > .05$].

Interactions among the experimental variables. The analysis of variance revealed no significant two-way interactions of ARMSE heading angle error for

Table 14

Duncan Multiple Range Test for the Main Effect of Heading Angle Using
ARMSE Heading Angle Error as the Dependent Variable

Heading Angle (Degrees)				
0.0	12.0	-12.0	-7.0	7.0
<hr/>				
Mean ARMSE Heading Angle Error in Degrees				
2.938	3.0405	3.0681	3.0816	3.0831
				<hr/>
				<hr/>
				<hr/>

Any two means **not underscored** by the same line **are significantly** different (e.g., 3.0831 and 2.938 are different).

Any two means **underscored** by the same line **are not significantly** different (e.g., 3.0831 and 3.0405 are not different).

Figure 5.

ARMSE Heading Angle Error as a Function of Required Heading Angle.

error for Display Type X Replication, [$F(2, 18) = 1.769, p > .05$]; Heading Angle X Replication [$F(8, 72) < 1, p > .05$]; nor for Display Type X Heading Angle X Replication [$F(8, 72) < 1, p > .05$]. However, there was a significant two-way interaction for Display Type and Heading Angle [$F(4, 36) = 4.199, p < .05$].

As can be seen in Figure 6 performance decreased as heading angle increased with the grid display (the lower the heading angle error, the better the performance). This linear relationship is not present, however, for the results of the dot display.

Duncan multiple-range tests were performed to determine the significant differences among the heading angles for the two displays. The results for heading angle error differences will be discussed with respect to the grid display only, the dot display only, and lastly, the grid and dot display together.

When only examining the grid display, the left 12.0 deg heading angle, which showed the highest heading angle errors, was significantly different from 12.0 deg right, and 7.0 deg left and right. Similarly, the 0.0 deg heading angle, which reflected the best performance was significantly different from 12.0 deg left and right, as well as 7.0 deg left and right (see Figure 6). No significant difference was found between 7.0 deg left and right (see Table 15).

Figure 6.

ARMSE Heading Angle Error as a Function of Display Required Heading Angle.

Table 15

Duncan Multiple Range Test for Heading Angle and Grid DisplayComparisons Using ARMSE Heading Angle Error as the Dependent Variable

Heading Angle (Degrees)				
0.0	-7.0	7.0	12.0	-12.0
<hr/>				
Mean ARMSE Heading Angle Error in Degrees				
2.8787	3.0238	3.0314	3.0578	3.1196
<hr/>				
<hr/>				

Any two means **not underscored** by the same line **are significantly** different (e.g., 3.1196 and 3.0578 are different from all of the others).

Any two means **underscored** by the same line **are not significantly** different (e.g., 3.0238 and 3.0314 are not different).

When only assessing the dot display again 7.0 deg left and right were not significantly different, nor was the difference between 12.0 deg left and right (see Table 16). An interesting finding was that 7.0 deg left and right were significantly different from 0.0, while 12 deg left and right were not.

Upon examining the difference in heading angle performance for dot and grid displays and the five heading angles, several important findings were uncovered. Significant differences in performance were found for 0.0 deg between the dot and grid; 7.0 deg right between dot and grid displays; 7.0 deg left between dot and grid displays; and 12.0 deg left between dot and grid displays (see Table 17). As can be seen in Figure 6 heading angle error was smallest for the grid display for 0.0 deg, and 7.0 deg left and right, whereas performance was best with the dot display for 12.0 deg left and right.

A significant difference was found for 12.0 deg left between the dot and grid displays. However the difference for 12.0 deg right between the dot and grid displays was not significant. Two *t*-test were performed to determine if the difference for 12.0 deg right, between the dot and grid displays, was significantly different from the difference found for 12.0 deg left between the dot and grid displays. The results for 12.0 deg right comparisons [$t(29) = .6211$, $p > .05$] were not significant as were those for the 12.0 deg right comparison [$t(29) =$

Table 16

Duncan Multiple Range Test for Heading Angle and Dot DisplayComparisons Using ARMSE Heading Angle Error as the Dependent Variable

Heading Angle (Degrees)				
0.0	12.0	-12.0	7.0	-7.0
<hr/>				
Mean ARMSE Heading Angle Error in Degrees				
2.997	3.016	3.023	3.134	3.1395
<hr/>			<hr/>	
<hr/>				

Any two means **not underscored** by the same line are **significantly** different (e.g., 3.134 and 2.997 are different).

Any two means **underscored** by the same line are **not significantly** different (e.g., 3.1395 and 3.134 are not different).

Duncan Multiple Range Test for Heading Angle and Display Type Using ARMSE Heading Angle Error as the Dependent Variable

Any two means **not underscored** by the same line are **significantly different** (e.g., 3.031 and 3.057 are different).

Any two means **underscored** by the same line are **not significantly different** (e.g., 3.119 and 3.195 are not different).

Note. D= Dot and G= Grid

1.762, $p > .05$]. These results indicated that even though a significant difference was found between 12.0 deg left for the dot and grid displays, this difference was not significant from that between 12.0 deg right for the dot and grid displays.

It must be pointed out that several post hoc tests have been conducted to understand the significant main effects that were reported. As is always the case when several post hoc test have been conducted, caution should always be exercised when interpreting the findings.

Discussion

The present investigation has been concerned with examining how well people can maintain heading angles using grid and dot displays. According to Gibson (1955, 1966, 1979), the focus of expansion can be used to determine where one is going in the environment. Other sources of information which can also be used include changes in lateral and forward edge rates which will be discussed in relation to differential motion parallax as described by Cutting (1986).

Most of the past research trying to answer questions that deal with way-finding have used passive identification tasks. However, no definite conclusions have been reached as to what role, if any, the focus of expansion

plays. The reason for this may be due to such factors as the type of task, presentation of the stimuli, and the different types of graphic displays used across the studies. An additional factor was introduced in the present study. The participants were given the opportunity to actively control their simulated movement over the environment. The questions addressed in the present study were 1) do the magnitude of the heading errors differ for the two displays, 2) are some heading angles more difficult to maintain than others, 3) and do the magnitude of some heading angle errors differ as a function of display type (dot vs grid) and heading angle?

Before discussing the results, the difference between mean absolute heading angle error and ARMSE heading angle error will be explained. Mean absolute heading angle error is a measure of bias, or more simply, the average difference between the instantaneous heading angle the subject was maintaining, and the required heading angle. Both signed and unsigned values for mean absolute heading angle error were calculated. The signed values show whether there is a left or right bias, whereas the unsigned values are representative of the subjects' ability to locate the required heading angle (location error). On the other hand, ARMSE heading angle error is the variability about the mean heading angle that the subjects were maintaining. This is

representative of the subjects' ability to maintain the heading angle. The important distinction between the two performance metrics is that (a) mean absolute heading angle error refers to **accuracy in locating** the specified heading angle, while (b) ARMSE heading angle error refers to the ability of the subjects to **maintain** the angle they had judged to be correct. The results for mean absolute heading angle error will be discussed first, followed by those for ARMSE heading angle error.

Mean Absolute Heading Angle Error Effects (Accuracy Errors)

There were no significant differences for the signed mean absolute heading angle error for heading angle, display type, nor any combination of these variables. This indicates that there was no left/right bias for either display. Of importance is the magnitude and range of the absolute mean heading angle errors. As can be seen in Tables 1 and 2, the magnitude of the mean heading angle errors were as small as 0.005 deg of visual angle, and only as large as 0.996 deg of visual angle. The significance of these values and those presented below will be discussed with respect to previous work shortly.

The results presented above, however, do not indicate how well a person is able to control the noise, as the average of the noise would yield the same non-significant results. In order to remove the potential contamination due to

the noise, an analysis was run using the unsigned mean absolute heading angle error values. These results showed significant main effects for heading angle and display type, as well as a significant two-way interaction for display type and heading angle. Duncan tests performed for the main effect of heading angle showed no significant difference for 12.0 deg left and right, nor for 7.0 deg left and right. However, 0.0 deg was significantly different from the other four heading angles. As can be seen in Tables 3 and 4 the magnitude of the unsigned values were as small as .07 deg of visual angle, and only as large as 1.21 deg of visual angle. These values are comparable to those for the signed values and indicate that subjects were highly accurate in picking out heading angles. Examination of the results for the interaction of display type and heading angle however do indicate that subjects were more likely to be off in determining where the heading angle was using the grid display. This may be due to the ambiguity or complexity of the display.

Previous research pertaining to way-finding, such as that conducted by Llewellyn (1962, 1971), Johnston et al. (1973), and Warren (1976) found that subjects' average heading location errors were much greater than those found in the present study (6 deg, 10 deg, and 5 deg of visual angle, respectively). However, other studies such as that performed by Ferrante (1979) found

absolute mean horizontal angular errors for estimations of aim point ranging from 0.394 to 1.148 deg. The magnitude of error rates reported by Ferrante (1979) is more comparable to those found in this investigation. Also reported, however, is the fact that the focus of expansion was of little use until the last few thousand feet of a descent (Palmer, 1968; Ferrante, 1979).

The reason for the vast differences between the results of this study and previous research may be explained by methodological differences across the studies. In the studies by Ferrante (1979) and Palmer (1968) subjects descended during forward motion which was not a factor in either Llewellyn's (1962, 1971) work or this study. Also, Johnston et al. (1973) and Llewellyn (1962, 1971) used motion toward a fronto-parallel plane, whereas this study, as well as those performed by Ferrante (1979), Warren (1976), and Palmer (1968), all simulated motion over a surface.

Another factor that may be responsible for the difference between previous findings and those presented here is the type of graphics used to display the simulated motion. That is, the physical characteristics of the display or the graphics engines that generate the scene have varied greatly across the studies.

Finally, all of the studies mentioned above have used a passive paradigm. That is, the subjects were not able to actively control any part of the visual scene. The tasks generally included pointing to the area on the screen that corresponded to where they were moving (the focus of expansion) after all simulated motion had stopped. One aim of the present study was to eliminate this passivity by enabling the subjects to actively control their heading angle, thus enabling them to interact with the simulated environment. By actively participating in the event, subjects in the present investigation were able to see the consequences of their actions, whereas this was not possible for passive participants.

Held (1965) discovered that giving animals control over stimulation was critical to the development of coordination between perception and action. Thus, by providing subjects in the present study with the opportunity to have control over stimulation in the current circumstance, sensitivity to pertinent optical variables may have increased performance by aiding coordination between perception and action. The small magnitude of the signed and unsigned absolute mean heading angle errors show that subjects were extremely accurate in locating the required heading angle, and that there was no left or right bias in performance.

Median ARMSE Heading Angle Error Effects (Maintaining Heading)

Main Effect for Display Type . The results of the main effect for display type failed to show a significant difference in median ARMSE heading angle error. This indicates that there is no difference in the ARMSE heading angle errors (i.e., variability) for the two displays. These results are consistent with Larish and Flach (in press) who found only a marginal difference in performance using dot and grid displays in their examination of the perception of egospeed. Their results showed a trend towards increased use of edge rate information with the dot display in which no regular texture spacing was provided.

Their results indicate that regularly spaced edges do not have to be present in order for edge rate to be a salient cue for way- finding. Larish et al. (in press) state that the term discontinuity rate, rather than edge rate, may be more appropriate as regularly spaced edges are clearly unnecessary for the use of edge rate information. The results of the current study are consistent with this in that no main effect for display was present. However, the reason for this may be associated with strategy or may be an artifact of the displays. These possibilities will be discussed with the results for the interaction.

Main Effect for Heading Angle. The analysis showed a significant main effect for heading angle with respect to median ARMSE heading angle error. As

indicated earlier, the results from the Duncan multiple range tests revealed that 0.0 deg heading angles were maintained best. In Figure 5 these results are apparent; median ARMSE heading angle errors for the 7.0 and 12.0 deg heading angles (left and right samples) are significantly higher than those for 0.0 deg. No significant differences in heading angle error were found between 7.0 deg left and 7.0 deg right, nor between 12.0 deg left and 12.0 deg right. These data indicate that there were no left/right differences in the variance for these heading angles.

From these findings, it appears that once the heading angle is located, there is less variability in maintaining a 0.0 deg heading angle, and that maintaining angles other than 0.0 deg appears to be equally difficult. This may be due to the type of displays or strategy used to maintain the heading angles.

Interaction: Display by Heading Angle. A significant interaction was found for the variables display type (dot vs grid) and heading angle for median ARMSE heading angle error. As can be seen in Figure 6 performance was best (lower ARMSE heading angle error) for 0.0 deg with the grid display. In both displays, linear perspective was a dominant cue; therefore, it was expected that there would not be a significant difference between the 0.0 deg heading angles for the two displays. A possible explanation for the difference in the variance found for

the 0.0 deg heading angles for the displays may lie in the strategies used to maintain the required headings. Two possible strategies could have been used to maintain heading angle: (1) Locate the focus of expansion and keep the center of the radial flow in one location with respect to oneself, or (2) Maintain a velocity vector by keeping the ratio of the flow of lateral and forward edge rates constant.

The first strategy pertains to Gibson's (1950, 1955, 1966) notion that as a surface is approached the scene radially expands from the point of intersection of the surface and the direction of travel. Both displays contain potential information for detecting the focus of expansion.

The second strategy entails maintaining a velocity vector and will be discussed in relation to Cutting's (1986) differential motion parallax. Differential motion parallax refers to the notion that if a person fixates on a point while moving, objects beyond that point will appear to move in the opposite direction, and at different rates than objects between the fixation point and the observer. As a result, when an observer gazes off the angle of their direction of movement, asymmetric optical flow occurs around the observer's line of sight. Fixations can occur for brief periods; thus, many fixations can take place in a short time. In the displays used, the objects were texture elements. These texture elements were

the shapes formed by the lines or the dots (i.e., squares). As an observer moved across the surface, the texture elements (squares) were distorted at a specific rate, depending on such factors as altitude, speed, range to the fixation point, and the distance and direction of a given texture element from the fixation point.

If differential motion parallax were utilized for heading control, it would be dependent on the perceptual constancy of the texture elements. That is, the subject would be able to perceive and follow a given texture element (square) as its shape was apparently transformed. This apparent transformation would occur from viewing the texture element from different eye points as a person was moved.

Another factor in maintaining texture element constancy in this study involved the velocity of the craft. Once the simulated motion began, the structured texture associated with linear perspective may have been enhanced in the dot display, whereas this structure was perceptually evident in the grid display even when it was static. Therefore, if differential motion parallax were utilized, the spacing of the lines (or dots) and the rate at which the transformations were occurring may have hindered or aided the subject in maintaining texture element constancy.

This consistency may have proven to be an advantage in the grid display, as the distinction between lateral and forward edge rate change may not have been as evident in the dot display. Changes in the consistency of these edges may have made it easier to detect the differential flow patterns as lateral changes could be differentiated from forward ones. In the dot display, there is no physical connection between the dots, which would make it more difficult to detect changes associated with differential motion parallax. It appears that the salience of the type of optical information in the two displays may have led subjects to use the focus of expansion with the dot display, and differential motion parallax with the grid display in order to maintain the required heading angles. A pilot study was performed to determine the parameters under which the control task could be performed. The findings from this study provide some support for the ideas presented above. See Appendix D for further details.

The linear relationship of increased median ARMSE heading angle error at larger required heading angles found for the grid display may also be accounted for through differential motion parallax. Again, at 0.0 deg the subject had available not only cues from changes in lateral and forward edge rates for detecting asymmetries in optical flow, but also cues from linear perspective. This may establish why the lowest variance was found for 0.0 deg and why

performance for 7.0 deg (left and right samples) was better than for 12.0 deg for the grid display. By examining Figure 7 it is clear that the area near the horizon at 12.0 deg is heavily clustered with lines, which may have made it hard to detect changes when an observer fixated in this area. At 7.0 deg the density of the meridian and horizontal lines was at a level at which an observer could differentiate them. However, this discrimination was not as easy (higher variability) at 12.0 deg, which may account for the decrement in performance at this heading angle.

The possibility remains that subjects were using the focus of expansion. But as can be seen in Figure 7 it is extremely difficult to locate the focus of expansion at the horizon. The changes in lateral and forward edge rate provided subjects with an easily detectable method of utilizing differential or asymmetrical flow patterns. The meridian and horizontal lines provided a constant texture which offers orthogonal information regarding edge rate change. The meridian lines supplied optical edge rate information useful for detecting lateral changes, while the horizontal lines offered information about changes in forward motion.

As mentioned previously, if these two flow rates are kept at a constant ratio, a velocity vector can be maintained, which could have been used to approximate the required heading angle. When the lateral noise introduced

Figure 7.

Grid Display.

changes to lateral and forward edge rates, there was a different asymmetrical flow indicating that the subject was off the required heading angle. The distinct separation of these two sources of information, which was easiest to differentiate at 0.0 and 7.0 deg, may explain why performance was better at these angles than at 12.0 deg.

Overall performance was better with the grid display. However, at 12.0 deg (left and right samples) performance was better with the dot display. Again, this may be directly the result of the displays used, or that subjects were using different strategies, one with each display. At 12.0 deg, the numbering and spacing of the dots (see Figure 8) may have been optimal for maintaining texture element constancy and detecting and accurately using the focus of expansion. Maintaining this angle with the grid display appears to be more difficult, possibly due to the compression of the lines, making it harder to use differential motion parallax. To sum, the interaction found for display type and heading angle may be related to how well subjects were able to make use of the optical flow information from the focus of expansion for the dot display, and asymmetrical flow patterns for the grid display.

Figure 8.

Dot Display.

SUMMARY

The present study used active control of heading to determine performance differences in locating and maintaining headings over two simulated environments. The type of display and required heading angle were varied, and performance was recorded for ten subjects. The subjects' task was to actively control heading angle of simulated motion after viewing a period of passive flight. Performance errors (the angular difference between the required heading angles and the angles the subject maintained) were recorded 10 times a second for a period of 103 seconds. Absolute mean heading angle errors (location errors) and median ARMSE heading angle errors (control errors) were derived from these raw scores. The results from these dependent measures show that subjects were able to locate and maintain 0.0 deg headings with both displays better than the other required headings. Overall, performance was better (lower angular errors) with the grid display than for the dot display at smaller heading angles. However, at larger heading angles, performance was best for the dot display. This may be explained by the differences in the salience of the texture structure of the two displays.

The differences in the salience of the texture structures in the two displays may have theoretical implications for generalizing the results found

here, as well as making comparisons with previous studies. It is possible that the results found in the present investigation differ from past studies in part due to the different graphics used across the studies. The current findings, as well as previous findings, may be laboratory specific; that is, the differences in the displays may partly account for the discrepancies of the results.

Another source of the differences may have been due to the fact that the subjects actively controlled the stimulation. In previous studies, the tasks generally involved pointing to an area on the screen, after the motion had stopped, that corresponded to where the subject was moving. The present study eliminated this passivity by having the subject actively control their heading, thus enabling them to interact with the simulated environment. By having subjects actively control the simulated motion they could see the consequences of their actions, whereas with a passive participant this is not possible.

An applied implication of the findings presented here relates to display design for cockpits and training pilots to use appropriate optical cues. It is apparent that the characteristics of the display are crucial in detecting and maintaining where an observer is moving. Performance with both displays used in the present investigation has shown that an observer can locate with extreme accuracy where they are moving, and maintain movement in that direction with

very little variance when allowed to control their motion. The differences found in the interaction of display type and heading angle perhaps can be nullified if the problems with density, too little for the dot display and too much for the grid display, are remedied. A possible follow up study would entail manipulation of the density of either array. However, the problem of different performance levels may still exist due to the type of graphics used to display the simulations. Therefore, further research regarding the use of vector and other types of graphics is essential for finding comparable performance levels across studies.

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Appendix A

Differential Motion Parallax

Refers to the notion that if a person fixates on a point while moving, objects beyond that point will appear to be moving in a different direction (in the same direction the observer is moving) and at different rates than objects between the fixation point and the observer (Cutting, 1986).

Egomotion

The perceptual experience of motion (Warren, 1976).

Focus of Expansion

The center of the expanding flow pattern which specifies the direction of locomotion. The visual scene radially expands from the focus of expansion (Gibson, 1966).

Global Optical Flow Rate

The velocity of forward motion scaled in altitude units (ie., if 1 altitude unit = 1 person height (2 meters), then 1 eyeheight = 2 meters, and the global optical flow rate = velocity/2 meter). It varies with path speed and altitude, but is independent of the texture pattern on the ground surface (Wolpert, Owen, & Warren, 1983).

Ground Track Heading

Refers to following a path or course to reach a particular destination in the environment.

Heading Angle

Refers to the direction an observer is moving in the environment irrespective of any target or path on the ground. It is the direction the longitudinal axis of the craft is pointing given the craft's velocity vector.

Motion Parallax

The apparent change in position of object resulting from a change in the direction or position from which the object is viewed (Gibson, Olum, & Rosenblatt (1955).

Motion Perspective

The radial inflow and outflow in the whole array at a moving point of observation (Gibson, Olum, & Rosenblatt, 1955).

Optical Edge Rate

The rate at which discontinuities (texture boundaries) cross a fixed reference point in the field of view (Warren, 1982).

Velocity Vector

The direction the craft is moving.

Appendix B

Instructions

The experiment that you are participating in involves a control task. The purpose of this research is to examine some of the visual information available during movement through an environment. Your task is to control the direction of movement of the vehicle with respect to its' nose. You will ALWAYS be traveling at the same height and the same speed.

The screen, which will display the world you are traveling over, corresponds to the "window" of your vehicle. The center of the screen will always coincide with the center of your craft. A joy-stick, located on the right armrest of your seat, will be used to control lateral (left, right) movement of the craft. During the experiment, turbulence and wind gusts will act as random forces bouncing you to the left and right. This will take you off of your "Heading Angle". Heading angle refers to where you are going in the environment irrespective of the center of your vehicle. In other words, it refers to your moving direction. This can be contrasted with your pointing direction, which corresponds to the center of the window. Therefore, your craft can be moving one direction and pointing in another direction.

Lateral deflection of the joy-stick will move your craft to the left or right, corresponding to which direction you deflect it. The further you move the joy-stick, the faster the craft will travel in that direction. Returning the joy-stick to center will stop any motion due to the joy-stick, but you may still see movement which is due to the winds. When you are taken off of your heading (moving direction) you must move the joy-stick the SAME way the wind blows you. Therefore, your task is to maintain the angular difference between the center of the window or POINTING DIRECTION" and your ground track heading, or MOVING DIRECTION". Please tell me when you have read up to this point so I can further explain this relationship.

During the AUTO period, you should carefully examine the world below for any information that may aid you when you take over. Pay close attention to any changes in the PATTERN of the world you are traveling over, especially as they relate to your moving direction. When the word "AUTO" is no longer displayed in the right hand corner, this is your signal to take over lateral control. Before the start of each trial I will tell you which direction you will be heading. Throughout each trial, try to maintain the MOVING DIRECTION that you were set on in the beginning of the trial the best you can. If you have any questions

please ask now, or during the experiment. You will be able to communicate with me through a set of headphones.

Appendix C

Verbal Instructions

Subjects were shown Figure 9 with the following explanation. In this diagram you will notice the craft is pointing a different direction than it is moving. This is also the case for the simulator behind us, which does not move, and hence it is always pointing in the same direction also. The task you will perform is to maintain the angle between the center of the screen, which represents your window, and the heading I assign you. The craft will appear to be crabbing to the left or right depending on which heading you are on. The computer has been programmed for each of the headings, and would maintain them for you, but winds will be introduced, which change the heading angle. Therefore, your task is maintain the heading angle I assign you. This can be done by keeping the angle between the center of the screen or your pointing direction and your assigned heading or moving direction constant. At the end of each trial I will give you an error score, the lower the error, the better you were at maintaining the heading angle for the trial. Next, the subject was asked to get in the cab.

The screen, which represents your window , allows you to view 28 visual degrees of the world below. During training I will ask you to maintain 8 and 11 visual degrees. I want you to keep in mind that from center to side, the screen

Figure 9.

Maitaining Heading Angle.

measures 14 visual degrees. Therefore, if your task is to maintain a heading angle of 8 degrees, you need to examine an area close to half way between the center and the side of the screen. By knowing the lateral visual dimension, you can get an idea of where you will be moving toward before the trial begins.

Appendix D

A pilot study was conducted to determine the parameters under which the control task could be performed. The subjects' task was to maintain a predetermined heading. A 10 second "Auto" period began each trial, which was controlled by computer. The purpose of this was to enable the subject to locate any pattern that may have aided them in maintaining the heading for that trail. After the "Auto" period the subject had control over the lateral motion of the simulated movement of the craft until the end of the trial. The frequency and the amplitude of the noise was considerably smaller than that for Johnson et al. This may be the result in differential sensitivity to translation and rotation.

The altitude for all trials was 1500 ft and the forward velocity was 1500 kts. The noise level for the lateral wind gusts was selected through previous pilot work as the level at which the task was neither too difficult, nor trivial. The values for altitude and forward speed were chosen partially on the basis of the study performed by Johnson et al., (in press), and partially through the outcome of pre-pilot work.

The displays used were a wire frame grid and a dot display. The layout of the two displays was such that the density of intersections and dots were equal.

The independent variables examined were display type (grid vs dot) and heading angle (0.0, 5.0, 6.0, 10.0 left and right samples). Adjusted root mean square error was used as the dependent variable. Subjects had to perform at better than the criteria which was determined to be the adjusted root mean square error (ARMSE) score obtained at the end of a trial in which there was no control for the lateral noise. The ARMSE criterion value used was 4.0.

An interesting finding was that subjects were able to maintain heading angles between 1 and 6 deg at the criterion level with the grid display, and not the dot display. One plausible explanation for this is that subjects were trying to locate a radial flow pattern in the dot display which was below threshold with the limitations of the current display at such small visual angles. Perhaps, subjects were able to maintain these heading angles (1 and 6 deg) with the grid display as the differential flow, due to changes in lateral and forward edge rates, were perceptible and were accurately utilized by the subjects.

This reasoning may also account for the better performance at 12.0 deg (left and right samples) than 7.0 deg (left and right samples) for the dot display found in the present investigation. At smaller heading angles, with the exception of 0.0 deg in which linear perspective may have played a major role, the dots were spaced farther apart. This sparsity may have thwarted the subjects ability

perspective and the frame of the screen for detecting changes in the heading angle. It appears that there may be an optimal dot density for locating and using the focus of expansion.