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13. ABSTRACT *(Maximum 200 words)*

Human observers' ability to perceive self motion using information contained within optic-flow patterns was investigated. Subjects discriminated changes in heading direction as stimulus parameters were manipulated. Some of the results were surprising and difficult to explain in the context of current theories. In order to better understand the results, the role of eye movements in self-motion detection and in speed discrimination was investigated. The end product is a model that can account for the findings. The optimal stimulus for motion detection was also explored to define the shape (x,y,t) of the human motion sensors, which are believed to be involved in the early processing stages of self-motion perception. A computational model for the extraction of 3D motion information from 2D motion information was also developed. The neural network model was able to qualitatively account for the human observer's ability to detect changes in heading direction.

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AFOSR #91-0154 Final Technical Report - Turano (P.I.)

(A) Objectives of the research effort:

One objective of the previously-funded research was to study the ability of human observers to perceive *self motion* by means of the spatial-temporal information contained within optic-flow patterns. To this end, we investigated subjects' ability to discriminate changes in heading direction as we systematically manipulated the stimulus parameters, e.g. locomotion speed (**Section B1** below), magnitude of the spatial area (**Section B2** below), and location of the stimulated visual field (**Section B2** below). Some of the results were *surprising* and difficult to explain in the context of current theories. In order to better understand the results, we investigated the role of eye movements in curvilinear-motion detection (**Section B3** below) and in speed discrimination (**Section B4** below). The end product is a model that can account for the previous findings. We also explored the optimal stimulus for motion detection and thereby defined the shape (x,y,t) of the human motion sensors, which are believed to be involved in the early processing stages of self-motion perception (**Section B5** below).

A second objective of the previous research was to develop and test a computational model for the extraction of 3D motion information from 2D motion information. The goal was to develop a biologically-feasible model that is built upon a foundation of psychophysical findings. To this end, we developed a neural network model that was able to qualitatively account for the human observer's ability to detect changes in heading direction (**Section B6** below).

(B) Status of the research effort:

(1) Completed Studies:

B1: Visual discrimination between a curved and straight path of self motion: Effects of forward speed. [**Turano, K.** and Wang, X. (1994) Vision Res., 34, 107-114.]

As an observer moves through a stationary environment, his/her motion path is specified by the optic flow. The velocity field of the optic flow can be analyzed as the sum of a translational and rotational component. A straight motion path generates a velocity field composed of a pure translational component, and the observer's heading direction is spatially coincident with the common point of origin of the velocity vectors. At the other end of the continuum, an observer twirling in place generates a velocity field composed of a pure rotational component which represents the angle of rotation around the axis passing through the point of observation. On the retina, the rotational component of the velocity field also reflects the effects of eye movements. Consequently, the same rotational component may represent an observer making eye movements while navigating a straight motion path or an observer navigating a curved motion path. Studies have shown that, with computer-generated simulations of optical flow, observers are able to distinguish between circular and straight paths of motion. In order to explain how the retinal flow produced by an observer

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moving on a curved path can be distinguished from the retinal flow generated by an observer moving on a straight path making eye movements, a model has been put forth by Rieger. The model is based on the idea that circular heading can be determined by the angular deviation between successive translational components. When an observer moves along a curved path, the orientation of the translational component of the velocity field changes over time, whereas if an observer moves along a straight path, the orientation of the translational component does not change.

In this study, we measured an observer's ability to discriminate between circular and straight paths of motion to (1) test Rieger's model by comparing psychophysical results to predictions generated from a computer simulation of Rieger's model and (2) to extend Warren *et al.*'s findings to circular paths of larger curvature. For both the psychophysical tests and the computer simulations, two sequences of simulated observer motion were presented to the subject (or computer): one sequence was a simulation of observer motion along a straight path and the other sequence was a simulation of observer motion along a curved path (the direction of the circular path was either right or left, randomly determined). The task was to determine which sequence was the curved path of motion. The angle of the deviation from a straight path occurring within a second of time (angular speed) served as the independent variable. Each subject was given 200 trials, 40 trials for each of 5 preselected angular speeds. A psychometric function was obtained by plotting the proportion of correct responses against angular speed, and a Weibull function was fit to the proportion-correct distribution. The angular speed corresponding to 82% correct defined threshold. Thresholds were measured at forward speeds ranging from 2.0 - 26.4 m/s. The means of four subjects' angular-speed thresholds and standard errors for each forward speed are shown in Figure 1 together with angular-speed thresholds calculated from the simulation results. As shown, subjects can detect a departure from a straight path of motion when the deviation is as small as 2.0 - 4.0 arcmin/s at a forward speed of 2.0 m/s. At faster forward speeds, subjects require a larger deviation to detect a departure from a straight path. At a forward speed of 26.4 m/s, subjects require a deviation an order of magnitude greater than required for the 2.0- forward speed to attain the same level of performance. The simulation results show an opposite trend. Thresholds are infinite at forward speeds of 2.0 and 5.0 m/s and decrease with increasing forward speed. What could explain the difference in performance between the model and the human observer at slow forward speeds (Fig.1)? One difference between the model and the human visual system is the type of available information. In the model, the only information available to the

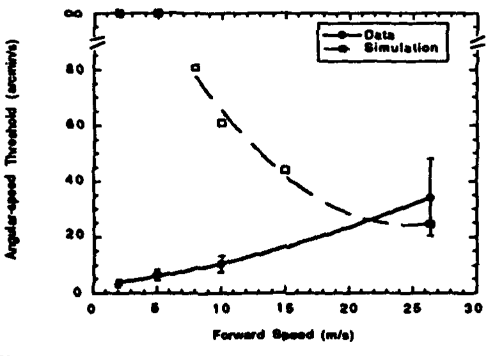

Figure 1

decision maker is the stimulus motion. In the visual system, however, the information available to the decision maker consists of retinal motion (i.e. stimulus motion plus motion components generated from eye movements) and extra-retinal information (e.g. proprioceptive feedback from the extraocular muscles or efference information). It could be that (1) extra-retinal information and/or (2) the altered retinal motion due to eye movements play(s) a role in an observer's ability to discriminate between a curved and a straight path of motion (discussed below).

Other possibilities for the failure of the model are that the visual system decomposes the velocity field into the two components by a method different from that utilized in the Rieger model (e.g. Perrone), or the visual system does not decompose the velocity field into translational and rotational components to discriminate a curved from straight path. An alternative hypothesis has been offered to account for the perception of circular heading. Warren *et al.* suggest that the observers do not perceive curved motion paths by determining the angular deviations between successive translational headings but by determining flow field curvature directly. In our study, when the data are plotted as a function of curvature (curvature=angular speed/forward speed), Fig. 2, the functions across the different forward speeds coincide reasonably well. Subjects discriminate between a straight and curved path at a constant path curvature, approximately 0.0004 m^{-1}, regardless of the forward speed. These psychophysical results are consistent with the Warren *et al.* hypothesis. However, given that the observers in the present study were free to move their eyes, it is unclear how eye rotations could be distinguished from circular movement with the Warren *et al.* hypothesis.

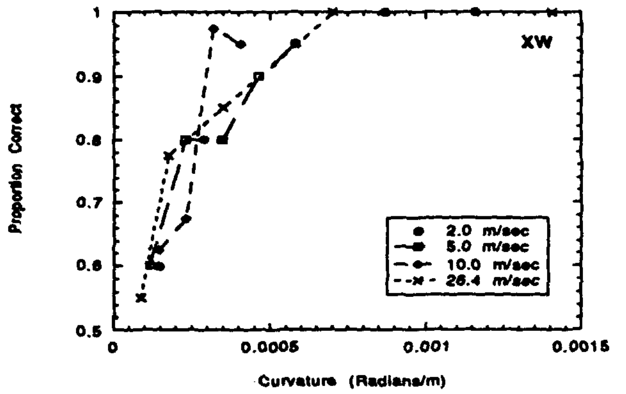

Figure 2

B2: Field of view required for optimal optic-flow discrimination. [**Turano, K.** (1991) Optical Society of America Technical Digest, 17, 217.]

This study examined (1) the minimum "window size" needed at different retinal locations and (2) the effectiveness of the stimulated retinal location of motion information for observers to make judgments about simulated self-motion.We used computer-generated patterns that simulate an observer moving along a circular path relative to a volume of randomly-positioned dots. The images simulated either motion curved to the right or left. The observer's task was to indicate the direction. The amount of angular change per second of time served as the independent variable. The higher the angular-speed threshold, the greater the required change in motion direction for correct discrimination.We measured angular-speed thresholds using motion restricted to "windows" of various widths and retinal locations.

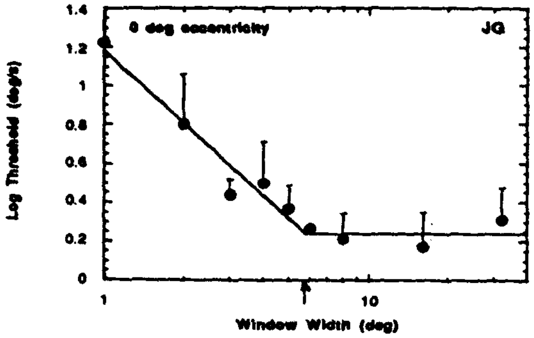

Figure 3

Observers required more of an angular change at small window sizes than large for correct judgments (Fig. 3). Above a critical size, increasing the size of the window had no effect on the thresholds. Piecewise linear regression was used to find the critical window size required to achieve the lowest threshold at each eccentricity. The function relating critical size to eccentricity has a slope close to unity, indicating that a larger window size is needed as the window moves further into the periphery. If optimal performance were not dependent upon the size of the window per se but rather by the nearest edge of the window to the fixation point then the functions relating window size to eccentricity should have a slope of 2.0. The function relating lowest angular-speed thresholds to eccentricity is flat, indicating that the central and peripheral retinal locations are equally sensitive for mediating visual self-motion information with optimally-scaled stimuli.

B3: Discrimination of a curved from straight path of self motion: Effects of eye movements. [Turano, K. (1992) Perception, 21, 49.]

This study explored the hypothesis that information generated from eye movements is a critical variable in the discrimination of a curved from straight path of self motion. We measured eye movements as subjects discriminated between a curved and straight motion path, and we measured thresholds for the discrimination of a curved and a straight motion path under conditions in which the image was stabilized on the retina to minimize the effects of eye movements. Stimuli were computer-generated images simulating an observer moving forward along a straight or circular path relative to a volume of randomly-positioned dots. The subjects' task was to judge whether the simulated motion was along a straight path or a curved path. The angular speed of the deviation from a straight path served as the independent variable, and angular-speed thresholds were measured across a range of forward speeds.

As a first step, we measured eye movements in the free-viewing condition and found no significant difference in the magnitude or direction for the straight vs. curved motion conditions (at any angular and forward speeds). We then measured discrimination thresholds in two conditions: In one condition, the retinal image was stabilized against the effects of eye movements by means of an SRI Dual Purkinje Image eyetracker with a stimulus deflector. In the other condition, eye movements were unrestricted.The results show that with stabilized viewing observers can discriminate a curved from straight path only when the angular-speed deviation between the two reaches approximately 45 arcmin/s, regardless of forward speed (Fig. 4). When eye movements are unrestricted thresholds are significantly lower for the slow forward speeds.

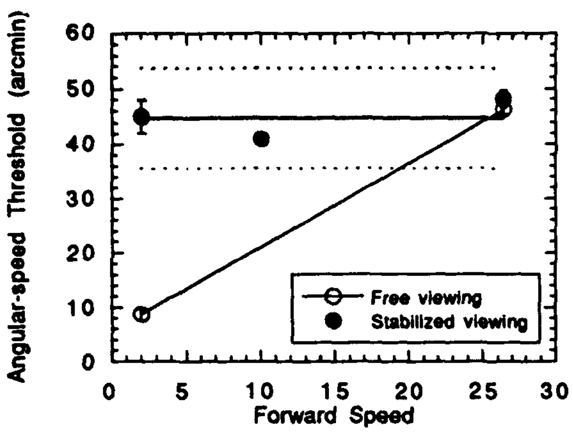

Figure 4

Why would stabilizing the retinal image against the effects of eye movements decrease performance? One possible explanation is that there is a mismatch between the expected and observed image motion in the stabilized-viewing condition. In the free-viewing condition, when the observer makes eye movements there is a corresponding change in the retinal-image motion, along with information about the eye movement from extra-retinal sources, such as proprioceptive feedback from the extraocular muscles or efference information. Thus there is a match between the expected retinal-image motion and the observed retinal-image motion. In the stabilized-viewing condition, the expected and observed retinal-image motion do not match. The observer may make eye movements, thus triggering extra-retinal information but there is no corresponding change in the retinal-image motion. According to this explanation, the mismatch between the two sources of information result in elevated thresholds.

B4: Speed discrimination in stabilized viewing. [**Turano, K.** and Heidenreich, S.M. (1993) Investigative Ophthalmology & Visual Science (Suppl.), 34, 1348.]

In a previously-described study, we showed that stabilizing the retinal image against the effects of eye movements degraded observers' ability to detect changes in the direction of self motion. In order to better understand the role of eye movements in motion perception, in this study we investigated the retinal-image stabilization effects on observers' ability to discriminate speed differences. For 3 observers, minimum detectable speed differences were measured for drifting sine-wave gratings (speeds from 0.5 to 8.0 deg/s; spatial frequencies of 1.5, 3.0, 6.0, and 9.0 c/deg; mean durations of 0.2 and 0.5 s). A Dual Purkinje Image eyetracker was used to measure eye movements and, with a stimulus deflector, to stabilize the image.

At reference speeds of 1 deg/s and faster the speed-discrimination thresholds measured under stabilized viewing were equivalent to those measured under normal viewing. But at the slowest reference speed, the thresholds measured under stabilized viewing were significantly *higher* than those measured under normal viewing for the 0.5-s duration. In normal viewing, at the

0.5 deg/s reference speed, eye velocities ranged from 1 deg/s in the same direction as the stimulus motion to 1 deg/s in the opposite direction. At the 4-deg/s reference speed, eye velocities were twice as large, ranging from 2 deg/s in the same to opposite direction of stimulus motion. Despite the large difference between retinal and stimulus velocities introduced by eye movements in normal viewing, observers are able to make accurate judgments about stimulus speed. It is also surprising that it is at the slowest reference speed, where eye-movement velocity is slowest, that performance is differentially affected. However, if one considers the eye-to-stimulus velocity ratios in the two conditions, ±0.5 at the 4-deg/s reference speed and ±2.0 at the 0.5-deg/s reference speed, it is apparent that the largest effect is at the slowest speed.The results can be explained by a model (Fig.5) wherein the input to the mechanism underlying image-motion processing is a composite of the stimulus motion and eye movements. The input to the decision maker is the information about eye movements (e.g. efference copy) added to the output of the processor. The contribution of the eye-movement signal to the composite signal feeding into the decision maker is proportional to the eye-to-stimulus velocity ratio.

Modified Afference + Efference Model

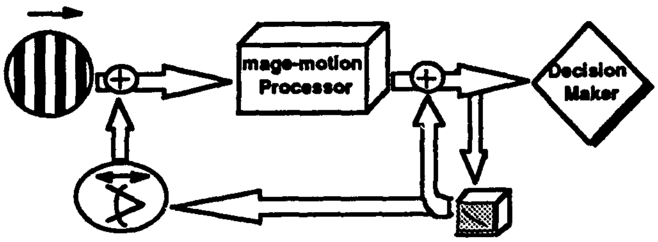

Figure 5

B5: What does the eye see (moving) best? [Watson, A.B. and **Turano, K.** (1992) Perception, 21, 64.]

In this study we determined the optimal stimulus parameters for the detection of motion and thereby defined the three-dimensional shape (x,y,t) of the human motion sensors, which are thought to be involved in the early processing stages of self-motion perception. We searched for that spatiotemporal stimulus whose direction (left vs right) is identified with least contrast energy. The search space consisted of Gabor functions with varied height, width, duration, velocity of the Gaussian aperture, spatial frequency and speed of the sinusoidal modulation. In the frequency domain, these stimuli are translations, scalings and shearings of a pair of three-dimensional Gaussians. For two observers, the best stimulus is at approximately 3 cycles/deg and 1.67 deg/sec (5 Hz). The optimal bandwidths are 7.06 Hz and 1-2 cycles/deg (1-0.5 octaves).

Sensitivity to aperture motion is nearly flat from -5 to 5 deg/s. This flatness may be explained by the minimal effect of aperture speed on the stimulus spectrum, due to the brief duration of the optimal stimulus. These results are consistent with a motion sensor whose spectral receptive field is ellipsoidal and highly elongated parallel the temporal frequency axis.

B6: Neural network model for human visual perception of 3D curvilinear motion.
[Wang, X. and **Turano, K.** (1992) Automatic Object Recognition II, **1700**, 466 - 475.]

We developed a neural network model to emulate the ability of the human visual system to detect a curved path of motion. The fundamental theory of the neural network model is the local difference model, but it uses a different computational approach than used by Rieger and Lawton. The network consists of three layers. The input to the network is a 2D velocity field, and the output is a signal proportional to the magnitude of curved motion. The first layer of the network computes local difference vectors of the velocity field. This minimizes the rotational component of the velocity field introduced by eye movements. The second layer of the network extracts the instantaneous heading direction from the translational component of the velocity field. The last layer of the network computes the acceleration component of the velocity field, i.e. changes in heading direction over time, and outputs a signal proportional to the part of the acceleration component whose direction is perpendicular to the translational component. The magnitude of curved motion is directly proportional to the magnitude of the perpendicular-acceleration component. The model can account qualitatively for human observer's ability to detect changes in heading direction under free- and stabilized-viewing conditions. The fact that the model failed to consider eye movement effects or interactions may account for the lack of a quantitative fit. It is also possible that adding eye movement effects will qualitatively affect the model's outcome.

(2) Current Study:

The proposed research continues along the same vein in the sense that we propose to investigate the role of vision in self-motion perception. We will measure subjects' ability to extract heading direction from visual patterns that simulate self motion as we systematically manipulate stimulus parameters. We will add a new facet to the study. We will also investigate the role of vision in self-motion perception *in the context of sensory-system interaction* by assessing body postural control.

(D) Publications:

Journal Articles

Turano, K. and Heidenreich, S.M. Speed-difference judgments are poorer when the eye moves faster than the stimulus. Submitted to Nature.

Watson, A.B. and **Turano, K.** The optimal motion stimulus. Submitted to Vision Research.

Heidenreich, S.M. and **Turano, K.** Speed discrimination under stabilized and free viewing conditions. Submitted to Vision Research.

Turano, K. and Wang, X. (1994) Visual discrimination between a curved and straight path of self motion: Effects of forward speed. Vision Research, 34, 107-114.

Wang, X. and **Turano, K.** (1992) Neural network model for human visual perception of 3D curvilinear motion. Automatic Object Recognition II, 1700, 466 - 475.

Published Abstracts

Turano, K. and Heidenreich, S.M. (1994) Speed discrimination during pursuit eye movements. Investigative Ophthalmology & Visual Science (Suppl.), 35, 2077.

Turano, K. and Heidenreich, S.M. (1993) Eye movements do not limit speed discrimination. Perception, 22, 88.

Turano, K. and Heidenreich, S.M. (1993) Speed discrimination in stabilized viewing. Investigative Ophthalmology & Visual Science (Suppl.), 34, 1348.

Watson, A.B., **Turano, K.** and Eckert, M.P. (1993) The optimal motion stimulus. Investigative Ophthalmology & Visual Science (Suppl.), 34, 1343.

Turano, K. (1992) Discrimination of a curved from straight path of self motion: Effects of eye movements. Perception, 21, 49.

Watson, A.B. and **Turano, K.** (1992) What does the eye see (moving) best? Perception, 21, 64.

Turano, K. (1991) Field of view required for optimal optic-flow discrimination. Optical Society of America Technical Digest, 17, 217.

Turano, K. and Schuchard, R.A. (1991) Speed discrimination in the fovea and parafovea: Statistical efficiency and internal noise. Investigative Ophthalmology & Visual Science (Suppl.), 32, 828.

Wang, X. and **Turano, K.** (1990) Perception of heading change in nonrigid motion flow. Investigative Ophthalmology & Visual Science (Suppl.), 31, 521.

Turano, K. and Wang, X. (1989) Perception of changes in heading direction from image flow. Optical Society of America Technical Digest 18, MA4.

(D) Professional personnel associated with the research effort:

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