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SENSITIVITY TO EDGE AND FLOW RATE IN THE CONTROL OF SPEED AND ALTITUDE

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A number of studies have examined the potential efficacy of global optical flow rate and edge rate for specifying changes in self-motion. These have ranged from passive judgments of simulated accelerating self-motion to the active control of altitude in the presence of changes in flow and edge rates. This report will summarize a number of these studies and attempt to reconcile their respective findings.

Edge rate, defined as the number of texture edges traversed per unit time, was studied by Denton (cf. 1980), first in a simulator and then on an actual roadway. Using an automobile simulator, he found that he was able to manipulate subjects' control of forward speed by spacing texture edges on the roadway at decreasing intervals. While the task was to maintain a constant forward speed, the resultant increase in edge rate caused the subjects to reduce their speed inappropriately.

In contrast to edge rate, which is dependent on one's forward velocity and the spacing of texture edges on the ground, global optical flow rate depends on one's forward velocity and instantaneous altitude, and is independent of the texture density over which one is travelling. Warren, Owen, and Hettinger (1982) and Owen, Wolpert, and Warren (1983) examined the effects of gains in edge and flow rate by manipulating the spacing of edges and the velocity with which observers traversed those edges during simulated level flight. Subjects were instructed to make judgments of acceleration and were found to be differentially sensitive to these two sources of information. While some observers were sensitive to the increase in edge rate, others were not affected by edge spacing at all, and were almost entirely sensitive to increases in optical flow.

Awe, Johnson and Schmitz (1989) questioned whether people could use flow rate information to control speed in an active control paradigm. Their subjects were instructed to attend to flow rate or edge rate information, or both, and to maintain a constant forward velocity. Even though feedback was provided, subjects continued to use edge rate information as the basis for controlling their forward speed in all conditions, including the flow rate one. This was interpreted as evidence of inflexibility in selectively attending to information for self speed.

In another "active" test of the effect of flow rate and edge rate, Wolpert, Reardon, and Warren (1989) required subjects to maintain a constant altitude in the presence of changing flow and edge rates. Increases and decreases in flow rate were effected by the use of a simulated accelerating tailwind or headwind, respectively, while the corresponding changes in edge rate were obtained by manipulating the spacing of edges over which the trials were flown. It should be noted that had the subjects not touched the control stick during the trial, altitude would have remained perfectly level with the exception of a minor, zero-mean disturbance due to the windgust. It was hypothesized that increasing optical flow during level flight would lead the flow-sensitive individuals to perceive a loss in altitude and would result in a compensatory action, i.e., an attempt to increase altitude. Conversely, on encountering decreasing optical flow, flow-sensitive individuals would reduce their altitude in an attempt to hold optical flow constant. Changes in edge rate should not have had any effect in altitude since edge rate is defined independent of altitude, and, only had subjects confused edge rate with flow rate, would we have expected results similar to those hypothesized for flow rate change.

Twenty naive subjects viewed the simulated scenes representing flight at an initial altitude of 64 feet over flat, rectangular fields. The texture pattern was made up of a black grid laid over a green world and displayed on a 90-deg wide projection screen. A pseudorandom windgust consisting of a sum of five sine waves with a mean rms error of 0 was used as a forcing function in the vertical dimension. The forcing function repeated itself four times over the course of the trial and remained in effect for its 25-s duration. Proportional change in flow rate ($Rx' = 0.95$, 1.00, and 1.05), was partially crossed with three levels of the second factor, proportional change in edge rate ($RE' = 0.95$, 1.00, and 1.05). The cells, $Rx' = 0.95$, $RE' = 1.05$ and $Rx' = 1.05$, $RE' = 0.95$ were omitted to yield seven events.

A number of dependent measures were recorded and analyzed. These included mean altitude, root mean square error in altitude, absolute (unsigned) error, and standard deviation in altitude over the entire trial. In addition, each trial was divided into four equal segments of 256 frames each, and the above measures calculated per bin.

Proportional change in flow rate (Rx') was significant ($p < 0.0005$) and accounted for 3.4% of the variance in altitude. Mean altitude rose from 65.3 ft at the $Rx'=0.95$ level to 74.4 ft at the $Rx'=1.05$ level. Similarly, RMS error, absolute (unsigned) error, and standard deviation in altitude grew significantly with increased proportional changes in flow rate. In contrast, proportional change in edge rate, while significant in terms of mean altitude ($p < 0.001$), accounted for only 0.8% of the variance in that measure. Mean error in altitude increased from 69.0 ft to 70.1 ft for $RE'=0.95$ and $RE'=1.05$, respectively.

When the time histories were divided into four equal temporal quarters, this variable had a significant main effect ($p < 0.0001$, $R2=4.5\%$) as indexed by mean altitude, which increased from 66.0 ft in the first segment to 72.8 ft in the fourth. This variable also interacted with proportional change in flow rate ($p < 0.0001$, $R2=2.3\%$). A proportional gain in flow rate, i.e., $Rx' = 1.05$, led to an increase in altitude from 66.2 ft in the first segment to 83.6 ft by the fourth segment. A proportional loss in flow rate, i.e., $Rx'= 0.95$, resulted in a decrease in altitude from 65.5 ft at the beginning of the trial to 64.4 ft at the end, while a constant flow rate ($Rx' = 0.0$) produced intermediate performance.

It should be reiterated that all the above results are "illusory" in the sense that, had the subject not touched the control stick at all during the event, altitude would have remained perfectly level except for the zero-mean windgust.

The fact that proportional change in optical flow had a much stronger effect than proportional change in edge rate on altitude control, (i.e., more than 4 times as much variance was accounted for), is interesting for a number of reasons. Firstly, while earlier passive studies (e.g., Owen, Wolpert, & Warren, 1983) had shown edge-rate gain to have a much stronger effect than flow- rate gain on "acceleration" reports, the latter was much more effective in "driving" altitude in the current experiment. Subjects were more susceptible to an illusory change in altitude when flow rate was increased or decreased, than when edge rate was proportionally modified. This was more noticeable when flow rate increased rather than decreased; their altitude was perceived as decreasing and the resultant compensatory control action led to an increase in altitude.

Secondly, slightly more observers in the passive "acceleration" study (Owen, et al., 1983) proved to be "edge-rate" sensitive than "flow-rate" sensitive. In the current study, 17 of the 20 subjects showed a heightened sensitivity to gains in flow rate rather than edge rate, and 12 of the 20 to losses in flow versus edge rates. This was probably due to the nature of the task. While the former study simulated level flight and the observer was required to detect "acceleration", the present study required the subject to maintain a constant altitude and no control over forward velocity was enabled. Since edge rate typically covaries with flow rate during level self motion, equal distributions of observer sensitivity are expected when the task demands a forward-velocity-related report or action. During altitude change, however, edge rate over regular texture remains constant while flow rate usually varies, so an increased sensitivity to proportional changes in this optical variable would be anticipated. This effect was obtained in the current study, albeit only for increases in flow rate. In fact, there was a tendency over the entire experiment to gain altitude during the trial, and in only a few trials was altitude "driven" downward. This bias could be considered as an attempt to maintain a "margin of safety" but needs to be further examined, i.e., by beginning the trial at a higher initial altitude.

How can the different sensitivities, i.e., to edge rate in the Awe et al. (1989) study, and to flow rate in the Wolpert et al. (1989) study be reconciled? Why were subjects in the former unable to hold flow rate constant even when instructed to do so, while in the latter study, flow rate had a much greater effect than edge rate in "driving" altitude? A speculative answer, perhaps, lies in the relationship between the independent variables and the dependant variables in the respective experiments. In the Awe et al study, altitude was held constant while subject were asked to control either optical flow (x'/z) or edge rate (x'/xg). Since altitude (z) was fixed and edge spacing (xg) was controlled by the experimenter, any control the subject exercised was necessarily on speed (x'). In the Wolpert et al study, on the other hand, forward velocity was under the experimenter's control, while the only degree of freedom available to the subject was in the altitude dimension. Since the altitude component is present in the optical flow notation but not in the edge rate notation, it is plausible that optical flow would be the dominant variable in this form of self-motion study. During level self-motion, both flow rate and edge rate covary, differing by a scale factor. In the absence of the altitude component, edge rate, comprised of edge spacing and the change of edge spacing, would dominate.

While the above explanation is admittedly speculative, a more rigorous test of this hypothesis would allow the subject control over both altitude and forward velocity and require the maintenance of a constant altitude and/or a constant flow or edge rate. By recording performance in both the altitude and the forward velocity domains, a better understanding of the individuals' sensitivities would be obtained.

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