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SUMMARY

Previous work on the perception and control of simulated vehicle speed has examined the contributions of optical flow rate (angular visual speed) and texture, or edge rate (frequency of passing terrain objects or markings) on the perception and control of forward speed. However, these studies have not examined the ability to selectively use edge rate or flow rate. The two studies presented here show that this ability is greater for pilots than non-pilots, as would be expected since pilots must control vehicular speed over a variety of altitudes where flow rates change independently of forward speed. These studies also show that this ability to selectively use these variables is linked to the availability of visual contextual information about the relative validity (linkage with speed) of the two variables. Subjective judgment data also showed that awareness of changes in ground texture density was accompanied by awareness of changes in ground speed.

INTRODUCTION

Researchers studying the visual perception of self-motion, or egomotion, have long assumed that specific optical patterns or variables (e.g., centers of optical expansion, optical density, optical flow, and edge rates) directly determine specific perceived attributes of egomotion (e.g., heading, height, ground speed) (refs. 1-3). More recently there has been interest in how people learn to actively regulate these optical variables in order to control egomotion (refs. 4-6).

The utility of such optical variables for the perception and regulation of egomotion attributes depends on the extent to which the behavior of these variables: (1) consistently varies with changes in the relevant egomotion attributes, while (2) consistently remaining invariant over changes in other egomotion attributes. Although Gibson (ref. 7) proposed that such perfectly specific (i.e., one-to-one) mappings between optical variables and egomotion attributes exist, most investigators have examined optical variables that meet only criterion (1) (refs. 3, 4, 8-10). That is, they examined situations that reflect a many-to-one mapping between environmental variables and a single optical variable. This failure to meet criterion (2) could pose a problem, particularly for theories that assume relatively direct perception of the egomotion attributes being investigated: If a perceiver cannot reliably associate a change in some particular optical variable with a change in a particular egomotion attribute, then uncertainty exists when attempting to perceive or control that attribute.

In addition, Cutting pointed out that several optical variables may be correlated with a single environmental (e.g., egomotion) attribute, yielding a one-to-many mapping between one environmental variable and several optical variables (ref. 11). Under certain circumstances this could provide a solution to the problem of a many-to-one mapping between environmental attributes and an optical variable. If contextual information (visual or nonvisual) can guide people to selectively use optical variables that are locally (presently) specific to some environmental property, then a perceptual theory based on direct registration and regulation of information can work in a much wider context. If context cannot lead to such selection, then the utility of a theory based on direct perception will be much more limited. Therefore, it is important to examine people's ability to selectively use optical variables as a function of their specificity.

This report presents two experiments designed to further explore how people control egospeed. In particular, the objective was to determine if people use contextual information to help them select between optical flow rate and edge rate to guide this control and, if they do so, how they use it. In the first experiment, the ability to intentionally use flow rate or edge rate as a function of instructions and feedback was examined. In the second experiment, ways in which the visual context may help determine which optical variable guides responding were studied. However, before turning to these experiments, the next section will present a brief review of previous work on the perception of egospeed.

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THE PERCEPTION AND CONTROL OF EGOSPEED

The visual perception or control of one's own speed (egospeed) has been studied by both applied and basic researchers. For those concerned with vehicular control applications, the operator's ability to detect and control accelerations and decelerations critical to maintaining safety on the highway and during aircraft landings is the primary focus. For more basic research, ability of people to perceive and control the velocity of movement over the ground (ground speed), as contrasted with the velocity or approach toward some object (approach velocity), is of interest because it reveals the abilities of people to extract a fundamental attribute of their motion from the three-dimensional world. This contrasts with the more numerous studies of visual speed that examine either motion in a two-dimensional plane—for example, J.F. Brown's work on motion across a real-world fronto-parallel plane (ref. 12) or R.H. Brown's work on the effects of motion on the retina (ref. 13)—or time-to-contact studies, such as those initiated by Lee (ref. 14).

For the case of approximately level movement over a textured, but otherwise flat ground plane, previous research suggests that people will use one or both of two optical variables as information for the perception or regulation of ground egospeed (refs. 4, 8, 15). The first of these variables is global optical flow rate *(FR)*. For approximately level flight, this variable is specific to the observer's ground speed in eye-heights/sec (ref. 15), or

$$FR = V_g / h \qquad (1)$$

where V_g is the observer's ground speed and h is the observer's altitude (eye-height). When FR is constant, the optical (angular) velocity at any locus within the optical array is constant. Changes in altitude disrupt the orderly relationship between ground speed and flow rate; for a constant ground speed, descent to a lower altitude creates a higher flow rate, and ascent to a higher altitude creates a lower flow rate. Therefore, flow rate is reliably and uniquely linked to ground speed only under the condition of constant altitude.

The second variable, optical edge-rate *(ER)*, is also proportional to the observer's ground speed, but is the frequency at which the optically specified edges of ground-texture elements or objects pass across some optical region, or

$$ER = V_g / T_x \qquad (2)$$

where T_x is the distance, on the ground, between the edges of texture elements or objects. When *ER* is constant, the frequency per unit time of optical elements passing across a region within the optical array is constant. However, changes in ground-texture spacing disrupt the orderly relationship between ground speed and edge rate; when ground speed is constant, edge rate increases as ground texture becomes more dense and decreases as it becomes more sparse. Therefore, edge rate is reliably and uniquely linked to ground speed when altitude varies, but not when texture density varies.

Since both flow rate and edge rate can vary independently of forward ground speed, accurate ground-speed perception may depend on using the optical variable that is most highly correlated, or best-linked, with ground speed, given the particular conditions at that time (e.g., changing altitude or changing ground-texture density). Several studies relevant to this issue have been conducted. For example, Denton found that subjects reduced ground speed when the spacing between stripes upon a simulated roadway surface was reduced (i.e., edge rate was increased) (ref. 4). And in a related study, Shinar et al. found that the accident rate dropped when they applied this manipulation on a roundabout where cars exited from a highway to secondary roads that required a lower speed (ref. 16). They also found that the effect of manipulating edge rate decreased over time as people had more practice at the highway roundabout. These studies suggest that people use edge rate to control automobile speed, even though flow rate is more strongly linked to automobile speed since eye-height remains constant. However, given sufficient experience, automobile drivers may turn to the better information for ground speed (i.e., flow rate), as suggested by Shinar et al.

Owen et al. undertook a more parametric examination of the influence of flow rate and edge rate on the detection of changing ground speed (ref. 15). They coupled simulated vehicle accelerations with systematic changes in ground-texture size (rectangular "fields" on a flat terrain) to produce events in which flow rate, edge rate, both, or neither, increased during simulated straight and level flights over flat terrain. When they asked subjects to indicate whether ground speed was changing or constant, they found that both flow and edge accelerations contributed faster and more frequent "acceleration-present" judgments, although edge accelerations tended to be more effective. Larish and Flach extended these findings to speed estimation in a task in which people judged simulated ground-speed magnitudes for level flights at different speeds and altitudes (ref. 8). They also found that both edge rate and flow rate affected the ground-speed judgments, with edge rate tending to have the greatest effect.

These studies demonstrated that perceptions of speed and acceleration are affected by both edge rate and flow rate, with edge rate producing the more pronounced effects. However, they did not tell us whether people can voluntarily select between flow rate and edge rate as the basis for the perception and control of ground speed, given that there is sufficient information available to permit a determination about which provides the most valid cue. Does the information present in the natural environment, or information derived from experience (e.g., cognitively based assumptions), somehow direct our attention to the most valid information? None of the above studies reported that subjects were informed about the manipulations. Furthermore, contextual visual information relating to variations in the important physical (non-optical) variables being simulated (e.g., texture size and altitude) was limited or absent.

This leads to three possibilities: (1) subjects failed to notice any change in optical density when it was manipulated within a trial, perhaps owing to the gradual nature of the change; (2) subjects thought that any change in optical density was due to a change in altitude (optical density increases with altitude) rather than to a change in texture density (the distance between edges of texture elements on the ground), thus leaving edge rate still fully linked to ground speed; or (3) subjects understood the nature of the manipulations but responded to edge rate and flow rate without regard for their relationship to ground speed. The first two possibilities assume that context (information other than that directly linked to ground speed) would drive the use of optical information for ground-speed control, and that poor performance is the result of poor contextual information about the cause of the changes in flow rate or edge rate or both.

The third possibility assumes a more direct perceptual response in which context is less important. That is, it is possible that people are strongly locked into edge rate as the primary source of information for self-speed, or egospeed, and cannot easily shift their attention to a different visual variable to maintain control. People's continued and inappropriate use of edge rate may be a result of their assumption that texture density is unchanging, or it may correspond to a less flexible perceptual concept of egospeed in terms of edge rate (see ref. 17 for a discussion of perceptual concepts in the area of object motion).

However, these studies did not examine how well people can use the less preferred, although, perhaps, more informative variable if instructed to do so. For example, can people use flow rate rather than edge rate to control ground speed if they know they should do so? Two experiments, undertaken to learn more about how we control egospeed, are described in the following sections.

Within both experiments the effects of various factors on the selection of flow rate and edge rate were examined in two ways: (1) the subjects' total responses to optical changes were directly measured by determining how much of imposed optical disturbances they offset; and (2) the motion adaptation of the subjects was measured by averaging responses across decelerations and accelerations. Motion adaptation, which is the tendency to perceive a constant visual speed as decreasing over time, was shown by Denton to be a significant factor in vehicular ground-speed control (ref. 18). This effect is usually thought to reflect the progressive decrement in sensory response to a continuous motion input, and may be valuable for differentiating functionally different sensory responses. If edge rate and flow rate form the basis for fundamentally different modes of sensing speed and acceleration, then they might lead to different motion-adaptation levels.

EXPERIMENT 1

Experiment 1 was designed to measure how people control ground speed when they are instructed to use flow- or edge-rate variables, and when they are told how flow rate and edge rate are related to experimental manipulations of ground speed and texture density. It was designed to parallel the designs used by Owen et al. who examined unconditional responses to changing edge rate and flow rate (ref. 15). That is, they examined responsiveness as a function of changes in optical variables rather than as a function of the ground-speed information provided by the optical variables. In particular, Owen et al. examined how quickly people responded to edge- and flow-rate changes when ground speed was systematically linked and unlinked to edge rate (by varying texture spacing), but when ground speed was always linked to flow rate (by holding altitude constant). In this manner they presented trials in which edge rate alone, flow rate alone, or both, changed.

Using a similar approach, the present experiment accomplished these manipulations by using a simulated tailwind that could be varied to push a vehicle forward at a constant rate, an increasing rate, or a decreasing rate, in constant-altitude flight. Tailwind and texture-size manipulations yielded trials in which the prevailing uncontrolled ground speed either changed or remained constant, and in which prevailing ground-texture size was sometimes proportional to uncontrolled ground speed.

The term "prevailing" is used for the uncontrolled ground speed and texture size because a zero mean sum-of-sines function was used to implement a wind buffet that was added to the tailwind and because expected texture size was perturbed about its expected value. The tailwind was perturbed in order to draw the subject into the control task and to cause vehicle ground speed to always be the result of active regulation. The texture size was perturbed in order to prevent subjects from using a simple counting strategy.

Changes in tailwind velocity and ground texture were quite gradual: ground speed changed at -0.5%/sec, 0%/sec, or 0.67%/sec; ground-texture size similarly changed at rates of -0.5%/m, 0%/m, or 0.67%/m (per meter traveled). (We intended to use equivalent positive and negative rates—±0.5%/m —but owing to a programming error the rate of increase was 0.67% for both ground speed and ground-texture size changes.) These manipulations were combined to yield trials in which uncontrolled edge rate, flow rate, or both, changed at -0.5%/sec or +0.67%/sec, and in which subjects were asked to maintain the initial speed, flow rate, or edge rate. These manipulations yielded scenes in which forward ground speed was reliably coupled with flow rate alone, or with both flow rate and edge rate; no scenes reliably linked ground speed with edge rate alone. Momentary rates of change in the optical variables (flow rate and edge rate) and physical variables (ground speed and texture size) were subthreshold but could be detected over time. Finally, a constant-ground-speed/constant-ground-texture baseline (i.e., constant flow rate and edge rate) was used to determine if the effects of the imposed accelerations and decelerations were approximately equal and opposite.

The questions examined were (1) What optical variables do people use spontaneously to control forward ground speed? (2) Can people selectively use flow rate or edge rate to control forward ground speed when instructed to do so? (3) Are people consciously aware of changes in forward ground speed and texture density? (4) How is awareness related to their control of ground speed? and (5) Will feedback enhance people's ability to use flow and edge rate for control of forward ground speed?

Subjects

Five right-handed subjects, four male and one female, served as paid participants. Subjects ranged in age from 18 to 55 years and had normal vision or corrected-to-normal vision.

Apparatus

The flight simulation was generated by a DEC PDP-11 computer, which controlled system dynamics, data collection, and an Evans and Sutherland Picture System 2 vector graphics scene generator. Scene update rates and data collection rates were both 10 frames/sec. The visual display was 31.75 cm^2 and was viewed from a distance of 63.5 cm. This resulted in a display subtending 28.0 visual degree in both the horizontal and vertical dimensions, but, because of equipment constraints, the depicted optical horizon bisected the display approximately 5 cm (4.41 visual degree) below the subjects' eye positions.

The study subjects used a right-hand, spring-centered MSI model 542 joystick to control forward ground speed. The control stick was configured as a first-order rate controller in which forward stick deflections caused the vehicle to accelerate, and backward stick deflections caused the vehicle to decelerate. The control gain yielded a change in the simulated ground speed of 1 m/sec for each degree of stick deflection.

Design

Figure 1 depicts the design of the 3-day experiment. The main design was a partially crossed, fully within-subjects five factor (3 x 2 x 3 x 2 x 6) study. In addition a (3 x 2 x 6) fully within-subject and fully crossed study of baseline conditions was also conducted. The factors in the main design were as follows:

1. *Optical Variables:* Either flow rate, edge rate, or both, changed when not controlled.

2. *Optical Change:* The selected optical variables accelerated or decelerated.

3. *Instructions:* Day 1, no description of experimental manipulations; Days 2-3, experimental manipulations were described and subjects were instructed to control edge rate or flow rate. Subjects were initially uninformed about experimental manipulations on the first day of the experiment, but then informed about the manipulations and instructed to control flow rate or edge rate on the final two days. For each subject this resulted in one third of the trials being flown in an uninstructed mode, one third with instructions to control flow rate, and one third with instructions to control edge rate.

4. *Feedback:* Days 1-2, no feedback; Day 3, feedback. Subjects were given feedback during half of the trials within the instructed conditions. During the uninstructed part of the experiment subjects were never given performance feedback in order to let them freely select the most preferred optical variable (this resulted in a partially crossed design).

5. *Replication:* Day 1, six replications per condition; Days 2-3, three replications per condition. There were six replications for all conditions within the uninstructed level of the Instruction factor. When collapsed across the Feedback factor within the instructed part of the study, there were still six replications, although this could be further broken down into three replications for conditions with no feedback and three replications for conditions with feedback. Since this factor was not analyzed, all tests collapsed across replications.

The baseline design, in which both flow and edge rates remained constant, was presented for all combinations of Instructions, Feedback, and Replication. This design was used to verify that the mean inputs averaged across the Optical Change factor (decelerating and accelerating) yielded the same value as the response to a constant ground speed.

Simulated Scenarios and Dynamics

Each trial displayed a forward-looking view from a simulated vehicle in level forward flight over a level terrain (fig. 2). The black terrain surface was demarcated by white texture lines oriented orthogonally to the direction of flight. During the first day of the experiment, the subjects' task was to control airspeed (V_a) so as to maintain a constant forward ground speed (V_g) despite a changing tailwind velocity, (V_w). Thus ground speed was

$$V_g = V_a + V_w \tag{3}$$

Airspeed, in turn, was solely determined by the control output from a simple first-order control plant with a stick gain of 1 m/sec per degree of control-stick deviation.

At the start of each trial, initial ground-texture size (T_x, the distance between successive lateral texture lines) was 25 m. The initial altitude was 6.25 m, the initial V_w and V_g were both 25 m/sec, and initial V_a was 0. These conditions simulated unpowered flight with a constant tailwind over a regular terrain and were held constant for the first 20 sec. During this automated flight phase, the subject could not control airspeed, V_a. The remainder of the trial, the manual flight phase, lasted 102.4 sec. During this period uncontrolled edge and flow rates were manipulated by making the spacing of the lateral texture lines T_x and tailwind velocity V_w linear functions of position x (see table 1).

Table 1. Effects of Texture-Size and Tailwind-Velocity Manipulations

Condition	Texture $T_x = 25\pm$	Tailwind velocity $V_w = 25+$	Uncontrolled edge rate	Uncontrolled flow rate/ground speed
Control			Constant	Constant
A	$-0.0050x$		Decreasing	Constant
B	$+0.0067x$	$+0.0067x$	Constant	Increasing
C		$+0.0067x$	Increasing	Increasing
D	$+0.0067x$		Increasing	Constant
E	$-0.0050x$	$-0.0050x$	Constant	Decreasing
F		$-0.0050x$	Decreasing	Decreasing

In addition to systematic linear changes, random local perturbations were also introduced into the tailwind velocity and into the lateral texture spacing. This was accomplished by adding a 0 mean, 7.82 SD, temporal sum-of-sines function, $V_B(t)$, to the tailwind (table 2); and by perturbing the texture size T_x by ±30% of the expected size determined by the linear function for T_x shown in table 1. The texture spacing variation was introduced in order to prevent subjects from using a simple counting strategy to maintain edge rate. The forward wind-speed variation was introduced in order to make it important for subjects to regulate ground speed in all tasks, even those in which a systematic tailwind change was absent. It also prevented subjects from learning a stereotyped response pattern.

Table 2. Sum of Sinusoids Pseudorandom Disturbance Function

$$V_B(t) = \sum_{i=1}^{6} \alpha_i(\omega_i t + \theta_i)$$

i	α_i	ω_i
1	5.043	0.0195
2	5.043	0.0293
3	4.883	0.0488
4	4.366	0.0684
5	3.778	0.1074
6	3.778	0.1270

Notes: α_i = amplitude (m/sec) of ith component
ω_i = frequency (Hz) of ith component
θ_i = randomly sampled phase angle of ith component

Procedure

The experiment was conducted over three consecutive days. At the start of the first day, subjects were seated in the simulator and shown how to use the joystick to control simulated forward ground speed. They were told that the first 20 sec of flight was an automated period during which their craft would fly at a constant altitude and at an "ideal" speed, after which winds would occur that would disturb this ideal speed. The buffeting was severe enough to make it clear when the automated period ended. Subjects were instructed to try to maintain this initial ideal speed during the final 102.4 sec of each trial. They were given a practice trial (using the baseline condition with no control instructions or feedback) to familiarize them with the task and then proceeded to the experimental trials. The experimental trials were arranged into six blocks of seven trials each (42 total trials), with each block being a random ordering of the six combinations of Optical Variables and Optical Change, plus the baseline condition.

During the final two days of the experiment, the subjects' task was to control either flow rate, which was functionally the same task as controlling ground speed, or to control edge rate, that is, ground speed scaled in texture unit size. Specifically, day 2 differed from day 1 in three ways. First, the subjects were told how wind speed and texture spacing were being manipulated and how this affected ground appearance, uncontrolled vehicle speed, flow rate (described as the speed of movement of the individual texture lines down the display screen), and edge rate (described as the number of texture lines per unit time passing any point on the screen, specifically the bottom of the screen). Second, at the start of each trial, the subjects were instructed to control either flow rate or edge rate. However, they were not told which condition they were about to receive on particular trials. Third, following each trial, the subjects were asked whether wind speed and texture size had tended to increase, decrease, or not change over the course of the trial.

Finally, on day 3, feedback was provided to the subjects at the end of each trial. The feedback came in two parts. First, mean flow rates or edge rates (depending on instruction type) for the first and last half of each trial were provided. Subjects were told to use these two values to determine if the relevant rates had increased or decreased during the trial. Second, the subjects were given the standard deviation of the flow rate or edge rate for the entire trial. They were told that this was also a measure of how well they maintained the assigned variable.

Performance Analyses

The dependent measure was the subjects' contribution to the overall acceleration/ deceleration expressed as an average percent per second change in ground speed (i.e., exponential rate of change in the vehicle ground speed owing to the subjects' input). This measure reflects how strongly the subject responded to the optical change. For example, a subject would have to generate 0.5%/sec to fully null an initial optical deceleration, and -0.67%/sec to fully null an initial optical acceleration.

$$x = (25/b)[\exp(102.4b) - 1] \qquad (4)$$

Equation (4) expresses the distance x traveled during the 102.4 sec of manual flight as a function of an exponential rate of increase or decrease in ground speed b, and given an initial ground speed of 25 m/sec. After determining the percent-per-second change in ground speed, b, that predicted x, any influence due to a changing tailwind velocity was removed (i.e., 0.5%/sec and 0.67%/sec were added or subtracted when the tailwind decreased or increased, respectively). The resulting value, the subjects' contribution to the overall acceleration/deceleration, was then analyzed.

Before proceeding, it should be noted that vehicle velocity can be expressed as the sum of an initial velocity and any additional imposed exponential influence on vehicle velocity. In the present case, this influence can be expressed as the sum of three exponential components—the imposed disturbance, the subjects' response to the imposed disturbance, and a motion-adaptation response (although motion adaptation is not necessarily exponential in form, an exponential function can be used to approximately describe its presumed negatively accelerated form). When the imposed exponential is removed, we are left with a reasonable measure of the subjects' combined response owing to motion adaptation and the control of the imposed disturbance.

For trials in which both flow rate and edge rate are linked to ground speed, subjects could eliminate the change in both by maintaining a constant ground speed. However, for trials in which only flow rate or edge rate changed, they could not accomplish this. For example, in trials with an initially changing edge rate and an initially constant flow rate, fully nulling the edge rate would cause ground speed to change and thus generate an equal and opposing flow-rate change. The reverse would happen with an initially changing flow rate and an initially constant edge rate. Thus, if subjects responded to both flow- and edge-rate change, they should have attempted to balance the opposing flow- and edge-rate changes at some intermediate value.

Since an incomplete factorial design was used, two ANOVAs were conducted on each of the two designs. The analyses of both the main design and the baseline design proceeded by first analyzing the data from days 2 and 3 when subjects were instructed about the type of optical change they should control. This allowed an evaluation of the Feedback factor. The second ANOVA collapsed over the Feedback factor and analyzed the remaining factors using data from all 3 days. Only the latter

ANOVAs, which covered all three days, will be reported here, since the first ANOVA showed neither significant, nor marginally significant, effects involving Feedback ($p > .10$) in either the main or baseline designs and the same significant effects were found in both ANOVAs.

For the main design, two types of effects were examined: response to the imposed change in optical rates (acceleration control response) and motion adaptation (motion-adaptation response). Only motion adaptation was examined for the baseline conditions.

Motion-adaptation response– Motion adaptation is the overall tendency to see a constant optical motion as decelerating, thus making acceleration less prominent and deceleration more prominent (ref. 18). This, in turn, should lead to less control of imposed accelerations (allowing more acceleration) and more control of imposed decelerations (adding more acceleration). Thus, this adaptation effect is independent of imposed accelerations/decelerations. Examining the adaptation effects collapsed over the Optical Change (acceleration/deceleration) factor should reflect how the remaining manipulations affect motion adaptation in the main design. On the other hand, all effects in the baseline design should reflect the influence of manipulations on adaptation. In the present design, we inadvertently imposed a greater acceleration than deceleration (0.67%/sec vs. -0.5%/sec); as a result, the estimate of the adaptation effect for the experimental design must be adjusted since the mean response is now a biased estimate of adaptation response. The bias can be removed by estimating the expected mean if no adaptation was present, and then removing this from the observed mean response. In the present case, this value will be 7.26% of the difference between the response to the acceleration and deceleration.

Note that for pairings of imposed acceleration and deceleration, a lack of adaptation yields, by definition, a proportionally equal response to both. For the present case, an absence of adaptation effects would yield an expected response to acceleration (R_p') that is (0.67/-0.5) times the response to the deceleration (R_n').

$$R_p' = (0.67/-0.5)R_n' = -1.34R_n' \qquad (5)$$

yielding a non-zero expected mean response (M') bias not due to adaptation of

$$M' = (-1.34R_n' + R_n')/2 = -.17R_n' \qquad (6)$$

We cannot calculate M' using the observed value, R_n, since an adaptation effect may exist in the study. However, the difference between R_p and R_n, (D) is unaffected by adaptation and we can substitute as follows:

$$D = R_p - R_n = R_p' - R_n' = -2.34R_n' \qquad (7)$$

$$R_n' = D/-2.34 = (R_p - R_n)/-2.34 \qquad (8)$$

$$M' = -0.17(D/-2.34) = 0.072D \qquad (9)$$

To continue, if subjects responded proportionally to decelerations and accelerations, then their acceleration control inputs should be 134% (0.67/0.5) of their deceleration control inputs, yielding a corresponding net deceleration input. Thus, the mean response, which is the estimate of adaptation, must be corrected by this factor.

No statistically significant motion-adaptation effects were found for the mean performances in either the baseline or main designs. For the main design, figure 3 shows the mean input during manual flight collapsed across the Feedback factor (Feedback produced no significant main effect or interactions). The overall mean inputs were of similar magnitudes in the experimental and baseline designs, 0.148%/sec and 0.135%/sec respectively. Even when the mean input in the experimental design was adjusted upward from 0.148 to 0.169 to account for the asymmetry in the imposed accelerations and decelerations, neither was significantly greater than 0 ($p > .10$). However, within the experimental design there was a marginally significant main effect of Optical Variable ($F(2,8) = 3.49$, $p = .082$), with a mean input for initially changing flow rate (0.121%/sec) that was less than the mean input for changing flow rate plus edge rate (0.141%/sec) or for changing edge rate (0.183%/sec).

Because of the small number of subjects used in this experiment, ANOVAs on the individual data were conducted using replications as the random variable. Figure 4 shows the mean individual adaptation for the baseline and main designs, with an accounting of which values are significantly different from zero ($p < .01$). The similarity in individual magnitudes across the two designs further validates the assumption that the responses in the main design reflect a combination of response to the optical changes (accelerations and decelerations) and a general adaptation effect. Also note that three subjects had strong and significant positive adaptation effects, and two subjects had virtually no adaptation.

No statistically significant individual adaptation effects associated with the Optical Variable factor were found, although four of the five subjects generated the most motion adaptation for the initially changing edge rate. There was also a statistically significant main effect of Instructions ($p < .05$) for one subject in the baseline design and for four subjects in the main design. However, these appeared to be highly idiosyncratic. For the baseline design, the one subject generated a significantly higher motion-adaptation response when asked to control edge rate; for the main design, two subjects generated higher motion-adaptation responses when asked to control flow rate, one subject generated a higher response when asked to control edge rate, and one subject generated a higher response when given no instructions.

Acceleration control response– The direction and magnitude of the response to an imposed change in optical rate reflects how strongly the subject perceives this optical change as indexing a true change in ground speed. This magnitude, the acceleration control response, is obtained by subtracting the response to an optical acceleration from the response to a corresponding optical deceleration. This shows how much more acceleration people generate to offset imposed optical decelerations than to offset optical accelerations. Therefore, since difference scores (i.e., response to deceleration minus response to acceleration) are the proper indicators of overall response magnitude, the relevant statistical tests for the acceleration control response are tests of the interactions involving the Optical Change factor in the main design. No examination of the acceleration control response is possible in the baseline design since no imposed optical change was present.

No significant effects involving Instruction were found. However, clear and statistically significant effects of Optical Change ($F(1,4) = 60.79$, $p < 0.01$) and of the Optical Variable x Optical Change interaction ($F(2,8) = 48.62$, $p < .001$) can be seen in figure 3. Relative to mean inputs, which estimate mean adaptation levels, decelerating optical changes generated positive inputs whereas accelerating optical changes generated negative inputs. Figure 3 also clearly shows that the inputs were strongest when edge rate changed. This interaction effect, the acceleration control response, is plotted in figure 5 as the difference between the deceleration and acceleration inputs.

Fully nulling initial accelerations and decelerations would require inputs of -0.67%/sec and 0.5%/sec, respectively, for a difference of 1.17%/sec. However, as already noted, when flow or edge rate changed alone, a full nulling of an initial optical acceleration or deceleration would not be expected if the subjects were responsive to both flow- and edge-rate change. Instead, a balancing of opposing flow- and edge-rate changes would result in some intermediate value (given the lack of an Instruction effect). This was found. The acceleration control response for the initially changing flow rate was 0.179%/sec and 0.623%/sec for the initially changing edge rate. However, the difference between these values shows that an initial edge-rate change was clearly more effective in generating a control response. For the case of the simultaneously changing flow rates and edge rates, fully nulling one optical variable would also fully null the other, so it would be reasonable to expect an acceleration control response of 1.17%/sec. However, the acceleration control response was only 0.831%/sec.

Planned follow-up comparisons showed that, collapsed across Instructions, the acceleration control responses at all three levels of Optical Variable were significantly less than the 1.17% which would signify a full nulling ($p > .05$). This was true even when flow-rate and edge-rate variables were changing together.

Within each level of the Optical Variable factor, the pattern of means in figure 5 is consistent with the expected influence of the instructions. However, this statistically nonsignificant effect is clearly small when compared with the significant Optical Variable effect, that is, the bias to control edge rate. Overall, instructions to control flow rate neither strongly facilitated the control of flow rate, nor strongly inhibited the tendency to control edge rate. When the individual data was examined, two subjects showed significant effects of the instructions in the expected direction ($p < .05$), but in none of the five cases did the "control flow rate" instruction lead subjects to respond as strongly to an initial flow-rate change as they did to an initial edge-rate change.

Subjective Ratings Analyses

The purpose of the subjective judgment analyses was to determine if the subjects' conscious (verbal) sensitivity to systematic changes in texture size influenced their conscious judgments of systematic changes in wind speed.

A 3 x 3 fully within-subjects analysis of variance was performed for judged wind speed change and judged texture-size change. The factors were Instructions, "none," "control flow rate," "control edge rate," and True Change, "shrinking/decelerating," "no change," and "expanding/accelerating." Judged changes of "shrinking/decelerating," "no change," and "expanding/accelerating" were coded -1, 0, and +1, respectively, for the analysis. Subjects showed moderate, but statistically significant, sensitivity to the changes in both texture size ($F(2,8) = 20.62$, $p < .001$) and wind acceleration ($F(2,8) = 26.79$, $p < .001$) (see fig. 6). No other significant effects were found ($p > .10$).

Although these analyses show that subjects were sensitive to both manipulations, they do not show if the ratings of wind-speed change depended on the ratings of texture change. That is, they do not show if a changing edge rate led subjects to infer a changing wind speed simply because they failed to note that edge spacing changed. In order to test this possibility, all trials were coded as correct or incorrect upon the two manipulated physical variables and a 2 x 2 analysis of variance (Texture Judgment—correct or incorrect; Wind-speed Judgment—correct or incorrect) was conducted. The dependent variable in this analysis was the number of the various judgment patterns (e.g., "correct Wind-speed Judgment and incorrect Texture Judgment") generated by each subject. If such a dependency between these judgments existed, it would show up as an interaction, where the number of incorrect Wind-speed Judgments would depend on whether the Texture Judgment was correct or incorrect. No significant effects were found in this analysis. Thus, there is no evidence that the probability of making a correct judgment of wind-speed change was enhanced by making a correct determination of texture-size change.

Results Summary

This experiment showed, as did previous studies, that both edge rate and flow rate affect the perception and control of one's own ground speed and acceleration, but that edge rate exerts a greater effect than flow rate. In addition, this experiment disclosed very little evidence that people can consciously select which of these two optical variables to use in the control of forward ground speed, at least not with the amount of training and instructions given here. This study made a clearly reasonable attempt to convey the instructions and the lack of any significant effect of Instructions indicated a strong predisposition to use edge rate.

Consistent with the results of Owen et al. (ref. 15) and Denton (ref. 4), Experiment 1 also showed that people respond to changes or differences in these variables even when these changes do not specify corresponding differences in true ground speed acceleration. Furthermore, there is no evidence from the subjective judgments that the influence of edge rate is due to misperceiving the change in texture spacing. That is, when subjects incorrectly identified a compressing texture as a change in forward ground speed, they did not show a significantly higher probability of classifying the texture as being constant. This indicates that the dominance of edge rate did not result from a failure of the subjects to consciously apprehend the nature of the change in the ground-texture line spacing. Three of the five subjects showed a clear and strong motion-adaptation effect, although the mean effect was not statistically significant. Finally, although only marginally statistically significant, the data suggest that changing edge rates lead to greater motion adaptation than changing flow rates.

EXPERIMENT 2

The results of Experiment 1 strongly indicate that subjects cannot easily and arbitrarily direct their attention to edge rate or flow rate in a ground-speed control task. The subjective reports indicated that the reliance on edge rate was not due to a failure to notice the spacing change in the ground texture, but this result does not preclude an unconscious effect more closely linked to the nature of the visual scene itself. This, in turn, relates to two particular limitations in Experiment 1 and in previous studies of egospeed perception/control. First, in both Experiment 1 and in the corresponding study by Owen et al. (ref. 15), responding was analyzed independently of the manipulation of true ground speed. That is, neither Experiment 1 nor the Owen et al. study attempted to determine if the response to an edge-rate or flow-rate change varied as a function of whether it specified a true change in ground speed.

Second, Experiment 1 may have provided insufficient contextual information to discriminate which of the two optical variables was linked to ground speed. Verbal directions and feedback were provided, but subjects may have needed better contextual visual information about which optical variable was specific (linked) to ground speed. In particular, although the subjects were told that all trials were flown at a constant altitude, they were shown scenes in which a gradual change in the optical spacing of the lateral ground lines was consistent with either a change in ground-texture density or in altitude. Thus, it was visually indeterminate how changing flow and edge rates were linked to altitude and ground-speed changes.

The study by Larish and Flach also contained a similar problem (ref. 8). They held terrain-edge spacing constant while varying simulated altitude in order to affect flow rates and varied simulated ground speed while holding terrain-edge spacing constant in order to affect edge rates. However, there was nothing in the simulated scene that specified altitude; thus, the subjects were free to see the variations in optical density across scenes as changes in either ground-texture density or in altitude (or a combination of the two). To the extent that they took the optical-density variation to be a function of a change in altitude, their speed judgments would rise with edge rate, whereas assuming that optical density changes were due to changing ground-texture density would lead them to link their speed judgments to flow rate.

Experiment 2 was undertaken to untangle some of these issues by presenting trials in which ground speed was uniformly linked to either edge rate or flow rate, but not to both, and by asking subjects to actively maintain ground speed. On trials in which edge rate was linked to ground speed, the size of the ground texture remained approximately constant while altitude was varied in order to introduce the systematic irrelevant flow rate changes. On trials in which flow rate was linked to ground speed, altitude remained constant, while ground texture size was varied in order to introduce systematic, but irrelevant, edge-rate changes.

These manipulations were again accomplished by propelling the vehicle forward by a simulated tailwind the velocity of which increased, decreased, or remained approximately constant. This tailwind manipulation was used within trials in which either altitude or prevailing ground-texture size, but not both, was proportional to uncontrolled ground speed. In all cases, the manipulations were again very gradual: ground speed changed at ±0.5%/sec, altitude changed on a glide slope of $\pm 0.00125^\circ$ (±4.3 arc min), and ground-texture size changed at a rate of ±0.5%/m traveled. These manipulations, in turn, yielded trials in which edge rates or flow rates, but not both, were linked 1:1 with ground speed. The resulting momentary rates of change in altitude, ground speed, and texture size were subthreshold, but could be detected over time.

The linkage of edge and flow rates with ground speed was manipulated by using regularly spaced texture with a varying altitude in some conditions (making edge-rate change a valid cue to ground-speed change, and flow rate an invalid cue to ground-speed change), and by varying ground-edge spacing while holding altitude constant in other conditions (making flow-rate change a valid cue to ground-speed change, and edge-rate change an invalid cue to ground-speed change). This makes it possible to determine if subjects can selectively respond based on true ground-speed changes, and if flow-rate or edge-rate changes have a greater effect on ground-speed control. Note that this differs from Experiment 1, and other previous studies of ground-speed perception and control, not only in the overt manipulation of ground speed, but in defining the linkage of ground speed with the optical variables as a factor in the design. In previous studies, a change in initial optical edge rate or flow rate was used as a factor. However, when the linkage of optical variables with ground speed is manipulated, flow rate (or edge rate) can be linked to ground speed, whether the flow rate (or edge rate) is changing or being held constant.

An additional factor included in this study was flight experience. Shinar et al. found that increased experience with roadway textures that caused edge-rate change to be unlinked from ground-speed change at a roundabout, led to the decreasing effectiveness of edge rates (ref. 16). Therefore, it was hypothesized that pilots might be better able to selectively respond to optical changes that specified a true change in ground speed. On the other hand, since pilots are accustomed to frequently varying their altitudes, flow rate may not be tightly linked with ground speed. Hence, pilots might alternatively exhibit a bias to use edge rate to control ground speed.

Finally, to remove any possible types of indeterminacy, in this study two types of visual information about altitude change were presented and subjects were verbally informed that altitude, texture size, and uncontrolled ground speed were being manipulated. The dependent measures for each trial were the same as those used in Experiment 1, except for the addition of subjective ratings about the nature of altitude change during the trial.

Subjects

Twenty right-handed male subjects served as paid participants. Nine of the subjects held private pilot licenses; 11 were not pilots. Subjects ranged in age from 18 to 55 years and had normal or corrected-to-normal vision.

Apparatus

The visual display system used for the flight simulation in Experiment 2 was of higher fidelity than the one used in Experiment 1. An IBM 80486 25-MHz computer with XTAR Falcon 2000 image-generation boards generated the flight simulation displays and dynamics. A 31.75-cm square, 1024 x 1024 pixel, non-interlaced, non-antialiased scene was displayed on a Hitachi 4119D monitor with a scene update rate of 20 frames/sec. The display was viewed from a distance of 63.5 cm, yielding a visual angle of 28.0° in both dimensions. Unlike the display in Experiment 1, the optical horizon correctly bisected the display at eye level. The joystick and control gain were the same as those used in Experiment 1.

Design

The experimental design was a mixed factorial with three within-subject factors and one between-subjects factor. The between-subjects factor, Flight Experience, reflected the division of the subjects into one group of 9 pilots, and a second group of 11 nonpilots. The within-subject manipulations formed a (2 x 2 x 2 x 6) design (see fig. 7). The within-subject factors were as follows:

1. Tailwind Acceleration: present or absent. Tailwind acceleration was present when tailwind velocity (and therefore uncontrolled vehicle ground speed) changed as a linear function of craft location (e.g., for initial tailwind velocity $T(0)$, craft position X, and exponential rate of increase or decrease k, $T = T(0) \pm k X$).

2. *Linked Optical variable:* edge rate or flow rate. Either edge rate or flow rate was reliably coupled with (informative about) changes in vehicle ground speed.

3. *Optical Change:* positive or negative. Edge rate or flow rate accelerated or decelerated during uncontrolled flight. When Tailwind Acceleration was absent, the changing optical variable was misinformative. When Tailwind Acceleration was present, the changing optical variable was informative.

4. *Replications:* 1-6. All conditions were repeated six times for each subject. This factor was not analyzed and all tests collapsed across it.

Simulated Scenarios and Dynamics

The simulated scenarios and dynamics were the same as those used in Experiment 1, with the following modifications. In Experiment 2, each trial displayed a forward-looking view from a simulated vehicle during level, ascending, or descending flight over a level green terrain (fig. 8). The terrain surface was demarcated by a grid composed of black texture lines oriented both orthogonal to the direction of flight (lateral lines) and parallel to the direction of flight (longitudinal lines). In addition, there was a 25-m-wide black "road" displayed directly beneath the vehicle and five 12.52-m-high by 6.26-m-wide black and white "towers" placed 25 m from the center of the road (three towers on the left of the road and two on the right). These towers were divided into five 2.5-m-high segments to give a good visual scale for altitude change. The five towers were longitudinally spaced such that at least two of them were always easily within view. The towers and the road were included to make altitude variations more readily apparent; a change in altitude yielded a change in both the optical size of the road and the location at which the horizon line cut through the towers. Finally, during the manual flight phase, flow rate was also manipulated by making altitude *(h)*, a linear function of position, x, (see table 3.)

Procedure

The experiment was conducted in a single 3.5-hr session, with a 15-min break midway through the session. The procedure was similar to that of Experiment 1, with the following changes. First, subjects were told that their task would be to maintain a constant forward ground speed during a flight over a black road that would take them past several identical towers. They were informed how wind-speed acceleration, texture density, and altitude were being manipulated and were given feedback on the mean and standard deviation of their ground speed following each trial. They were instructed to report at the end of each trial, but before the feedback was given, whether there was an upward, downward, or zero trend in wind speed, texture size, and altitude. After receiving the instructions, the subjects were given one or two demonstration trials to familiarize them with the task, followed by six blocks of eight experimental trials each (48 total trials), with each block containing a random ordering of the eight combinations of Linked Optical Variable, Optical Change, and Tailwind Acceleration.

Performance Analyses

As in Experiment 1, the dependent measure was the subject's contribution to the overall acceleration/deceleration expressed as an average percent per second change in ground speed (i.e., exponential rate of change in the vehicle ground speed input by the subject). This dependent measure was calculated as in Experiment 1 except that the accelerations had rates of ±0.5%/sec instead of the -0.5%/sec and 0.67%/sec used in Experiment 1. The resulting value, the subject's contribution to the overall acceleration/deceleration, was then analyzed using a 2 x 2 x 2 x 2 Flight Experience x Linked Optical Variable x Optical Change x Tailwind Acceleration mixed analysis of variance. Again, the results were examined in terms of adaptation effects and acceleration control response.

Table 3. Effects of Manipulating Altitude, Texture, and Tailwind Velocity

Condition	Altitude $h = 6.25+$	Texture $T_x = 25+$	Tailwind velocity $V_w = 25+$	Uncontrolled edge rate	Uncontrolled flow rate	Uncontrolled ground speed	Linked variable
A	-0.00125x		-0.005x	Decreasing	Constant	Decreasing	Edge rate
B	+0.00125x		+0.005x	Increasing	Constant	Increasing	Edge rate
C	+0.00125x			Constant	Decreasing	Constant	Edge rate
D	-0.00125x			Constant	Increasing	Constant	Edge rate
E		-0.005x	-0.005x	Constant	Decreasing	Decreasing	Flow rate
F		+0.005x	+0.005x	Constant	Increasing	Increasing	Flow rate
G		+0.005x		Decreasing	Constant	Constant	Flow rate
H		-0.005x		Increasing	Constant	Constant	Flow rate

Motion-adaptation response– Figure 9 shows the mean input during manual flight control collapsed across the Flight Experience factor and broken out by Flight Experience. The mean input, 0.187%/sec, was significantly above zero (F(1,18) = 40.464, p < .001), showing an overall motion-adaptation effect that resulted in positive acceleration inputs in almost all conditions, even when the uncontrolled change in the optical variable already represented a positive acceleration. There was also a greater adaptation effect for the pilots than the nonpilots (mean accelerations of 0.125%/sec and 0.263%/sec for nonpilots and pilots, respectively, (F(1,18) = 5.459, p < .05).

Two other statistically significant effects that did not involve the Optical Change factor were found: a main effect of Linked Optical Variable (F(1,18) = 11.932, p < .01) and an interaction of Linked Optical Variable with Flight Experience (F(1,18) = 6.437, p < .05). Figure 9 shows that subjects, particularly pilots, generated more positive input to flow-rate-specified ground speed than to edge-rate-specified ground speed. These effects are interesting because they indicate that motion-adaptation effects depend on which variable specifies ground speed, and upon experience. This in turn suggests that the subjects' responses, particularly those of the pilots, may reflect fundamentally different inputs across types of ground-speed-linked variables.

Acceleration control response– In addition to the adaptation effects, there was also a clear and pronounced effect of Optical Change (F(1,18) = 300.29, p < .001). Figure 9 shows that, relative to the mean input (an estimate of the general adaptation level), decelerating optical changes generated positive inputs, and that accelerating optical changes generated negative inputs in all conditions.

Figure 10 plots acceleration control as the difference in response to optical accelerations and optical decelerations. Large acceleration responses show a marked effect from the direction of the optical acceleration, and low values indicate that subjects' responses did not depend on the direction of the change. As noted, the significance of changes in this measure over levels of Flight Experience, Linked Optical Variable, and Tailwind Acceleration are given by the tests of their interaction with the Optical Change factor.

The conditions with a changing tailwind are of special interest. Here we would expect the subjects to generate an average acceleration control response of 1.0%/sec, or an input of ±0.5%/sec for the two conditions, if they were fully nulling the tailwind effects. However, the average response was 0.44%/sec, an input of about 0.22%/sec for each condition. This is not significantly different from the value of 0.25%/sec that would result if subjects were attempting to balance the rates of change in the two optical variables (follow-up planned comparison, $p > .10$). That is, attempting to control the initially changing optical variable will generate an opposing rate of change in the initially constant optical variable, and, on average, about 50% control (0.25%/sec) will lead to equal indications of acceleration and deceleration on the two optical variables. This suggests that subjects were probably responding to both optical variables.

No three- or four-way interactions involving both Linked Optical Variable and Optical Change were statistically significant ($p > .25$). Thus there was no effect of Linked Optical Variable on the acceleration control response; subjects were equally affected by edge- and flow-rate information. However, these analyses do not test whether subjects were more sensitive to edge-rate change or flow-rate change, per se. That is, across levels of Tailwind Acceleration and Linked Optical Variable, edge-rate change may be more salient than flow-rate change, and the subjects might tolerate less edge-rate change overall (since we know that subjects respond to both types of change in all conditions).

This is the kind of sensitivity that has been examined in the work on edge-rate and flow-rate as discussed in the introduction. If edge-rate sensitivity is dominant, then given equivalent tailwind conditions, events that have an uncontrolled changing edge rate (conditions A, B, G, and H in table 3) should engender more acceleration control response than events that have an uncontrolled changing flow rate (conditions E and F, and C and D). Figure 10 shows that this did not happen. Nor were there significant interactions of Linked Optical Variable x Optical Change x Tailwind Acceleration interaction ($F < 1.0$), or of Linked Optical Variable x Optical Change x Tailwind Acceleration x Flight Experience ($F < 1.0$).

The acceleration responses show less sensitivity to the Optical Change factor in the constant tailwind condition than in the changing tailwind condition. This Optical Change x Tailwind Acceleration interaction was statistically significant ($F(1,18) = 29.41$, $p < .001$), demonstrating that subjects must have been responding to other optical variables coupled with a changing tailwind. The expected improvement attributable to Flight Experience (the Flight Experience x Tailwind Acceleration x Optical Change interaction) was only marginally significant ($F(1,18) = 3.427$, $p = .081$), although an examination of figure 10 clearly shows an appropriate trend; that is, pilots show a greater effect of Optical Change when there is a changing tailwind, and a smaller effect when the tailwind is constant.

Subjective Ratings Analyses

Three independent 3 x 2 (True Change x Flight Experience) analyses of variance were conducted upon the ratings given by the subjects. The results, shown in figure 11, indicate a moderate degree of sensitivity to these manipulations. For all three ratings the effect of the manipulation on the ratings was significant (F(2,18) = 36.701, p < .001 for changing texture size; F(2,18) = 111.19, p < .001 for changing altitude; and F(2,18) = 88.886, p < .001 for changing wind speed). The judgments of wind-speed change also showed the adaptation effect, with the mean rating being significantly less than 0 (mean rating = -0.178, F(1,18) = 8.211, p < .05) indicating a bias to see events as decelerating. Also, the effect of Flight Experience was marginally significant (F(1,18) = 4.359, p = .051) with a greater adaptation effect for pilots (-.3210) than nonpilots (-.061). The only other statistically significant effect was a tendency for pilots to rate the texture as decreasing more often than increasing (mean rating = -.120) whereas the opposite was true for the nonpilots (mean rating = .093). No statistically significant interactions of Flight Experience with the levels of the manipulations (i.e., decreasing, constant, increasing) were found.

Although the above ratings analyses show that subjects were sensitive to the manipulations, they do not show if the ratings of wind acceleration were dependent on the ratings of texture or altitude change or both. In order to test this, all trials were coded as correct or incorrect upon the three manipulated physical variables. This yielded eight potential judgment patterns (e.g., "correct texture judgment, correct altitude judgment, incorrect ground speed judgment") and the frequencies of each of these eight patterns was calculated. These were then used as the dependent measure in a 2 x 2x 2 x 2 (Flight Experience x Texture Change Judgment x Altitude Change Judgment x tailwind-speed Change Judgment) fully within-subjects analysis of variance. The results, plotted in Figure 12, show that subjects were significantly more often correct than incorrect in their judgments of altitude change (F(1,18) = 29.771, p < .001). In addition, the interaction of Texture Change Judgment with Wind-speed Change Judgment was statistically significant (F(1,18) = 4.833, p < .05). This interaction is due to subjects making more errors in wind-speed change judgments when they also made incorrect texture change judgments. Thus, unlike Experiment 1, this analysis provides evidence that the probability of making a correct judgment of wind-speed change was enhanced by making a correct determination about altitude or texture size change.

Results Summary

Two dimensions of performance were found to be affected in this study. First, events that linked ground speed to edge rate were found to exhibit a smaller motion-adaptation effect, especially with the pilot subjects. Second, response to uncontrolled optical accelerations and decelerations was most pronounced when there was a concurrent linked-change in simulated vehicle ground speed, with some marginally reliable evidence that this is most true for the pilots. Third, the subjective measures now yielded some evidence that awareness of changes in texture size (i.e. changing visual context) was accompanied by awareness of changes in forward speed. On the other hand, altitude awareness was very strong and apparently independent of forward speed awareness.

Since adaptation levels are typically thought to be a physiological manifestation of a system adapting to some input, this suggests that in this task the nature of the physiological inputs may depend on their relationship to ground speed. This, in turn, must be due to people selectively giving more weight to the input from the appropriate optical variable. The interaction between Linked Optical Variable and Flight Experience thus appears to be a result of learning to selectively focus attention. This result, in turn, predicts that pilots should exhibit better control than nonpilots.

Finally, no evidence was found that people are more intrinsically sensitive to edge-rate variation nor that pilots are biased toward using edge rate to control ground speed. This does not necessarily contradict all earlier studies in which such a bias was found since a study that examines control will necessarily confound both the sensitivity to an optical variable and the tendency to use that optical variable. However, it does indicate that the findings in Experiment 1 may have resulted from an unconscious, or preconscious, tendency to see changing optical flow rate and optical density as arising from changing altitude.

These findings are of both theoretical and pragmatic interest. For both pilots and nonpilots, adaptation level was a function of the informative optical variable. This suggests that attention to the two optical variables depended on which was informative. Furthermore, since pilots were better than nonpilots at discriminating optical changes caused by ground-speed changes, and also exhibited a greater differential adaptation effect (different adaptation levels to flow- and edge-rate linked ground speed), focusing attention on the informative optical variable may have led to both effects. Thus, these findings suggest that people learn how to detect the relevance of the two optical variables and then modulate attention to them. The verbal judgments also implicate visual context in ground speed awareness, showing that awareness of ground texture size and forward speed covaried.

The practical significance of these findings is that the regulation of ground speed using edge-rate information is less affected by adaptation. Therefore, edge-rate information about ground speed is more stable. This stability is particularly important in situations in which visually based ground-speed assessment and control are either intermittent (i.e., frequent re-adaptation is required) or those in which the time allowed for ground-speed assessment is limited. One real-world situation that requires such re-adaptation is when pilots break out of clouds near the runway. Therefore, a good stable and regular texture (which provides edge-rate information for ground speed) near the runway is valuable.

Finally, if the theoretical linkage between the relative adaptation effect and better control is true, then the provision of information to emphasize changes in altitude or texture size or both may be important. In any case, a better understanding of the basis for discrimination of relevance could contribute to both how we provide important visual information to pilots and to training pilots to make this discrimination.

CONCLUDING REMARKS

The main purpose of these two experiments was to examine the adaptive selectivity of attention by trying to answer (for the control of ground speed): What is being controlled? Does this change in an adaptive way over situations? Evidence was found that the ability to selectively use optical variables as information for ground speed depends on the context provided by the visual scene and not on the type of conscious direction of attention that can be given by verbal instructions. The results of Experiment 2, in particular, suggest that selective attention is being manipulated by this visual context.

As a result, these studies have advanced the way in which we consider the effect of optical variables on perception and control. Specifically, they have shown that the "informativeness" of an optical variable has an effect on how it is perceived and used. The studies have furthermore suggested that this ability to select may not be a part of the conscious intent of the observer/controller but is perhaps more intimately linked to unconscious perceptual skills that detect visual information concerning relevance. Further research is needed to determine how optical or other variables are selectively utilized to control self motion. It is not enough to determine what types of variables influence reports of subjects or their behavior; how humans deal with the varying informativeness of these variables must also be examined. These findings point to a need to explore the optical environment for a potentially new class of information—information that reflects the connection between optical variables and environmental attributes.

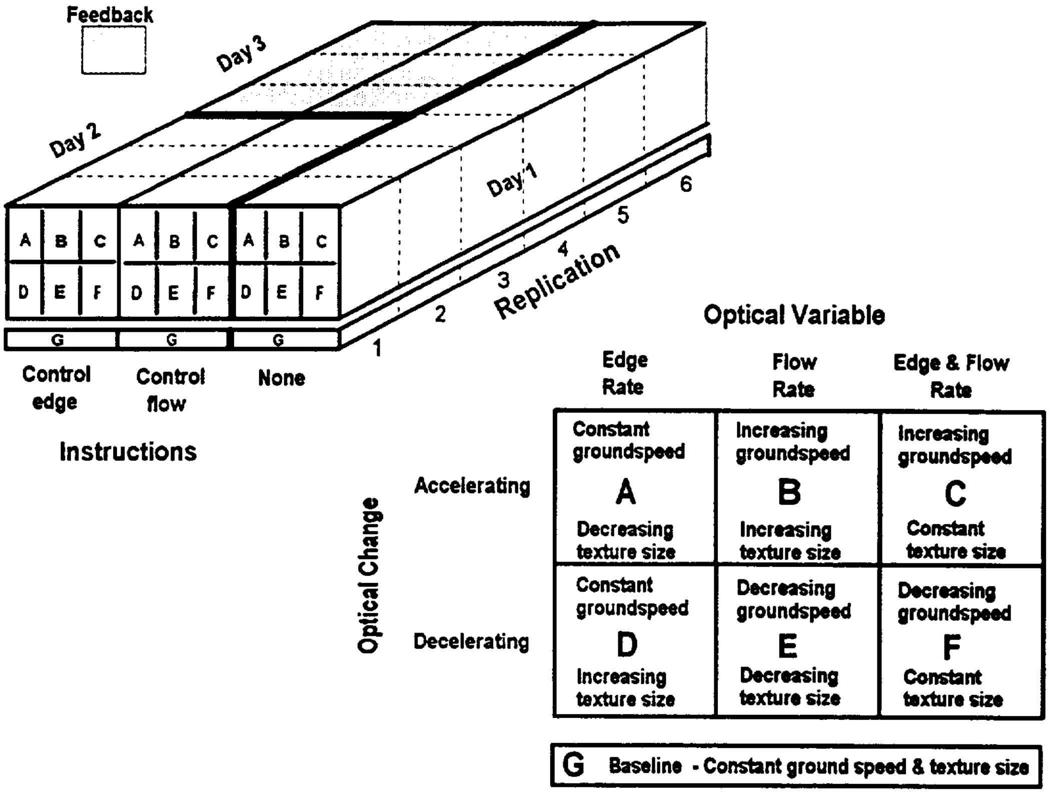


Figure 1. Design of Experiment 1.

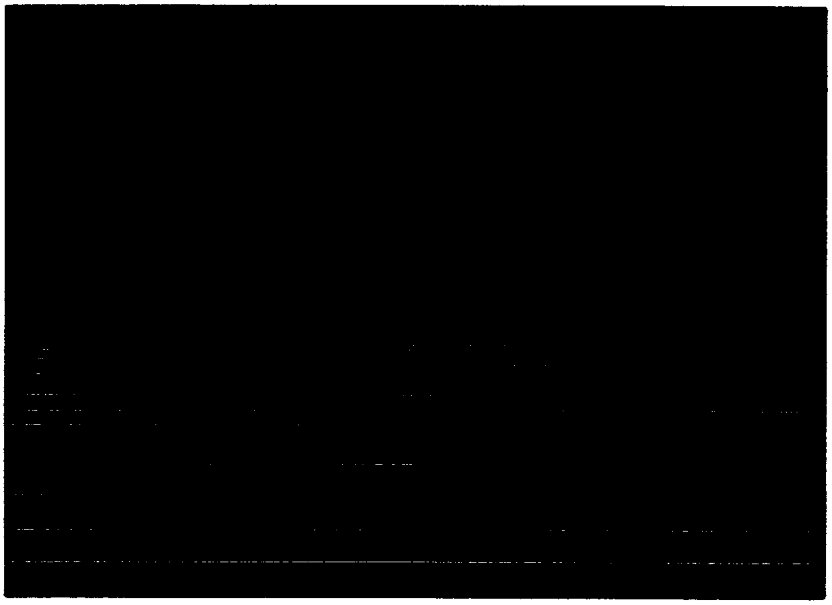


Figure 2. Illustration of forward-looking view in Experiment 1.

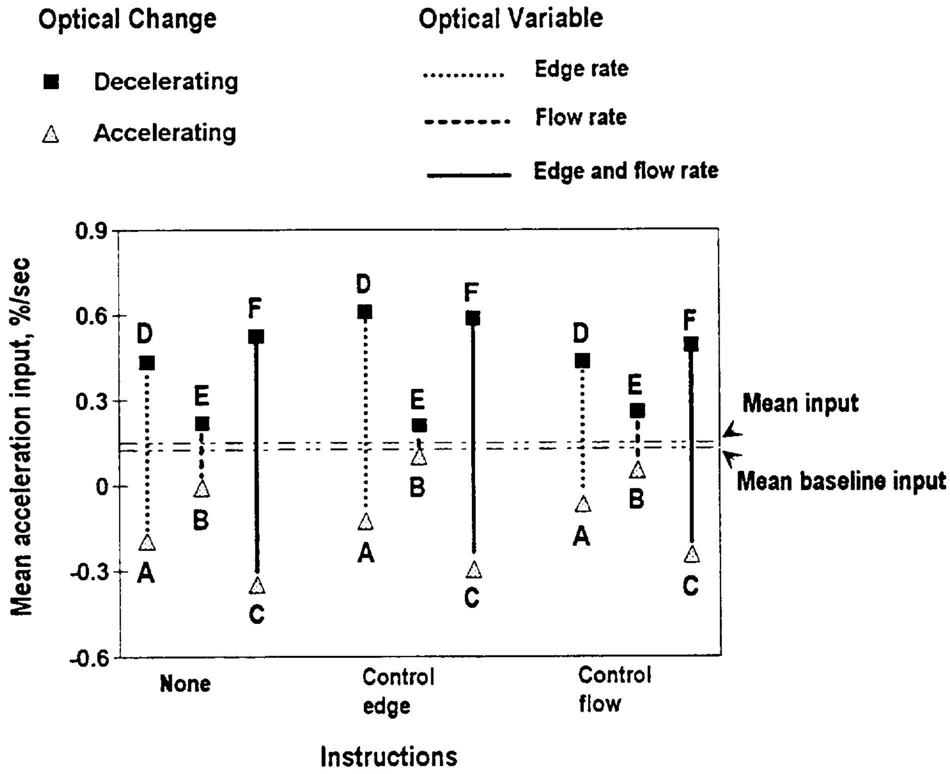


Figure 3. Overall mean exponential input acceleration during manual flight for conditions A-F (see table 1).

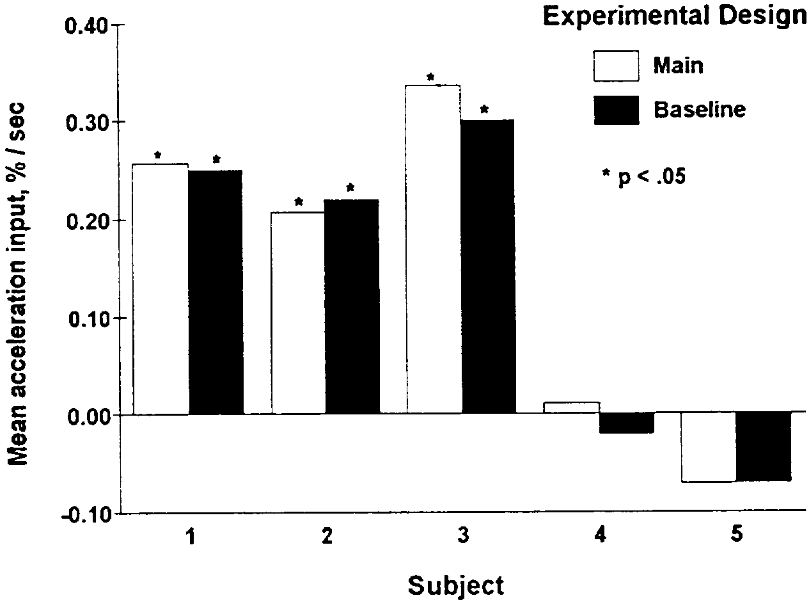


Figure 4. Mean adaptation response as a function of individual subject and experimental design.

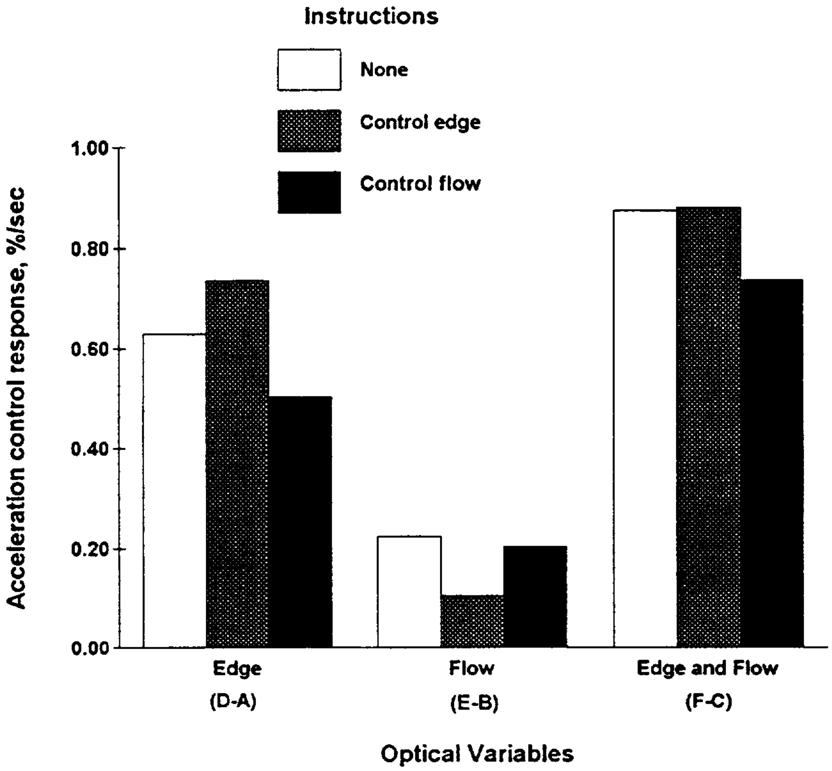


Figure 5. Acceleration control response as a function of Instructions and Optical Variables for conditioning A-F (see Table 1).

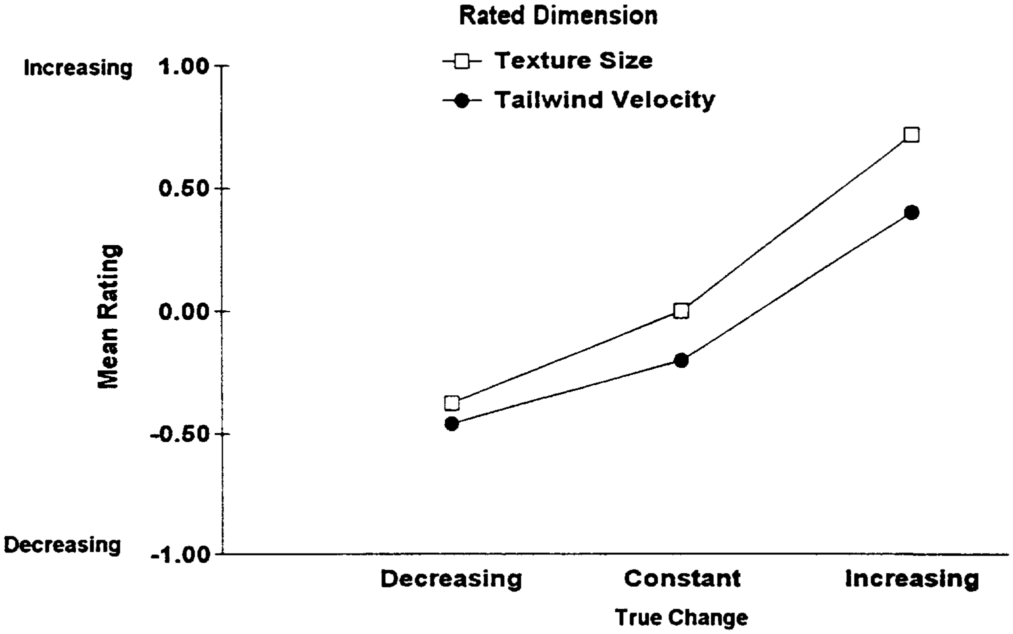
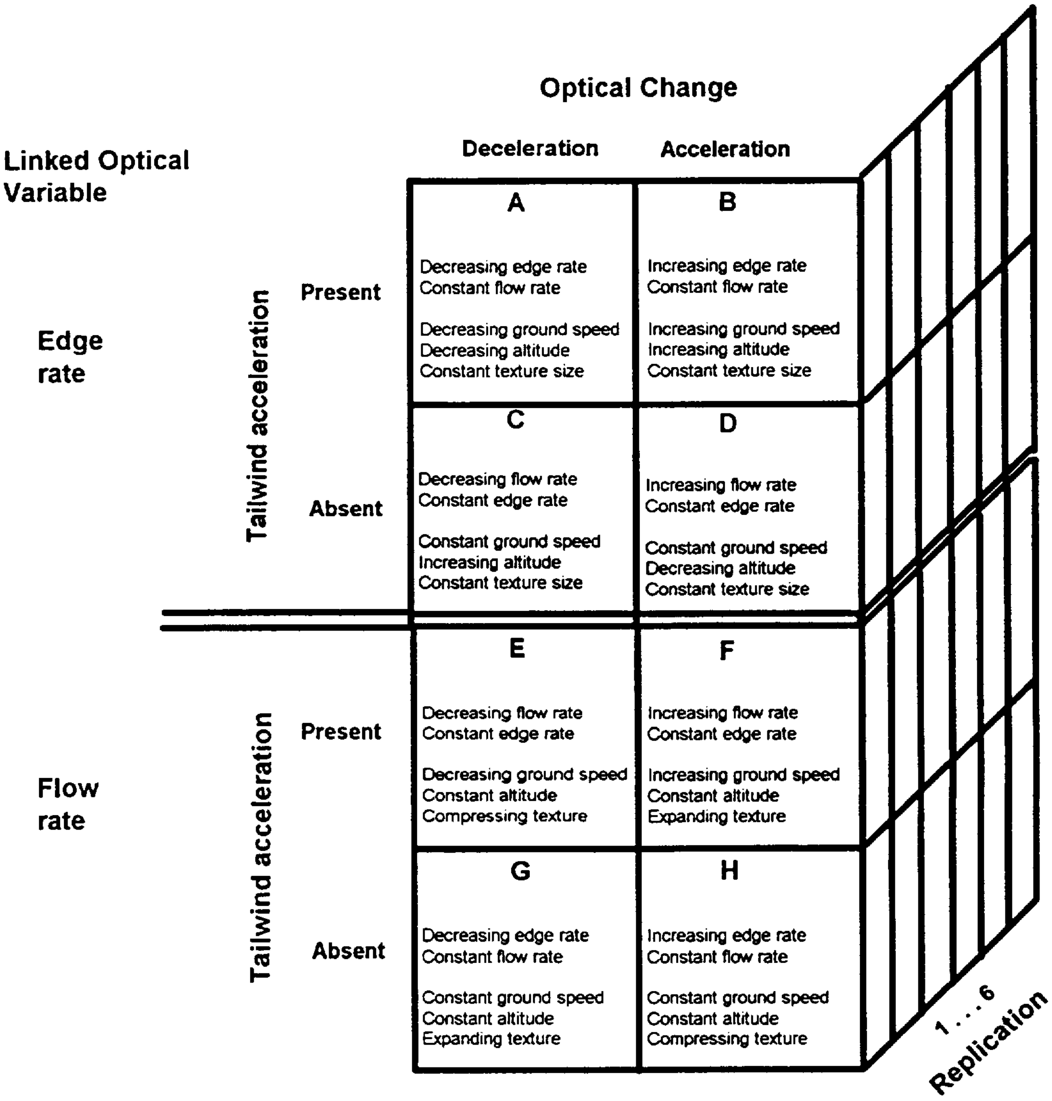


Figure 6. Subjective ratings of texture and tailwind change as a function of true change.



Linked Optical Variable	Tailwind acceleration	Optical Change Deceleration	 Acceleration
Edge rate	Present	A Decreasing edge rate Constant flow rate Decreasing ground speed Decreasing altitude Constant texture size	B Increasing edge rate Constant flow rate Increasing ground speed Increasing altitude Constant texture size
	Absent	C Decreasing flow rate Constant edge rate Constant ground speed Increasing altitude Constant texture size	D Increasing flow rate Constant edge rate Constant ground speed Decreasing altitude Constant texture size
Flow rate	Present	E Decreasing flow rate Constant edge rate Decreasing ground speed Constant altitude Compressing texture	F Increasing flow rate Constant edge rate Increasing ground speed Constant altitude Expanding texture
	Absent	G Decreasing edge rate Constant flow rate Constant ground speed Constant altitude Expanding texture	H Increasing edge rate Constant flow rate Constant ground speed Constant altitude Compressing texture

Figure 7. Design of Experiment 2 (within-subject factors).

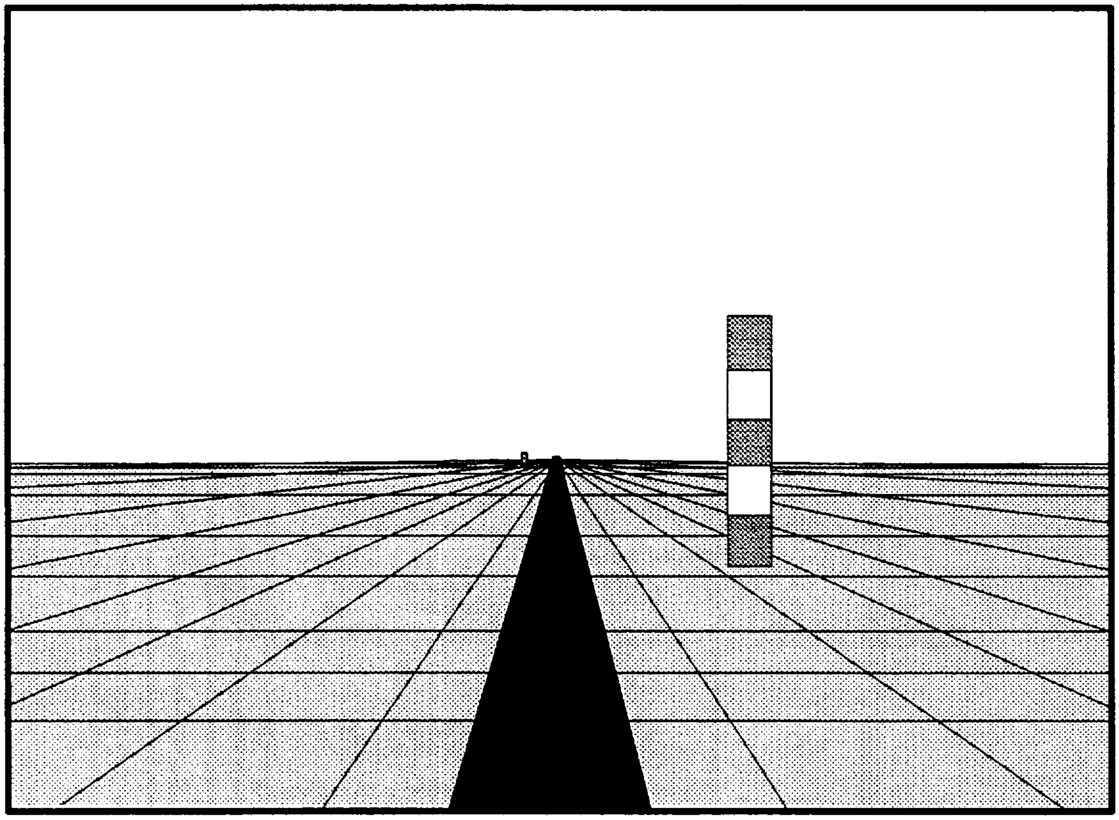


Figure 8. Illustration of forward-looking view in Experiment 2.

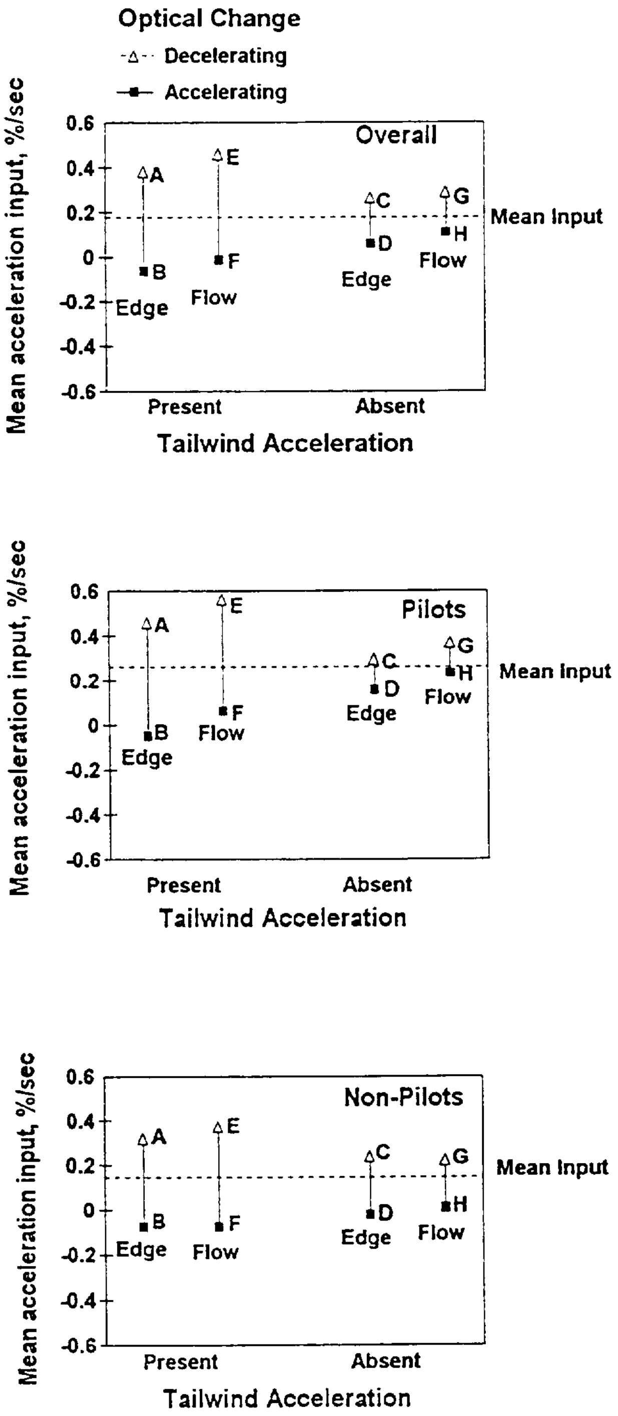


Figure 9. Overall mean exponential input acceleration during manual flight and as a function of flight experience for conditions A-H (see table 3).

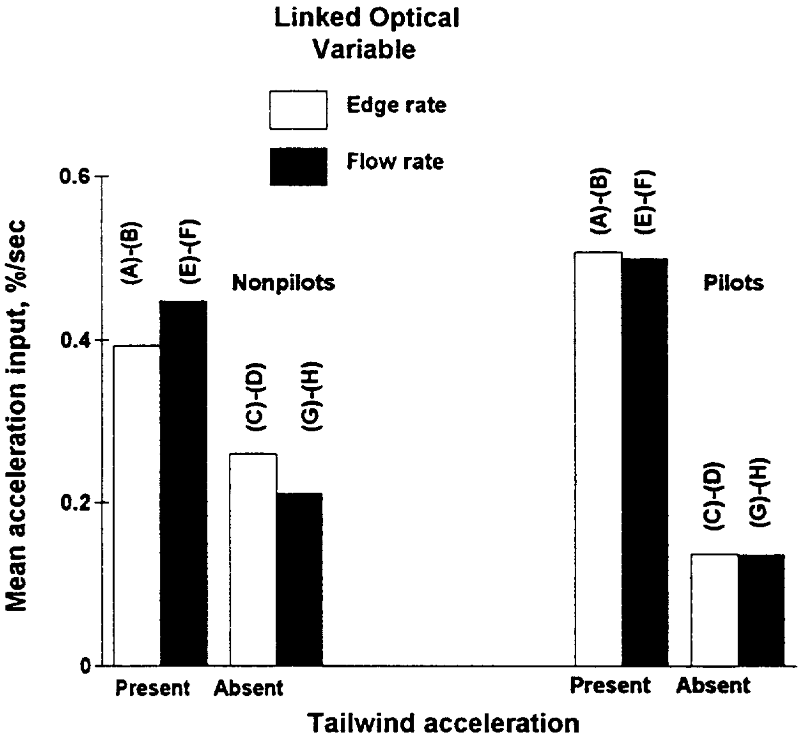


Figure 10. Magnitude of acceleration response to optical accelerations (deceleration exponent minus acceleration exponent) as a function of flight experience for conditions A-H (see table 3).

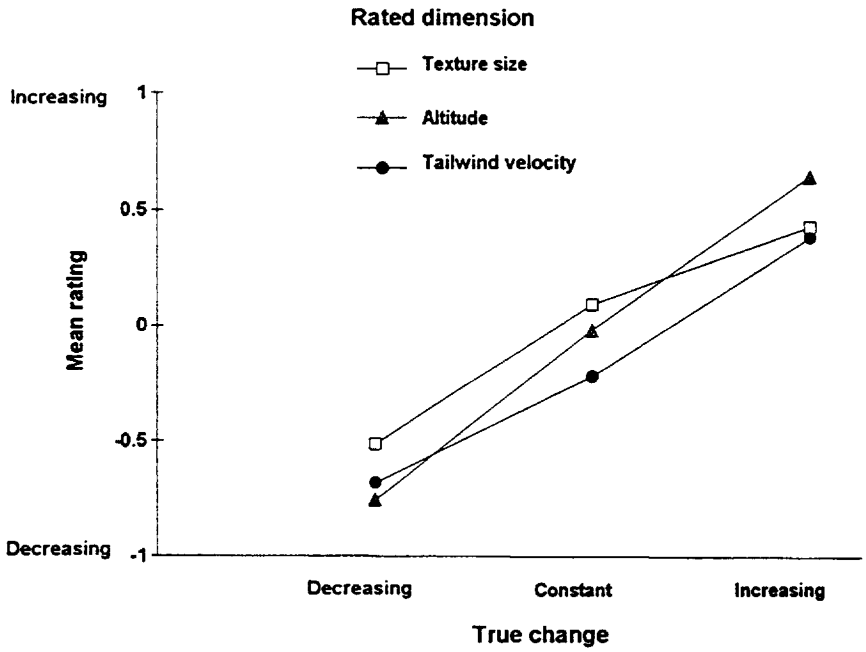


Figure 11. Judged change in texture size, altitude, and tailwind speed as a function of true change.

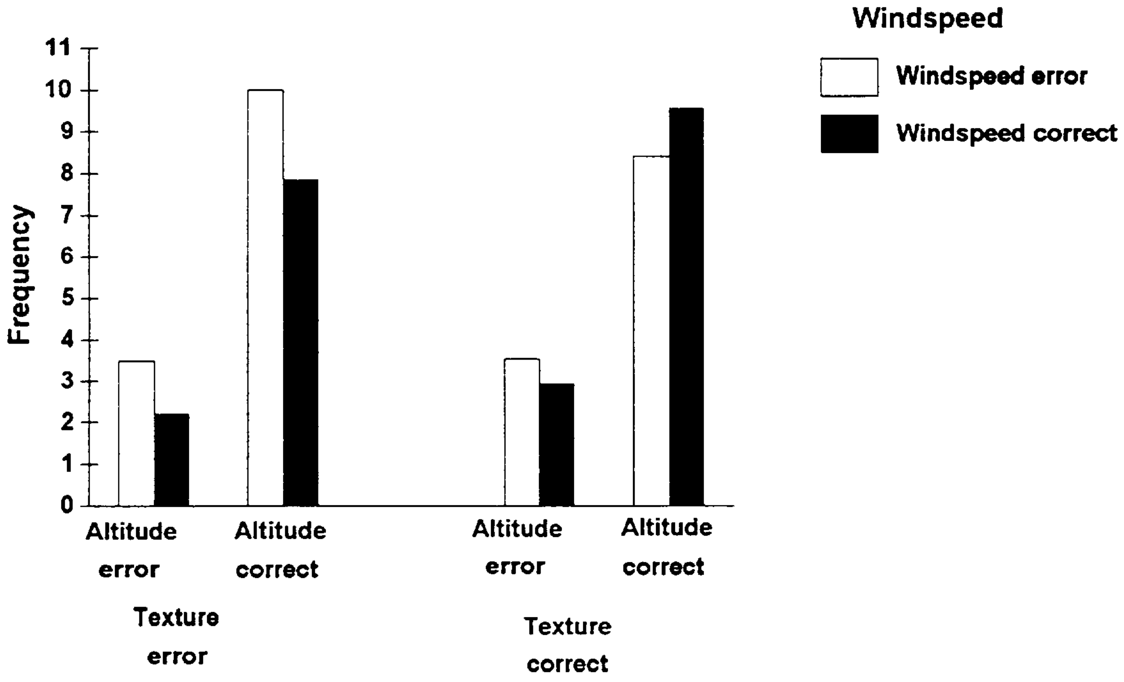


Figure 12. Error pattern for judgments of change in texture size, altitude, and tailwind speed.

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Previous work on the perception and control of simulated vehicle speed has examined the contributions of optical flow rate (angular visual speed) and texture, or edge rate (frequency of passing terrain objects or markings) on the perception and control of forward speed. However, these studies have not examined the ability to selectively use edge rate or flow rate. The two studies presented here show that this ability is far greater for pilots than non-pilots, as would be expected since pilots must control vehicular speed over a variety of altitudes where flow rates change independently of forward speed. These studies also show that this ability to selectively use these variables is linked to the visual contextual information about the relative validity (linkage with speed) of the two variables. Subjective judgment data also indicated that awareness of altitude and ground texture density did not mediate ground speed awareness.

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