Difference Thresholds for Judgments of Sink Rate during the Flare

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Past studies have shown that touchdown rates of descent (sink rates) are higher in aircraft simulators than in aircraft under similar conditions. The objective of this paper was to use a psychophysical technique to investigate a pilot's ability to distinguish between two different sink rates close to the ground. The pilots observed a collimated computer graphics display of a typical runway with edge, zone, and centerline lights. The results showed that, with a forward velocity of 120 knots, pilots could distinguish reliably between a sink rate of 0.5 m/sec (1.7 fps) and 0.9 m/sec (2.9 fps). The results also showed that the absolute rate of sink did not affect significantly the perception of sink rate. Time of sink and total height drop during the sink did affect the minimum detectable difference between sink rates (the differential threshold). The effects were such that a greater time of sink and greater height drop produced lower thresholds.

Introduction

MOST current visual simulators utilize either a TV camera and terrain model or a computer graphics system to provide the pilots with an out-the-window view of an airport terminal area. For both training and research, it generally is agreed that the simulators are acceptable during the approach to the runway, but the task of height control during the flare and touchdown is still unrealistically difficult. In particular, previous studies[1] have indicated that sink rates at touchdown are considerably higher on simulators than in flight. Pilots also require more landings in simulators to attain "acceptable" sink rates at touchdown.

In trying to determine why pilots make hard landings on simulators, researchers usually have pilots fly simulated aircraft and make touchdowns as elements or parameters of the visual simulator are varied. Typical data consist of pilot opinion and overall system performance measures such as touchdown position and sink rate at touchdown. The basic assumption of this approach is that the experimental condition with the highest visual fidelity will result in overall system performance and learning curves that are closest to those measured in actual flight. Experiments of this type have shown that simulator performance is worse than actual landing performance and/or that there is an excessive amount of learning required to reach acceptable performance. The experimenter now has the difficult problem of determining what caused the poor performance. The combined pilot-aircraft simulator is a complex closed-loop control system. Inadequacies in any of the simulator subsystems can cause total system performance to degrade.

Barnes[2] listed a number of problems that plague simulator subsystems, such as mechanical servodrive irregularities, poor picture resolution, and absence of critical visual and motion cues. He postulated that each of these increases visual thresholds that must be exceeded before the pilot can initiate action. A delay in response occurs which is equivalent to a dead band in the control loop. Poor performance therefore could be due to oscillations caused by increased perceptual thresholds. Barnes proposed that thresholds for variables such as attitude, position, and sink rate be measured directly. In his study, he measured pilots' thresholds for heading and bank angle on a visual simulator. He hoped that, by measuring thresholds, he could isolate more directly the simulator subsystem that was causing the poor touchdown performance.

The purpose of the study presented herein was to extend this line of research and use a psychophysical technique to investigate how well pilots perceive the critical parameter of sink rate close to the ground. In particular, difference thresholds for sink rate were measured for 16 pilots on a computer-graphics night visual simulator. As a secondary purpose, this study attempted to assess the relative effects of sink rate and time of sink on thresholds for detection of sink-rate differences.

Method

Apparatus

All perceptual judgments were based on a night runway scene produced on an Evans and Sutherland Line Drawing System 2. This computer graphics display consists of a two-dimensional perspective representation of a runway and surrounding city lights on a 53-cm (21-in.) cathode-ray tube. The horizontal and vertical field of view (FOV) was 28°. The scene was viewed through a collimating lens that was set empirically to give an image distance of 10 m with unity magnification.

Subjects

Sixteen airline pilots were paid to participate in this study. Total time per subject was about 2 hr. Each pilot held a current Class I or Class II (Federal Aviation Agency) (FAA) Medical Certificate.

Experimental Design

Each of the 16 pilots completed all nine conditions listed in Table 1 in a unique random order. One threshold value was obtained from each of the nine series of trials for each pilot. Two sequences of trials corresponding to two randomly chosen conditions were performed as practice sets that did not serve as data. A 5-min rest was provided after each pair of conditions.

Task

A computer graphics system was programmed to display a view of the runway shown in Fig. 1 with edge, zone, and centerline lights. The pilot initiated each trial by pushing a button. The runway then would appear, with the pilot's eye 5 m above it and the the pilot/"vehicle" appearing to move forward with a velocity of 120 knots. After 1 sec, the

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Table 1 Summary of sink rate v, time of sink t, and drop in height ΔH for each experimental condition

Time of sink, sec	Height drop, m		
	$v = 0.30$ m/sec	$v = 0.52$ m/sec	$v = 0.90$ m/sec
1.33	0.40	0.69	1.20
2.31	0.69	1.20	2.08
4.00	1.20	2.08	3.60

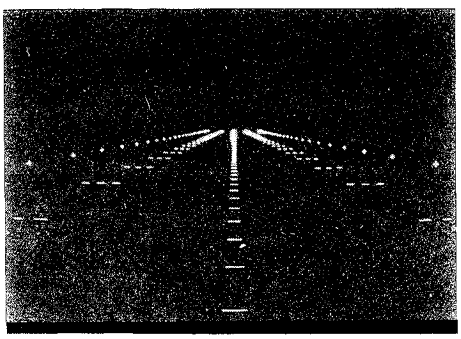

Fig. 1 Pilot's view of the computer graphics night visual attachment.

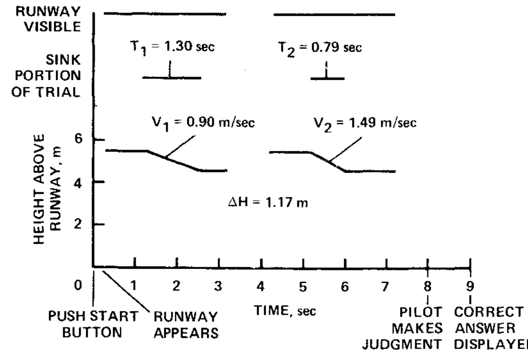

Fig. 2 Time sequence of events during a typical trial.

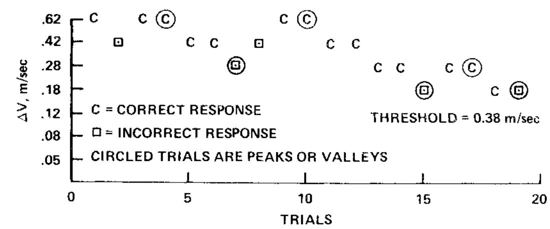

Fig. 3 Typical sequence of trials for one subject for one measurement of the difference threshold. In this condition, $\Delta H = 1.17$ m, $T = 2.3$ sec, and $V = 0.52$ m/sec.

simulated "vehicle" would start to sink toward the runway for a fixed time. Then the "vehicle" would stop sinking, and, after a few seconds, the screen would go blank. After 1 sec, the runway appeared again, and the preceding events were repeated, except that the sink rate was different in the second presentation. After the second presentation, the pilot was asked to make a forced-choice response, whether the vehicle had descended faster in the first or second presentation. The pilot was told whether or not he was correct, and a new trial could begin. Figure 2 shows the sequence of events during a single trial. No pitch, roll, or yaw excursions were produced. The vehicle never reached the end of the runway; 300 m runway was always visible.

Experimental Conditions

Nine conditions were used, as summarized in Table 1. These represent various levels of the three variables: 1) change in height during the trial, 2) the standard vertical velocity during the sink portion of the trial, and 3) time elapsed during the sink portion of the trial. Comparisons thus can be made between difference thresholds determined with 1) change in height constant, 2) descent velocity constant, and 3) descent time constant, where in each case the other two variables vary proportionately to one another. The three variables are confounded with one another, since $h = v \cdot t$.

Adaptive Psychophysical Method of Determining Thresholds

The individual threshold values were determined by a modified single staircase method,[3] using a simple arithmetic means of maximum and minimum points as the threshold value for a given set of trials. This was accomplished by starting at a standard velocity difference of 0.62 m/sec between the first two trials. One of the two trials of each pair was chosen randomly to have a sink rate equal to the nominal sink rate for that condition. Each successive pair of trials was made to be 33.33% closer together in sink rate than the pair before as long as no incorrect responses had been made. When the first incorrect response was made, the next pair of trials was 50% further apart in sink rate. For the remainder of the trials, a 50% increase in stimulus difference followed every incorrect response, and a 33.33% decrease in stimulus difference followed every two consecutive correct responses; thus the step sizes were the same when the stimulus difference was increased as when it was decreased. For example, a subject might respond incorrectly to a stimulus difference of 0.28 m/sec, so that the next pair of trials would be 50% further apart in sink (0.42 m/sec). If the subject then responded correctly to the next two trials, the stimulus difference would be decreased by 33.33% back to a 0.28-m/sec sink-rate difference. Trials continued until three nonconsecutive errors had been made. The threshold was computed from the latter six maximum and minimum values (three "peaks" and three "valleys"). Figure 3 shows a typical sequence of trials for one subject.

Results and Discussion

Threshold means and standard deviations for each of the nine experimental conditions are shown in Table 2. It can be

Table 2 Means and standard deviations of sink-rate thresholds (m/sec)

Time of sink, sec	Mean (standard deviation)			Average of means
	$v = 0.30$ m/sec	$v = 0.52$ m/sec	$v = 0.90$ m/sec	
1.3	0.27 (0.18)	0.23 (0.10)	0.23 (0.12)	0.25
2.3	0.28 (0.18)	0.24 (0.16)	0.17 (0.15)	0.23
4.0	0.23 (0.16)	0.13 (0.09)	0.13 (0.07)	0.16
Average of means	0.26	0.20	0.18	0.22

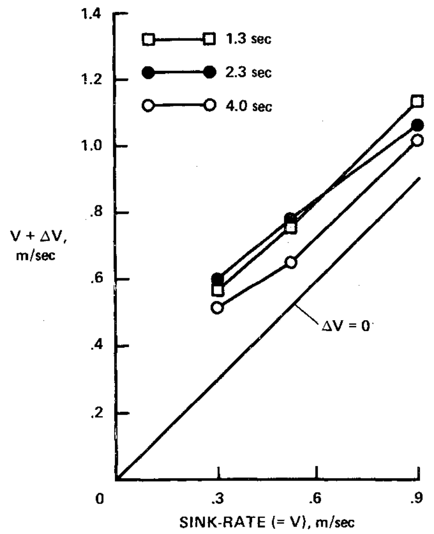

Fig. 4 Sink rate plus threshold ($V+\Delta V$) as function of sink rate.

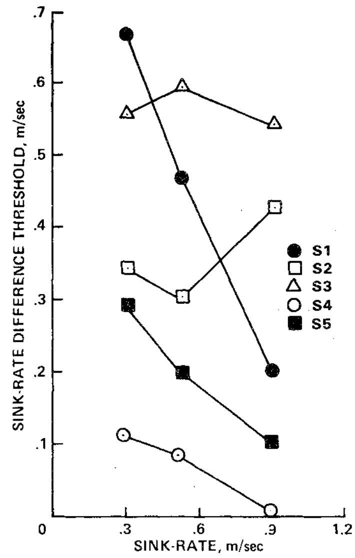

Fig. 5 Sink-rate difference thresholds for five subjects.

seen from these results that, for the lowest sink-rate condition, the threshold values are nearly equal to the rate of sink for that condition. This suggests that the minimum detectable sink rate (i.e., absolute threshold for sink rate) is of a magnitude in the range of sink rates used in this experiment. Pilots may have been deciding whether there was any noticeable sink during trials rather than deciding which of two sink rates was greater. That this was true of conditions in which the nominal sink rate was 0.3 m/sec is supported by comments from the pilots about the difficulty of the task in those conditions. If a 0.3-m/sec sink rate is barely discriminable from a 0.6-m/sec sink rate, as the present data show, it can be expected that 0.3 m/sec also will be only marginally discriminable from zero sink rate. Further evidence that 0.3 m/sec was near the absolute threshold comes from extrapolation of the curves of Fig. 4. This is a plot of the sink rate plus difference threshold ($V+\Delta V$) as a function of the sink rate. For a given point, the value of the ordinate is the smallest sink rate that can be detected as faster than the value of the abscissa for that point. By extrapolation of the three curves back to the Y axis, it can be seen that they would intersect the axis in the range of 0.3 to 0.4 m/sec. If the extrapolation is valid, it suggests that, when one of two stimulus sink rates is zero, the other must be at least 0.3 m/sec before a difference can be detected.

The results of this experiment indicate that, as the sink rate increases, the ratio of the threshold to sink rate $\Delta V/V$) decreases. This is contrary to nearly all psychophysical studies of differential thresholds. A constant ratio of $\Delta V/V$ usually is found when velocity is varied.[4] This follows the formula $\Delta W = 0.10\ W$, where W is the angular velocity of the stimulus and ΔW is the differential threshold. Such a relationship is known as a Weber ratio. Notterman and Page,[5] however, found that, as they reduced the velocity of an object near the absolute threshold (minimum detectable velocity), the ratio $\Delta V/V$ increased. It seems very likely that this phenomenon was responsible for the relationship between thresholds and sink rates found in the present study. This would imply either that pilots in the real landing situation usually depend on other cues for sink rate or that they are landing aircraft at nearly the slowest rate of sink which they can see.

The large $\Delta V/V$ ratios and the large standard deviation of the thresholds show that considerable visual estimation errors or observational noise existed for the sink-rate comparisons. A foremost source of noise was the 120-knot forward velocity, which contributed a much larger component to every velocity vector in the scene than did the vertical velocity. The values of the thresholds were nevertheless small when compared to the 0.5-m/sec rate of sink typical for aircraft landings or especially the 1.0-m/sec rate for simulators, two factors probably degrade landing performance to the extent that touchdown sink rates are not as low as thresholds for sink-rate detection. First, as Barnes[2] demonstrated, the effect of a threshold on a closed-loop control task is to degrade performance. The amplitude of performance oscillations is much larger than the threshold value, because of the effect of the dead band. A second source of performance degradation is the increased observational noise and higher thresholds caused by pitch, roll, and yaw fluctuations. The experimental situation used was conducive to concentrated observation, whereas the actual aircraft or simulator landing situation is not. The visual scene used, however, also may have lacked some salient cues for sink rate, such as pitch attitude and vertical acceleration. Heffley[6] developed a model of the flare maneuver and landing based solely on pitch attitude. The model replicated quite accurately the empirically observed dynamics of the landing. The thresholds found in the present experiment might have been lower if pitch attitude cues had been added to the scene. It is not possible from the results of this study to tell whether pilots in real landings use such cues in addition to direct sink-rate cues or in place of them.

One striking finding of this experiment was the large degree of individual differences seen. Figure 5 shows the threshold values of five of the pilots for the three conditions in which the time of sink was 2.3 sec. It can be seen from this that nearly an order of magnitude difference existed between the extremes in each condition. These differences existed in spite of the fact that all pilots held current FAA Medical Certificates attesting to their visual acuity. This may be indicative of a wide variation between pilots in strategy of observation. Perhaps some watched the runway edge lights, whereas others observed the centerline. This diversity is supported by the large differences between trials observed with virtually every subject. Figure 3 reveals this to some extent, in that there were some trials in which the subject correctly distinguished in a sink-rate difference of 0.28 m/sec and others in which a sink-rate difference of 0.42 m/sec could not be detected. Many sequences of trials included five or six pairs of consecutive correct responses followed by as many incorrect responses, and many other sequences included the reverse ordering of responses. It appears that even the very simple cues provided by the scene used in this experiment may have been so numerous as to allow a sizable effect of individual differences on the thresholds obtained.

There were three important variables that determined the nine conditions used in this experiment: 1) the sink rate of the simulated aircraft 2) the time elapsed during the descent portion of the trial, and 3) the change in height during the trial. The differences between mean values for each of the three sink rates were tested for significance by means of two-tailed t-tests. None of the three differences (0.30 vs 0.52 m/sec, 0.52 vs 0.90 m/sec, and 0.30 vs 0.90 m/sec were significant. The three differences between means for time-of-sink conditions were tested also. The differences between the 1.3- and 4.0-sec conditions and between the 2.3- and 4.0-sec conditions were both significant at the 0.05 probability level. This shows that, as time of sink increased, the ability to detect differences between sink rates improved. There are many possible explanations for this, such as 1) limitations of the pilots' ability to focus attention on the stimulus in a short period of time, and 2) the degrading effects on short-term memory of having trials presented as frequently as they were in the 1.3- and 2.3-sec conditions. In these short-time conditions, there was also a methodological phenomenon that may have elevated the thresholds. Two trials of a given pair always differed in sink rate and in time of sink and were always equal in height drop. The time of sink necessarily would have to be shorter for the trial during which the faster sink rate was presented in order to maintain equality of height drop between the two trials. When the pilot responded incorrectly, the next pair of trials would be 50% further apart in sink rate; thus one of the two trials would have a shorter time of sink than either of the two trials in the preceding pair. The poor thresholds in the 1.3- and 2.3-sec conditions could be explained by the inability to recognize even the sink portions of those trials in which the time of sink was very short. The mean threshold for each of the five height drops (0.4, 0.7, 1.2, 2.1, and 3.6 m) was compared by means of t-tests. Significance was obtained in several of the tests, but these are not reported because of the limited importance that they appear to have. Height drop during the trial was equal between the two trials of each pair, and so it seems highly unlikely that height drop could have any relationship to difference thresholds except as a correlate to the time of sink. It is presumed here that, since greater height drops were accompanied by longer times of sink, the time of sink actually was responsible for the significant differences between height-drop conditions.

Concluding Remarks

Thresholds for detection of a difference between two sink rates were found to be low relative to touchdown performance but high relative to velocity difference thresholds reported in psychophysical research. The results show that there was a considerable amount of observational noise in this simulator system. Time of sink and total height drop were found to affect difference thresholds, but sink rate itself did not affect the thresholds. Future research will attempt to develop an analytical model to relate these data on sink-rate difference thresholds to pilot performance during simulator touchdowns.

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