# N94-13313 

# Visual Cueing Aids for Rotorcraft Landings 

Walter W. Johnson<br>Rotorcraft Human Factors Research Branch<br>NASA Ames Research Center<br>Moffett Field, CA<br>Anthony D. Andre<br>Western Aerospace Laboratories, Inc.<br>NASA Ames Research Center<br>Moffett Field, CA


#### Abstract

The present study used a rotorcraft simulator to examine descents-to-hover at landing pads with one of three approach lighting configurations. The impact of simulator platform motion upon descents to hover was also examined. The results showed that the configuration with the most useful optical information led to the slowest final approach speeds, and that pilots found this configuration, together with the presence of simulator platform motion, most desirable. The results also showed that platform motion led to higher rates of approach to the landing pad in some cases. Implications of the results for the design of vertiport approach paths are discussed.


## INTRODUCTION

Rotorcraft landings in physically constrained environments, such as urban vertiports, present potential hazards not commonly faced by fixed-wing or rotorcraft landings at conventional airports. One major hazard is the presence of buildings or other obstructions beneath their glideslope and directly behind the landing pad. In such environments it is necessary for pilots to accurately maintain their assigned glideslope and to reliably regulate their speed so as to achieve zero velocity at the landing pad.

The present study examined the effect of different combinations of visual and motion information upon simulated descents to hover. Specifically, the study was designed to determine the effects upon performance and

Presented at Piloting Vertical Flight Aircraf: A Conference on Flying Qualities and Human Factors, San Francisco, California, 1993.
subjective ratings of 1) three approach lighting configurations, and 2) the presence/absence of simulator motion. It was also designed to explore how theoretically significant types of optical and motion information combine to yield different deceleration and glideslope profiles.

## Optical Cues For Speed Control

Pilots in aircraft and aircraft simulators require information in order to accomplish their tasks. However, selecting what information to supply the pilot is not easy, especially since many potential information sources are costly (e.g., simulator motion) and/or may not provide much benefit in terms of training effectiveness, performance or flight safety (Andre and Johnson, 1992). Understanding the pilots' reactions to optical information in the environment during flight and in piloted flight simulation can lead to improved visual approach training procedures and may have an impact on the design of heliport approach paths.

There are three important optical variables that a pilot could use to control speed during the descent to hover. Optical Expansion Rate is the relative rate of growth in the optical size of the landing pad, and is proportional to the vehicle velocity divided by distance to the pad (i.e., physical closure rate). This optical variable provides information useful for deceleration since maintaining its value at or below some critical positive value will ensure that the vehicle arrives at the landing pad with zero touchdown velocity, with lower values yielding more gradual decelerations. Further, this cue is insensitive to altutude deviations. Figure la shows how constancy of optical expansion rate requires speed to be proportional to distance-togo.

Optical Flow Rate is the angular velocity of surface elements in any one area of the field of view. This velocity in turn is proportional to vehicle velocity divided by the distance to the viewed surface, and is typically scaled in units of eye heights per second (Owen, Wolpert, and Warren, 1984). This is different from Optical Expansion Rate since that variable is defined with respect to contour expansion rate, while Optical Flow Rate is simply optical (angular) speed. When descending over a ground surface, deceleration can be governed by maintaining optical speed, at some locus in the field of view, at or below some critical positive value. (US Army training manuals instruct rotorcraft trainees to "make it look like a brisk walk" during landings. This is an explicit instruction to maintain a constant Optical Flow Rate). Figure lb shows how constancy of angular flow rate requires speed to be proportional to altitude.

Finally, there is Optical Edge Rate, the frequency at which optical elements pass through some visual locale (e.g., the lower portion of the windscreen). For descents over a surface this is proportional to vehicle velocity divided by the spacing between the elements on that surface. When the elements are spaced apart evenly, this yields a frequency that is directly proportional to speed. To the extent that information about true speed is important in managing decelerations, this variable may prove valuable for speed regulation. Figure lc shows how constancy of edge rate requires texture
elements and speed to be proportional to distance-to-go.

Previous research by Moen, DiCarlo and Yenni (1976) examined altitude, ground-speed and deceleration profiles of visual approaches for helicopters. One goal of their research was to define the mathematical relationships describing nominal visual deceleration profiles. However, the effects of visual cues in the environment were not examined. More recent research has specifically addressed the influence of visual environmental cues on vehicle deceleration control.

For example, Denton (1980), in a somewhat related context, examined the influence of ground texture spacing (i.e., optical edge rate information) on driver's control of forward speed. Using an automobile simulator, he found that gradually reducing the spacing between horizontal stripes on a simulated roadway surface resulted in drivers reducing their speed. He then applied this finding in a field study where he placed horizontal stripes with gradually reduced spacing across the roadway at a highway exit ramp. This resulted in a reduction of a previously high accident rated caused by excessive speeding upon exiting the highway to lower speed roads. Other research has shown edge rate and flow rate to have roughly equal impact on the perception of selfspeed (Larish and Flach, 1990; Owen et al., 1984).


Figure 1. Optical variables useful for controlling deceleration. a) constancy of optical expansion rate requires speed to be proportional to distance-to-go; b) constancy of angular flow rate requires speed to be proportional to altitude; c) constancy of edge rate requires texture elements and speed to be proportional to distance-to-go.

## Optical Cues for Glideslope Control

There are two important optical variables potentially useful for glideslope control: 1) Form Ratio the angular optical height of the pad divided by its optical width, and 2) aim point Declination Angle, the optical angle subtended between the center of the landing pad and the horizon. If the pilot acts to keep either of these constant after the glideslope intercept, then he will still be on the initial glideslope (see Lintern and Liu, 1991 and Mertens, 1981, for a more complete discussion of these variables). Similarly, pilots can maintain a constant glideslope by simply keeping the image of the landing pad at a fixed point below the horizon.

## THE PRESENT STUDY

The present study examined visual approaches in a rotorcraft simulator with various approach lighting configurations, under platform motion and non-motion conditions. These configurations were designed to highlight the utility of one or more of the three types of optical information about vehicle speed discussed above.

In one condition, only the landing pad itself, together with the horizon line, was visible. For control of speed, this makes available closure rate information in the form of the relative rate of the optical expansion of the landing pad surface itself. The reciprocal of this value, called tau, is the time to arrival at the landing pad if present vehicle speed is kept constant. By either maintaining relative closure rate information at a constant value, or by not allowing it to exceed some critical value, a pilot would be ensured of arriving at the pad with zero velocity.

A second condition added two rows of regularly spaced approach lights extending out from the edges of the landing pad. Now, in addition to the closure rate information mentioned above, the optical motion of the lights passing beneath the simulated vehicle provide information, in the form of optical flow rate and optical edge rate, about vehicle speed. For descents along a given glideslope, flow rate will be proportional to speed divided by altitude. By maintaining flow rate at a constant value, or not allowing it to exceed some critical value, one will ensure arrival at the landing pad with zero velocity. For descents over regularly spaced
ground elements, optical edge rate is proportional to speed, but does not afford the pilot any simple available optical strategy for ensuring arrival at the pad with zero velocity. Similarly, there is no simple or obvious optical cue associated with the approach lights that a pilot can use to judge glideslope.

Finally, a third condition added a middle row of lights to the second condition configuration. This middle row light spacing was proportional to distance from the pad, so that the lights were spaced half as far apart when the distance to the pad was decreased in half (i.e., exponential). Here, the pilot could hold the edge rate associated with this middle exponential light string at or below some fixed value, and thus ensure arrival at the landing pad with zero velocity.

The impact of simulator platform motion upon descents to hover was also examined in the present study. Previous research has shown that the presence of flight simulator motion appears to help performance, but not transfer to the aircraft (Koonce, 1979; Lintern, 1987). Our interest here was in assessing if simulator motion interacted with the utility of the approach light patterns under investigation.

## METHOD

## Design

Five factors were manipulated in the present study: 1) Flight Control Instruction (undirected and directed), 2) Simulator Motion (moving and fixed), 3) Approach Lighting Pattern (no lights, linear lights, and exponential +linear lights), 4) Initial Closure Rate (slow vs. fast--see Figure 2), and 5) Initial Range (near vs. far--see Figure 2). These variables were factorial crossed in a $2 \times 2 \times 3 \times 2 \times 2$ within-subjects design. Pilots performed 2 repetitions of each of the 48 unique factorial combinations for a total of 96 landing trials. An overview of the experimental design is shown in the top panel of Figure 2.

## Simulation Apparatus

All trials were performed in the Vertical Motion Simulator (VMS) at the NASA Ames Research Center. The VMS, shown in Figure 3, is a large motion-base simulator which utilizes a four-window computer-


$\alpha=G$ Id estope $=6 d e g$
$\beta=$ Look-down nngle $=15 \mathrm{~d} \oplus g$


Figure 2. Experimental Design. Description of Factorial Structure (top panel) and of Flight Profiles (bottom panel).


Figure 3. NASA's Vertical Motion Simulator
generated image system for displaying visual scenes to the pilot. The simulator was outfitted with a rotorcraft cab with conventional controls.

Vehicle Model. The experiment utilized a modified rotorcraft model with only two degrees of freedom: longitudinal and vertical. The three angles that describe the orientation of the vehicle and the lateral position were fixed at zero. Thus longitudinal velocity changes were achieved without pitching the aircraft. Physically, this situation would be realized with a helicopter that had an auxiliary $x$-force device to control longitudinal acceleration.

This simplification was made for several experimental reasons. First, since straight-in, decelerating approaches were of interest, the three lateral-directional degrees of freedom were unnecessary. Second, since the vertical field-of-view in the simulator was substantially less than in a typical helicopter, pitch-up maneuvers in simulation would result in a drastic loss of visual ground cues. Accordingly, to ensure that the approach lights
were always in view during the approach, pitch attitude and rate was held constant. The pilots had acceleration command in the longitudinal axis. Acceleration command was proportional to longitudinal center stick position, with a sensitivity of $5 \mathrm{f} / \mathrm{sec}^{2} / \mathrm{in}$. The longitudinal travel of the center stick was $+/-5$ in.

The vertical axis dynamics were more complicated than the longitudinal axis. The collective sensitivity and the aircraft's vertical damping depended upon airspeed. The aircraft was also given a steep power required curve, so that as the helicopter slowed, increased collective was required. The combination of these dynamics made the vehicle sufficiently challenging to fly, thereby inhibiting the pilots from flying the task open-loop (i.e., essentially flying the vehicle without regard to the visual cues). Pilot comments indicated that while the vertical axis exhibited helicopter-like qualities, the longitudinal axis did not (due to the lack of pitching required to change speed).

## Visual Landing Configurations

As shown in Figure 4, Three visual landing scenes were examined: 1) no approach lights with only a landing pad present (None); 2) the landing pad plus two linear strings of equally spaced lights leading up to the landing pad (Regular); and 3) the landing pad, the two linear strings, and an exponentially spaced string of lights (Exponential).


Figure 4. Approach light configurations.

Regular. The Regular configuration presented two rows of white approach lights in addition to a $100 \mathrm{ft} \times 100 \mathrm{ft}$ landing pad and the horizon. These lights were aligned with the sides of the landing pad, spaced either 23 ft or 46 ft apart (a manipulation of light density used to affect initial edge rate), and extended out 5000 ft from the landing pad. The lights at 1610 and 805 ft out were green, while the rest of the lights were white, and the pilots were instructed to intercept the glideslope when these lights passed out of view at the bottom of their windscreen. They were instructed to use the first set of green lights when flying at the higher altitude ( 278 ff ) and the second set of green lights when flying at the lower altitude ( 139 ft ). The left panel of Figure 4 depicts this lighting configuration. The bottom panel of Figure 2 shows how the combination of intitial altitiude and positions of the intercept lights combined to yield a $6^{0}$ glideslope capture.

None. This configuration was similar to the Regular configuration, but the approach lights were truncated at 805 ft from the pad for the 139 ft initial altitude, and 1610 ft from the pad for the 238 ft initial altitude. The pilots were told to intercept the glideslope when the last approach light passed out of view, and thus during the descent to hover only the landing pad and the horizon were visible. This configuration, depicted in the middle panel of Figure 4, does not provide either Optical Flow Rate or Edge Rate information, but provides all of the other information contained in the Regular configuration.

Exponential. This configuration was similar to the Regular configuration with the addition of a third row of lights aligned with the center of the landing pad. These extended out either 816 ft or 1609 ft (depending on initial altitude), and were exponentially spaced such that the inter-light spacing was 0 at the threshold of the landing pad, 53.9 ft at 816 ft , and 106 ft at 1609 ft for conditions using the high-density light spacing, and 106.9 ft and 212 ft for the low-density light spacing (inter-light separation divided by distance to the landing pad was approximately 0.066 ). (For the lowdensity spacing every other light in the Exponential light array was removed, so that
inter-light spacing divided by distance to the landing pad was approximately 0.132 ). In both cases the lights in the center row were continued, using the final spacing found at 816 or 1609 ft so that the pilots would already be using the lights when they intercepted the glideslope. The pilots were again instructed to intercept the glideslope when the appropriate set of green lights passed from view. This configuration, depicted in the right panel of Figure 4, provides all of the information contained in the regular configuration, plus the exponential string of lights makes it possible to reach zero velocity by maintaining an edge rate for this middle row at or below some critical value. As in the other examples, the lower this critical value the milder the deceleration.

## Procedure

Each landing trial consisted of a cruise phase and an approach phase. The cruise phase, which lasted approximately 10 seconds, did not require manual control as the vehicle maintained its initial level attitude. During this phase, a set of linear lights was present extending from the initial position to the glideslope intercept lights, regardless of the approach light condition (see Figure 4 above). This was done to allow the pilots to determine any altitude deviations due to the collective trim.

The approach phase began when the pilot crossed the glideslope capture position. This is the point where the green glideslope intercept lights just passed out of the lower field-of- view. At this point, the pilot was instructed to intercept the 6 deg glideslope down towards the center of the landing pad. The trial ended when the pilots reached a point approximately 15 ft AGL with the VTOL sign in their view.

The 96 experimental trials were completed over 4-6 sessions. Simulator motion and flight control instruction conditions were blocked between groups of 12 trials, while initial position and approach light pattern were counterbalanced and randomized within each block of 12 trials.

Following each trial, pilots were given feedback on their glideslope variation only.

Instruction. This task was performed under two sets of flight control instructions. In the undirected trials, the pilots were instructed to perform the approach in a way that was "comfortable" or "normal" for them. In the directed trials, the pilots were instructed to maintain a velocity profile that was proportional to their distance from the pad.

Subjective Ratings. Test pilots are trained to fly to some specified degree of performance and then judge difficulty in terms of the effort necessary to attain that degree of performance (e.g., Cooper-Harper Ratings). To this end test pilots generally want that level of performance to be made explicit (e.g., do not deviate more than $\pm 10 \mathrm{ft}$ in altitude). However, when exploring flight performance on tasks where no standardized measure of goodness exists, or even where it may be presumed to vary across pilots, this is a difficult method to implement.

In this situation we can only try to use the inverse method, and require pilots to fly to some fixed level of effort, and then have them judge difficulty in terms of what they see as good flight performance. This is what we required in this study, defining the level of effort as "flying as well as possible". Thus difficulty (which we called "doability" to focus the pilots on task constraints) was judged in terms of performance variations relative to this fixed high level of effort. In addition we also asked pilots to judge their own performance in terms that took into account the "doability" of the task. Thus, average performance on a difficult task should get the same performance rating as good performance on a more simple task. If the pilots could truly distinguish these ratings, then the performance ratings should not vary as a function of the doability ratings (i.e., task condition).

Pilots were asked to provide the two subjective ratings, each on a 7-point scale, following each trial. For the doability (difficulty) rating, we asked, "how difficult was the task, independent of how well you performed?" The performance rating was to be considered relative to the doability rating. Here we asked, "given the doability of the task, how well did you perform?"

Practice. Each pilot received a practice session of 12 landing trials under motion, undirected conditions. Before the practice session, each pilot was given a set of instructions which explained the various approach conditions and experimental procedures. In addition, the visual information afforded by each approach light pattern, in the form of edge rate and closure information, was described.

## Subjects

Six NASA helicopter test pilots participated in the experiment. Each had previous experience in the VMS.

## RESULTS

## Dependent Measures

Only the data from the undirected trials (where the pilots were free to choose their own approach speed) were analyzed to date.

Subjective Ratings. Prior to analysis normalized subjective difficulty and performance ratings ( $\mathrm{NR}_{\mathrm{i}}$ 's) were computed for each subject using the equation

$$
N R_{i}=\frac{R_{i}-M_{R}}{S D_{R}}
$$

where $R_{i}$ is the rating given by the subject, $M_{R}$ is the mean difficulty or performance rating given by that subject, and $S D_{\mathrm{R}}$ is the standard deviation of the ratings given by the subject. This transformation was used to adjust for individual differences in the amount of the rating scale used by the pilots to make their judgments.

Performance Data. For each trial the descent trajectory was divided into 100 foot segments beginning 2600 ft from the pad for the far initial range trials, and at 1300 ft from the pad for the near initial range trials. This yielded 26 segments in the first case and 13 segments in the latter case. Since no approach lights would have been within view, and final adjustments to hover position were not of immediate interest, data in the final segment was not included beyond the point at which the front of the landing pad was not visible. Within each
segment, mean velocity, glideslope, and closure rate were calculated.

## Subjective Ratings Analysis

A 2 (Replication) 22 (Initial Closure Rate) $\times 2$ (Initial Range) $\times 2$ (Motion) 33 (Approach Lighting) repeated measures analysis of variance (ANOVA) was used to analyze the Normalized Difficuity and Performance ratings.

The analysis of the Difficulty ratings yielded statistically significant main effects for Initial Range ( $F(1,4)=21.221, p=.01$ ) and for Motion $(F(1,4)=35.144, p=.004)$, and a statistically significant Range $x$ Approach Lighting interaction ( $\mathrm{F}(2,8)=10.533, \mathrm{p}=.006$ ). Figure 5 shows that the presence of approach lighting also led to the task being judged as easier, although follow-up tests showed that the differences between ratings of the Exponential and Regular lighting configurations were not statistically significant. It also shows that trials with longer Initial Ranges were judged as more difficult, particularly when approach lights were absent. This pattern is not surprising since, at longer ranges to the pad, the absolute (not relative) rates of optical expansion are lower, and therefore probably less discernible. Figure 6 shows that trials with a moving platform were reliably rated as being less difficult, although this was not a very large effect.

The analysis of the Normalized Performance ratings yielded a statistically significant main effect for Initial Closure Rate ( $\mathrm{F}(1,4)=9.97, \mathrm{p}=.034$ ) and a statistically significant Trial $x$ Initial Closure Rate $x$ Initial Range $\times$ Approach Lighting interaction ( $\mathbf{F}(2,8$ ) $=7.924, p=.013$ ). The effect of initial closure rate (not depicted) showed that the pilots rated their performance as lower on trials with high initial closure rates. The four way interaction is difficult to interpret.

Squared correlations of the Performance and Difficulty ratings yielded $\mathbf{r}^{2}$ measures of $.43, .43, .15, .10$, and .003 , showing that three of the five pilots succeeded well in keeping the estimates independent, while the other two had some problems in doing this. Together, these show that the pilots were moderately successful in separating task difficulty and performance contributions in making their judgements.


Figure 5. Average normalized difficulty ratings as a function of approach lighting and initial range for undirected descents to hover.


Figure 6. Average normalized difficulty ratings as a function of simulator platform motion for undirected descents to hover.

## Performance Analysis

2 (Replication) $\times 2$ (Motion) 3 (Approach Lighting) $\times 13$ (Segment) repeated measures multivariate analyses of variance (MANOVAs) were used to analyze glideslope and relative closure rate (i.e., ground approach velocity divided by distance-to-go) for the self-directed descents for each of the two initial closure rates in the near initial range condition. Similar analyses using 26 segments were conducted for the two initial closure rates in the far initial range condition. Where appropriate, HuynhFeldt adjusted degrees of freedom were used to compensate for correlated data in the repeated measures (due primarily to the correlation of measures between adjacent trajectory segments).

Glideslope Analysis. Table 1 shows all statistically significant ( $\mathrm{p}<.05$ ) effects on glideslope. In addition to significant variations in glideslope across Segments for all four types of descents (refer to Figure 2, top panel), there were also significant effects involving the Approach Lighting factor in all four types of descents, and significant effects of Motion in all but the Type $C$ descent.

Figures 7-10 show the glideslope profiles as a function of Motion (left panels) and Approach Lighting (right panels) for all four initial conditions. All figures also show an increase in glideslope with proximity to the landing pad (where distance-to-go approaches 0 ). This is not unexpected since an approach to hover at some distance above the landing pad will, necessarily, lead to increasing glideslopes as measured from the center of the landing pad. All four show the presence of motion yielded a higher glideslope during the final portions of the descent (upper panels), although this is not easily seen in the figures plotting height as a function of distance-to-go (lower panels). In addition, only the approaches from the farther range (types " B " and " D " descents-Figures 8
and 10) yielded statistically significant Motion $x$ Segment interactions.

The absence of approach lighting ("None" condition) led to consistently higher glideslopes in all four conditions, with no consistent direction to the difference in average glideslope of the Regular and Exponential Approach Lighting patterns (i.e., the Regular pattern led to a higher average glideslopes in conditions A and C , and a lower average glideslope in condition B , with the glideslopes for the two being about equal in condition D ).

Finally, there were two statistically significant interactions involving both Approach Lighting and Motion in Type B descents. These were an Approach Lighting $x$ Motion interaction, and an Approach Lighting $x$ Motion $x$ Segment interaction. Figure 11 shows that the two-way interaction was due primarily to motion leading to an increased glideslope in the presence of the Exponential pattern, and to a decreased glideslope without approach lighting. The three way interaction (not shown) was due to high variance across segments in the no lights condition.

Table 1. Statistically Significant Effects Upon Glideslope by Descent Type

| EFFECTS | Type A Descents | Type B Descents | Type C Descents | Type D Descents |
| :---: | :---: | :---: | :---: | :---: |
| Replication |  | $\begin{aligned} & F(1,4)=14.2 \\ & p=.0197 \end{aligned}$ |  |  |
| Lights | $\begin{aligned} & F(2,8)=10.5 \\ & p=.0058 \end{aligned}$ | $\begin{aligned} & F(2,8)=6.06 \\ & p=.025 \end{aligned}$ | $\begin{aligned} & F(2,8)=10.4 \\ & p=.0059 \end{aligned}$ |  |
| Path Segment | $\begin{aligned} & \mathrm{F}(2,15,8.59)=69.7 \\ & \mathrm{p}<.0001 \end{aligned}$ | $\begin{aligned} & F(1.58,6.3)=23.9 \\ & p=.0015 \end{aligned}$ | $\begin{aligned} & F(5.84,23.6)=120.3 \\ & p=<.0001 \end{aligned}$ | $\begin{aligned} & \mathrm{F}(2.16,8.62)=37.8 \\ & \mathrm{p}<.0001 \end{aligned}$ |
| Motion $\times$ Lights |  | $\begin{aligned} & \mathrm{F}(2,8)=5.1 \\ & \mathrm{p}=.0374 \end{aligned}$ |  |  |
| Motion x Segment |  | $\begin{aligned} & \mathrm{F}(3.75,14.98)=3.7 \\ & \mathrm{P}=.0293 \end{aligned}$ |  | $\begin{aligned} & F(5.96,23.84)=3.8 \\ & p=.008 \end{aligned}$ |
| Lights x Segment | $\begin{aligned} & \mathrm{F}(3.8,15.21)=3.97 \\ & \mathrm{p}=.0224 \end{aligned}$ |  |  | $\begin{aligned} & F(10.79,43.17)= \\ & 2.4 \\ & p=.021 \end{aligned}$ |
| Motion $\times$ Lights x Segment |  | $\begin{aligned} & F(6.51,26.06)=3.3 \\ & p=.0129 \end{aligned}$ |  |  |





Distance-to-Go (ft)


(8วр) adoโsəp!ŋ

(7) 7บริ! ${ }^{\circ} \mathrm{H}$




(ฮәр) әdo[səр!!ŋ


Distance-to-Go (ft)






(ภวр) วdoโsวp!!


- Fixed Base

(7コ) 7 บึ่เฉ


Figure 11. Glideslope as a function of approach lighting and platform motion for undirected Type $B$ descents.

Closure Rate Analysis. Table 2 shows all statistically significant ( $p<.05$ ) closure rate effects. Approach Lighting had a significant affect on closure rate for the Type A and Type D Descents, while Motion affected closure rate for both the Type B and Type D descents.

Figures 12-15 depict velocity (top panels) and closure rate (bottom panels) profiles as a function of Motion (left panels) and Approach Lighting (right panels) for all four descent types (refer to Figure 2, top panel). Similar to the findings for glidesiope control,
the Motion $x$ Segment interactions were statistically significant only for the descents from the longer initial ranges (Type B and D descents), although Figures 12-15 show that the presence of motion tended to yield higher closure rates towards the end of all descents. This dependence of closure rate upon initial range may be due to reasons similar to those suggested for the glideslope effects. That is, at the more extreme initial ranges, the pilots may have been more strongly influenced by the vestibular cues provided by motion and therefore responded less vigorously.

Only Type A and Type D descents yielded significant effects of lighting configuration upon closure rate, but the average final closure rate was lowest in the Exponential light configuration for all four initial conditions. Since the most critical impact of the Approach Lighting factor is upon closure rates closest to the landing pad, a follow-up 2 (Replication) $\times 2$ (Initial Closure Rate) $\times 2$ (Initial Range) $\times 2$ (Motion) $\times 3$ (Approach Lighting) repeated measures ANOVA was conducted using just the closure rate from the final segment. This yielded statistically significant interactions of Initial Closure Rate $x$ Initial Range ( $\mathrm{F}(1,4)=$ 0.04 ), Initial Closure Rate $\times$ Motion ( $\mathrm{F}(1,4)=$ 9.61, $\mathrm{p}=.036$ ), and Replication $\times$ Approach Lighting $(F(2,8)=6.346, p=.022)$.

Table 2. Statistically Significant Effects Upon Closure Rate

| EFFECTS | Type A Descente | Type B Descents | Type C Descent | Type D Descents |
| :---: | :---: | :---: | :---: | :---: |
| Lights | $\begin{aligned} & F(1.67,6.69)=7.09 \\ & P=.0249 \end{aligned}$ |  |  |  |
| Path Segment | $\begin{aligned} & F(1.58,6.31)=17.5 \\ & p=.0033 \end{aligned}$ | $\begin{aligned} & F(1.76,7.05)=14.47 \\ & p=.0037 \end{aligned}$ | $\begin{aligned} & F(1.34,5.34)=50.06 \\ & p=.0005 \end{aligned}$ | $\begin{aligned} & F(1.42,5.68)=33.37 \\ & P=.001 \end{aligned}$ |
| Motion $x$ Segment |  | $\begin{aligned} & F(5.43,21.73)=2.95 \\ & p=.0324 \end{aligned}$ |  | $\begin{aligned} & F(2.23,8.92)=4.99 \\ & n=.0 .327 \end{aligned}$ |
| Lighte $x$ Segment | $\begin{aligned} & F(9.63,38.54)=3.88 \\ & p=.0012 \end{aligned}$ |  |  | $\begin{aligned} & F(7.19,28.78)=4.40 \\ & p=.0019 \end{aligned}$ |

250 200
Approach Lighting

- Exponential \& Regular Spacing
- Regularly Spaced
- No Approach Lighting








Figure 14. Average Velocity and Closure Rate as a Function of Motion and Approach Lighting During Undirected Type 'C' Descents to Hover.



The top panel of Figure 16 shows that descents over shorter ranges led to smaller final closure rates that were unaffected by Initial Closure Rate, but that higher Initial Closure Rates led to higher final closure rates, especially for the descents from the farther Initial Range. The middle panel of Figure 16 shows that the presence of platform motion led to lower final closure rates for the lower Initial Closure Rate, but not for the higher Initial Closure Rate. Finally, the bottom panel of Figure 16 shows that the advantage of the exponential lighting configuration strongly increased in the second replication, suggesting that the pilots were still learning to use the information afforded by this configuration.


Figure 16. Final Closure Rate as a Function of Initial Closure Rate and Initial Range (top panel), Initial Closure Rate and Motion (middle panel), and Replication and Approach Lighting (bottom panel).

## DISCUSSION

Collectively, these results have shown that glideslope and speed control can both be affected by the patterm of approach lights to helipads, as well as the presence of platform motion.

## Approach Lights

The proposed impact of additional optical information afforded by the linear, and. to a greater degree, the exponential approach light configuration on control of deceleration was generally supported, although its effects tended to be confined to the most close in segments. This suggests that the effects of edge rate are most consequential during the final, and slowest, phase of the deceleration to hover. This may reflect an increased perceptual salience of this information in this phase, or perhaps more likely, a shift in relative emphasis, with pilots using the exponential pattern edge rate more during this phase.

The absence of approach lights also led to higher glideslopes, showing the influence of optical information in the linear and exponential approach light configurations other than form ratio and declination angle, since only these information sources were available in the nolight configuration. The specific nature of this beneficial information needs to be determined, but may reflect sensitivity to sink rate, since this will be heightened by having approach lights passing under the vehicle.

Finally, and perhaps not surprisingly, the pilots generally rated the linear and exponential + linear configurations as less difficult than the no lights configuration.

## Simulator Motion

Generally, the presence of platform motion led to slightly higher closure rates and glideslopes, although the pilots rated motion trials as less difficult than non-motion trials.

The effects of motion on glideslope performance suggest that, for longer ranges, motion may have led to an initial descent with an aimpoint substantially beyond the landing pad. At these longer ranges, vertical displacements lead to smaller changes in glideslope and thus to the visual information specifying glideslope. However, the detectibility of sink rate, as given by platform motion, is not as strongly affected by range to the pad. Thus, increased reliance on the vestibular cues may have led to these results.

The impact of Approach Lighting and Motion appears to be generally additive, except
for glideslope control during the Type B Descents. There, motion appeared to help most when visual cues were weakest (i.e., in the no lights configuration).

## Applications to Vertiport Design

The present findings may have important implications for the design of vertiport approach paths and other physically constrained landing sites. Specifically, they suggest that approach lights, or similar markings, that afford the pilot accurate edge rate information, might aid in regulating speed (and perhaps glideslope as well), especially as the pilot approaches the landing pad. An added and important benefit of such information is that it is a "natural" optical cue rather than an artificial information display. As such, abstracting the optical information should not require the attention of the pilot, leaving his/her attention to other aspects of the approach task.

## CONCLUSION

The present study used a rotorcraft simulator to examine descents-to-hover at landing pads with one of three approach lighting configurations. The impact of simulator platform motion upon descents to hover was also examined. The results showed that the configuration with the most useful optical information led to the slowest final approach speeds, and that pilots found this configuration, together with the presence of simulator platform motion, most desirable.

Future research should aim to generalize the current findings to actual flight conditions or to more complex simulated approaches.

## ACKNOWLEDGMENTS

The authors gratefully acknowledge Mr. Jeffrey Schroeder for his assistance with, and support of, this project. Thanks also to the staff of the NASA Ames Vertical Motion Simulator for providing the technical support for
this project. The second author was supported by Cooperative Agreement No. NCC 2-486 from the NASA Ames Research Center. Sandra Hart was the technical monitor.

## REFERENCES

Andre, A.D., and Johnson, W.W., Stereo effectiveness evaluation for precision hover tasks in a helmet-mounted display simulator. In Proceedings of the IEEE International Symposium on Systems, Man and Cybernetics, Vol. 2, Chicago, IL: IEEE, 1992

Denton, G.G., The influence of visual pattern on perceived speed, Perception, Vol. 9, 1980.

Koonce, J.M., Predictive validity of flight simulators as a function of simulator motion. Human Factors, Vol. 21, 1979.

Larish, J.F., and Flach, J.M., Sources of optical information useful for the perception of speed of rectilinear self-motion, Journal of Experimental Psychology: Human Perception and Performance, Vol. 16, 1990.

Lintern, G. and Liu, Y-T., Explicit and implicit horizons for simulated landing approaches, Human Factors, Vol. 33 (4), Aug. 1991.

Mertens, H.W., Perception of runway image shape and approach angle magnitude by pilots in simulated night landing approaches, Aviation, Space, and Environmental Medicine, Vol. 52, 1981.

Moen, G.C., DiCarlo, D.J., and Yenni, K.R, A parametric analysis of visual approaches for helicopters. NASA Technical Note TN D-8275, 1976.

Owen, D.H., Wolpert, L., and Warren, R. Effects of optical flow acceleration, edge acceleration, and viewing time on the perception of ego speed acceleration. NASA Scientific and Technical Information Facility 1984.

