JOURNAL OF AIRCRAFT
Vol. 37, No. 4, July–August 2000

Evaluation of a Motion Fidelity Criterion with Visual Scene Changes

Jeffery A. Schroeder*
NASA Ames Research Center, Moffett Field, California 94035
William W. Y. Chung†
Logicon Information Systems and Services, Moffett Field, California 94035
and
Ronald A. Hess‡
University of California, Davis, Davis, California 95616

An experiment examined how visual scene and platform motion variations affected a pilot's ability to perform altitude changes. Pilots controlled a helicopter model in the vertical axis and moved between two points 32-ft apart in a specified time. Four factors were varied: visual-scene spatial frequency, visual-scene background, motion-filter gain, and motion-filter natural frequency. Drawing alternating black and white stripes of varying widths between the two extreme altitude points varied visual-scene spatial frequency. The visual-scene background varied by either drawing the stripes to fill the entire field of view or by placing the stripes on a narrow pole with a natural sky and ground plane behind the pole. Both the motion-filter gain and natural frequency were varied in the motion platform command software. Five pilots evaluated all combinations of the visual and motion variations. The results showed that only the motion-filter natural frequency and visual-scene background affected pilot performance and their subjective ratings. No significant effects of spatial frequency or motion system gain were found for the values examined in this tracking task. A previous motion fidelity criterion was found to still be a reasonable predictor of motion fidelity.

Nomenclature

g	= gravitational acceleration, ft/s^2
$h, \dot{h}, \ddot{h}$	= altitude, rate, and acceleration, ft, ft/s, ft/s^2
$\ddot{h}_c$	= motion platform commanded acceleration, ft/s^2
h_{des}	= desired altitude, ft
K	= motion filter gain
n	= number of data points in each mean
p	= probability that effects are random
s	= complex variable, rad/s
δ_c	= collective lever position, in
ζ	= motion-filter damping ratio
ω_n	= motion-filter natural frequency, rad/s

Introduction

ALTHOUGH previous efforts have suggested and examined the requirements for helicopter flight simulators, it is acknowledged that much remains unknown.[1–7] In particular, if a simulator user wants to know precisely what visual and motion cues are needed to represent an in-flight task satisfactorily, rules of thumb are available based on experience. Only sparse data are at hand for their support. This situation has led to continuing controversy over the role of motion platforms, g-seats, texture, field of view, and many other visual and motion characteristics that contribute to simulator fidelity.

A previous study addressed motion platforms by developing a fidelity criterion in the vertical axis.[8] However, systematic visual-scene variations were not examined in that study. Because it is known that motion perception is affected strongly by the visual scene,[9] it is natural to believe that motion platform requirements need to be a function of the visual-scene characteristics. The purpose of this study was to determine if the previous motion platform criterion depends on an easily manipulated visual characteristic: visual spatial frequency. The number of repeating patterns per degree of visual angle measures this characteristic.[10]

With a realistic helicopter model five test pilots performed rapid 32-ft (9.7 m) altitude ascents and descents with six motion and six visual conditions. Included in the motion conditions was one in which the motion platform moved the same amount as the visual scene. In each visual scene constant-width horizontal black and white stripes were presented either across the entire field of view or on a board superimposed on a natural background. Stripe width was varied across the visual configurations. Pilots evaluated the handling qualities, motion fidelity, and the susceptibility to pilot-induced oscillations for all combinations of the visual and motion variations. Both objective and subjective data were analyzed.

Previous Relevant Research

To control altitude in a hovering helicopter, pilots likely use many feedbacks,[11] but they at least close the two outer loops shown in Fig. 1. The feedback of vertical rate of climb is important, as pilots are basically controlling vertical acceleration with collective position, and the feedback of only altitude to a collective command would result in a poorly damped closed-loop system.

Visual Research

Pilots must determine rate of climb from the available simulator cues. Although previous research has shown that estimates of rate of climb improve with addition of platform motion,[12] a variety of visual cues from the simulated scene predominate in the determination of speed, or here, rate of climb. Two of the most studied cues are visual flow rate and visual edge rate.[13–17]

Visual flow rate is the angular rate that an object moves in the visual scene. It is proportional to speed and inversely proportional to the distance from the contour or object. The number of contours or objects that pass by in a given time measures visual edge rate. It

Received 14 September 1999; revision received 7 January 2000; accepted for publication 14 January 2000.

*Deputy Chief, Flight Control and Cockpit Integration Branch, Army/NASA Rotorcraft Division. M/S 210-5. Associate Fellow AIAA.

†Deputy Site Director. M/S 243-6. Member AIAA.

‡Professor and Vice Chairman, Department of Mechanical and Aeronautical Engineering. Associate Fellow AIAA.

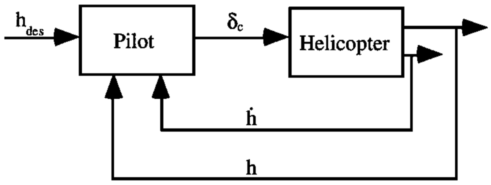


Fig. 1 Outer loops in altitude control.

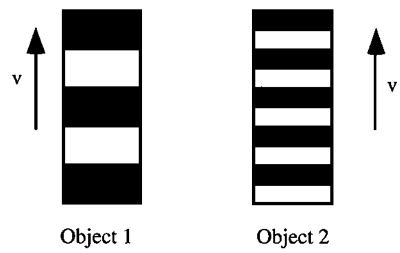


Fig. 2 Spatial frequency example.

is also proportional to speed, but it is inversely proportional to the object's size.

Studies have shown that some people inappropriately use edge rate when flow rate would be more appropriate,[13] some are more sensitive to one or the other,[14] some adapt over time,[15] and that the ability to switch between the two may not be consciously possible but may depend on unconscious perceptual skills.[16] The studies agree that both cues contribute to speed and acceleration perception, but edge rate may have a more pronounced effect.[17]

Figure 2 shows two objects placed at the same distance in front of an observer, and each object moves upward with a speed v. Object 2 has twice the spatial frequency of object 1, because its pattern repeats twice as often per degree subtended at the observer's eye. For the same speed v the edge rate provided by object 2 is twice that of object 1, but the flow rates provided by both are the same.

If observers gaze separately at one of the preceding objects, previous research indicates that the perceived velocity of object 2 will be greater than that of object 1 (Ref. 18). However, the perceived increase in velocity depends on the increase in spatial frequency. That is, object 2 will not seem to move twice as fast as object 1, even though the spatial frequency has been doubled. Specifically, Ref. 18 found a 31% increase in perceived velocity when the spatial frequency was doubled from 0.016 to 0.033 cycles/deg. When the spatial frequency was quadrupled (from 0.016 to 0.066 cycles/deg), the perceived increase in velocity was 240%. An additional result is that if the two objects moved at the same speed and had the same spatial frequency, the one covering the larger field of view seems to move more slowly.[18]

The preceding results are for a fixed gaze. If, instead, the eyes track the moving object, the perceived speed is less than with the eyes fixed. The disparity between the eye-tracked and the eye-fixed perception decreases as the spatial frequency decreases.[19] In fact, with an object consisting of a single edge, the disparity disappears.

Platform Motion Research

The effects of vertical platform motion on helicopters for tracking and disturbance rejection tasks were examined by Bray.[4] He concluded that the phase fidelity of the vertical acceleration cues should be accurate down to 1.0–1.5 rad/s. This conclusion was reached using several qualitatively different natural scenes, including tracking over a runway and behind a target aircraft.

Sinacori suggested a useful translational platform motion criterion based upon considerable experience by him and others in the simulation field.[3] That criterion compares the accelerations provided to the pilot by the motion platform against those produced by the simulation mathematical model. Taking a 1-rad/s math model acceleration as an input and the simulator platform acceleration at 1 rad/s as the resulting output, the relative attenuation and phase shift between these two signals is plotted.

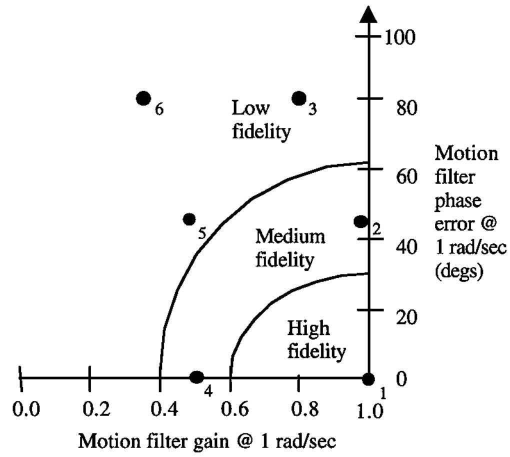


Fig. 3 Vertical motion criterion.

Figure 3 shows such a plot with the six-platform motion configurations examined in this study, as later discussed. Sinacori conducted a limited study to validate his suggested fidelity boundaries.[3] Reference 7 documents a detailed validation of the criterion and suggested modifications to the fidelity boundaries, which are those of Fig. 3. However, systematic variations in the visual cues were not made during the criterion's validation.

Summarizing the preceding previous visual and motion efforts, pilots use rate of climb to control altitude. Many different visual cues contribute toward their rate-of-climb estimate. Visual edge rate, which is directly proportional to spatial frequency, is an easily manipulated visual cue and seems to provide profound effects on velocity perception. Platform motion criteria have received considerable attention, but without systematically varying the visual cues. This experiment manipulated visual spatial frequency to determine if it affects the validity of a previous vertical motion criterion.

Experiment Description

Simulator Subsystems

Vehicle Math Model

The model was simplified intentionally to have a vertical degree of freedom only. This allowed pilots to focus on the vertical cues. The rate-of-climb transfer function was

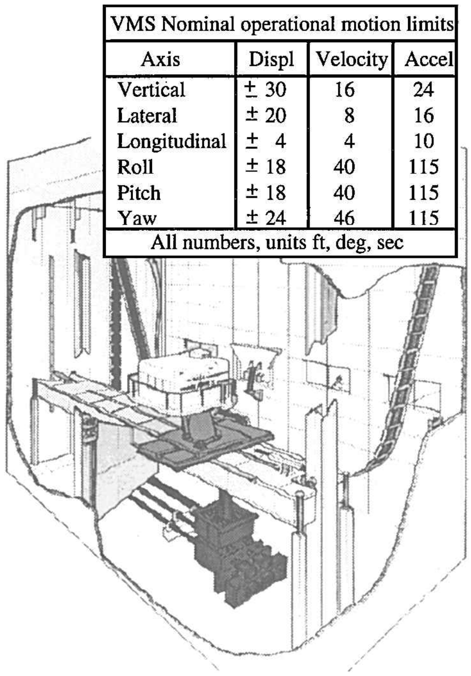
$$\frac{\dot{h}}{\delta_c}(s) = \frac{14.6(s + 4.82)}{(s + 0.122)(s + 12.9)} \tag{1}$$

This transfer function, with an additional 60 ms of equivalent time delay as discussed later, was identified directly from AH-64 Apache flight-test data and subsequently validated by AH-64 pilots.[20] The heave damping root at −0.122 is augmented by a lead lag to approximate the effect of dynamic inflow. All states in the other vehicle degrees of freedom remained zero. This linear model was perfectly suited for the perturbation task that was simulated, as described later, because it matched flight data more closely than any existing full-envelope component-level model.

Motion System

The vertical axis of the NASA Ames Vertical Motion Simulator (VMS), shown in Fig. 4, was used. Reference 21 gives a detailed description of the simulator and facility. The large vertical travel of the VMS allows pilots to fly reasonable altitude-repositioning tasks without any motion cue attenuation.

The phase response of the vertical-axis servo dynamics matches an equivalent time delay of 120 ms. As discussed just, Eq. (1) needs an additional 60 ms of time delay in order to be representative of the AH-64. Rather than insert this additional 60 ms in the math model, it was more than subsumed by the 120 ms of motion system delay. Thus, the visual and motion cues in the vertical axis of this AH-64 simulation had 60 ms more delay than would be expected in the actual vehicle.



VMS Nominal operational motion limits			
Axis	Displ	Velocity	Accel
Vertical	± 30	16	24
Lateral	± 20	8	16
Longitudinal	± 4	4	10
Roll	± 18	40	115
Pitch	± 18	40	115
Yaw	± 24	46	115
All numbers, units ft, deg, sec			

Fig. 4 Vertical Motion Simulator.

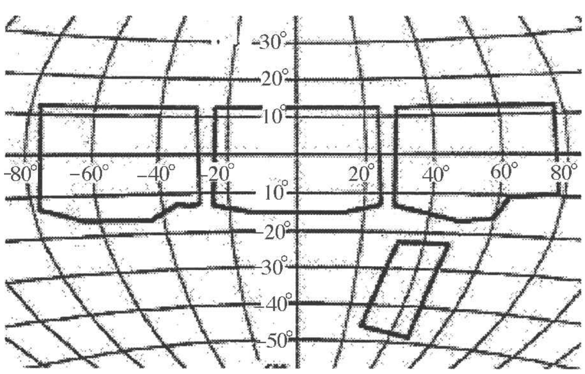


Fig. 5 Cockpit field of view.

A high-pass, or washout, filter calculated the command to the motion system from the vertical acceleration of the math model:

$$\frac{\ddot{h}_c}{\ddot{h}}(s) = \frac{Ks^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \tag{2}$$

Setting the gain K and natural frequency ω_n of the filter (the filter's damping ratio ζ is often left fixed) controls the amount of platform motion used during a simulation. Less motion is used as K decreases and ω_n increases. The predicted fidelity effect of changes in these two parameters can be found by finding the gain and phase shift of this filter at 1 rad/s and plotting the result on the Fig. 3 criterion.

Visual System

The experiment used the Evans and Sutherland ESIG 3000 image generator. A pure time delay was added to the nominal visual system time delay so that the total visual delay from stick input to image refresh was 120 ms. Thus, the visual and motion time delays were effectively identical.

The VMS's rotorcraft cab was used, but the visual scene was presented on only the top three windows (the chin window was not used in order to prevent the ground from being viewed in the "no background" visual case discussed later). The horizontal field of view spans ±78 deg, and the vertical field of view spans −16 to 12 deg for the upper three windows, as shown in the Fig. 5 Hammer chart. This available field of view is less than that in most actual helicopters.[4]

Table 1 Task performance standards

Segment	Desired	Adequate
Ascent	< 6 s	< 10 s
10 s at top	±2 ft	±5 ft
Descent	< 6 s	< 10 s
10 s at bottom	±2 ft	±5 ft

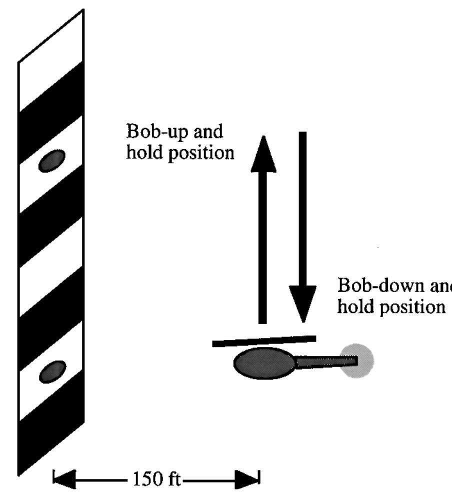


Fig. 6 Altitude repositioning task.

Cockpit

The only cockpit control was a left-handed collective from a UH-60 Black Hawk. This collective was freely moving (not spring loaded) with static friction that could be adjusted by the pilot. No instruments were present so that the pilot had to extract all cues from the motion system, the visual system, and the inceptor characteristics.

Subjects

Five pilots participated in the study. Four of the pilots were rotorcraft test pilots with extensive experience. The fifth pilot had minimal helicopter experience, but significant fixed-wing jet transport experience. Four pilots were from NASA Ames Research Center and one from the U.S. Army at Fort Rucker.

Task and Procedures

The task consisted of four segments, as illustrated in Fig. 6. Pilots started at a 45-ft (14 m) hover 150 ft (46 m) in front of a 4-ft-diam (1.2 m) red disk. The first segment was a 32-ft (9.7 m) ascent to the 4-ft-diam red disk at the top of the diagram. Pilots pushed a button with their right hand when initiating this first segment. After placing a set of crosshairs fixed on the canopy within the red disk and when confident that the crosshairs could be maintained within that disk, the pilots again pushed a button to start the second task segment. In this segment the pilot had to stabilize for 10 s, keeping the crosshairs within the red disk. The third segment was a 32-ft descent to the bottom red disk, again with button pushes beginning and terminating the reposition. The final segment was a 10-s stabilization keeping the crosshairs within the bottom disk.

The performance standards for each segment are given in Table 1. A set of colored lights on top of the cockpit panel indicated the performance to the pilots for each task segment. After completing the task, pilots assigned a motion fidelity rating (using the definitions in Table 2), a Cooper–Harper handling qualities rating,[22] and a pilot-induced oscillation (PIO) rating.[23] These ratings are not equivalent. For instance, a simulator can provide poor motion cues (poor motion fidelity rating) for a configuration that is still easy to fly (good handling qualities rating) and vice versa. Although the motion fidelity rating was the most important for this study, the other two ratings were collected to further probe the effects of each visual and motion configuration.

Table 2 Motion fidelity scale

Fidelity rating	Definition
High	Motion sensations are like those of flight.
Medium	Motion sensations are noticeably different from flight, but not objectionable.
Low	Motion sensations are noticeably different from flight and objectionable.

Table 3 Motion-filter configurations

Configuration	K	ω_n	Predicted fidelity from Ref. 7	Predicted fidelity for tracking only
1	1.0	0.00	High	High
2	1.0	0.52	Medium	Medium
3	1.0	0.89	Low	Low
4	0.5	0.00	Medium	High
5	0.5	0.52	Low	Medium
6	0.5	0.89	Low	Low

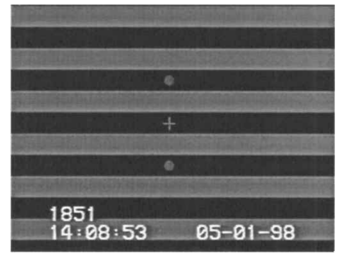


Fig. 7 Visual scene without background.

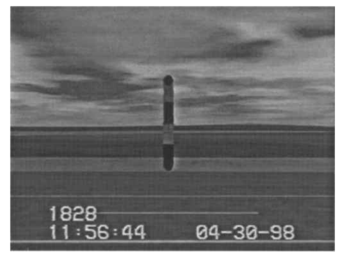


Fig. 8 Visual scene with background.

Configurations

The two variables K and ω_n for the motion filter of Eq. (2) were varied as shown in Table 3. The filter's damping ratio was held constant at 0.7. These values were selected to span a range of predicted motion fidelities per the criterion in Ref. 7, and each configuration number is plotted on Fig. 3. These predicted fidelities apply to tasks that have both tracking and disturbance rejection components. Here, no disturbances were present so that the task involved only tracking. For tracking-only tasks previous work has shown that the predicted motion fidelity is affected by motion-filter natural frequency, rather than by motion-filter gain.[4,7] As such, the predicted fidelity for the configurations with $K = 0.5$ would be expected to be that for $K = 1.0$ at each corresponding natural frequency. This is reflected in the last column of Table 3.

The amount of platform travel required for a particular filter depends upon the frequency content of the task. For the full motion configuration ($K = 1.0$, $\omega_n = 0.00$), if a pilot stays within the desired performance boundaries for the altitude reposition, the required platform travel would be 36 ft (32 ft between the two points plus 2 ft of allowed error at both ends). The amount of platform motion required for the other two configurations for which $K = 1$ was determined by randomly sampling 10 runs for each motion configuration and finding the range of platform motion used in each during the task. The mean and standard error of the travel required for the $K = 1$, $\omega_n = 0.52$ configuration was 19.0 ± 0.9 ft (5.8 ± 0.3 m) and for the $K = 1$, $\omega_n = 0.89$ configuration was 12.4 ± 0.8 ft (3.8 ± 0.2 m). When the gain K drops to 0.5, one-half of the preceding travels would be expected in each case.

Three stripe widths were tested: 2, 8, and 32 ft (0.6, 2.4, and 9.7 m). The vertical plane containing the stripes was 150 ft (46 m) in front of the pilot's eyes. These widths correspond to spatial frequencies of 0.65, 0.16, and 0.041 cycles/deg, respectively, as measured directly in front of the pilot's eyes.

The stripes were presented without and with a background, as shown in Figs. 7 and 8. The red disks, representing the ascent and descent end points, and the crosshairs are also shown in both figures. The position of the crosshairs indicates that the aircraft is centered between the two red disks. The numerals on Figs. 7 and 8 were not shown to the pilot.

Without the background the stripes covered the entire field of view across all three windows. With a background the stripes were on a vertical board 4 ft (1.2 m) wide. A sky and flat textured ground plane, including a runway (giving some familiar size cues), were behind this vertical board. The sky and ground plane projected into both side windows. Because the horizon is always level with the pilot's eyes, it cuts through the vertical board at that particular eye height. This provides a very compelling height cue. Also, with the background the visual scene was more natural appearing, and it was chosen as a configuration to break the monotony of flying against the laboratory-like scene without the background.

Even with this simple background scene, many additional visual cues for altitude and altitude rate become available. These cues include the additional visual flow rate from the contours on the ground, and angular size changes of the ground polygons, and the interposition cues arising from areas behind the vertical board appearing and disappearing during altitude changes. Reference 24 reported that pilots make effective use of the depression angles to lines that are orthogonal to the forward gaze in order to control altitude.

Specifying these cues quantitatively is more difficult than in the laboratory-like scene without a background, and no attempt was made to do so. Here we can only determine whether or not these additional cues had an effect on pilot performance or opinion.

Each of the five pilots evaluated the preceding four factors, which combine to give 36 configurations (2 motion-filter gains × 3 motion-filter natural frequencies × 3 spatial frequencies × 2 backgrounds). The configurations were randomized and unknown to the pilots.

Results

Both objective and subjective data were analyzed. The objective data consisted of the time to ascend and descend between the targets and the maximum error at the top and bottom targets. These four measures were examined because the pilot based the performance part of his subjective handling qualities rating on these four measures (Table 1). The subjective data analyzed consisted of the handling qualities ratings, motion fidelity ratings, and pilot-induced oscillation ratings.

To determine how both the objective and subjective measures depended upon the experimental manipulations, a repeated measures analysis of variance was performed.[25] Only the statistically significant results ($p < 0.05$) are reported. This means that the odds of being incorrect in saying a particular measure was affected by a particular manipulation (rather than the difference being caused by chance) is less than one in 20.

All of the subsequent plots are in a consistent format in that means and error bars indicating the standard error of the mean are plotted. The standard error of the mean provides a confidence band around the experimentally determined mean. The probability that the true mean of the entire pilot population lies outside twice the error bars is less than one in 20.

Objective Performance Data

Tracking Error at Upper Disk

Motion-filter natural frequency and scene background each affected tracking error at the upper disk. No interactions among the manipulations occurred.

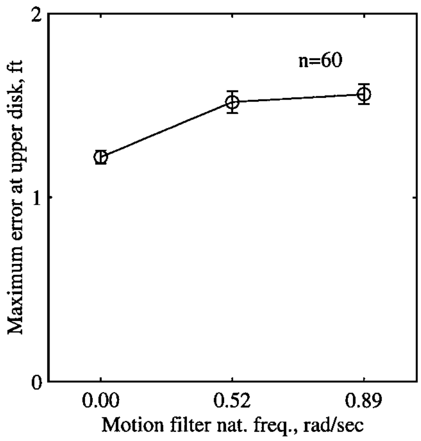


Fig. 9 Effect of motion filter ω_n on upper tracking error.

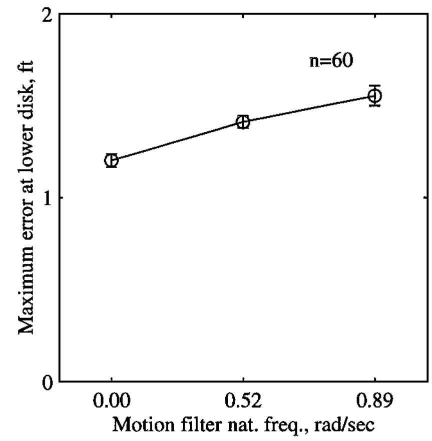


Fig. 11 Effect of motion filter ω_n on lower tracking error.

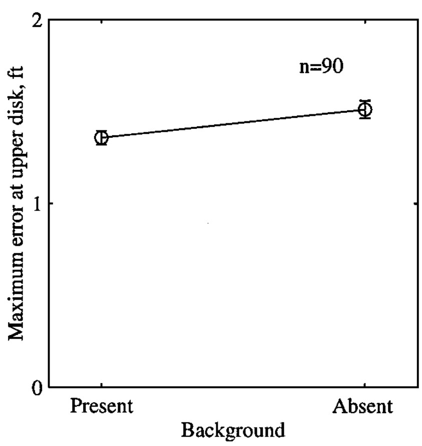


Fig. 10 Effect of scene background on upper tracking error.

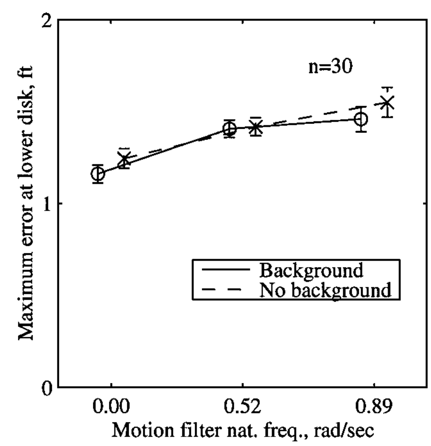


Fig. 12 Effect of motion filter ω_n and scene background on lower tracking error.

Figure 9 shows the means bounded by the standard errors of the mean for the maximum tracking error at the upper disk as the motion-filter natural frequency varied ($p = 0.003$). Here each mean is determined from the runs with motion-filter natural frequencies of 0.00, 0.52, and 0.89 rad/s, respectively, regardless of the other manipulations, because no interactions were found in the statistical analysis. So, it can be said that the motion filter natural frequency affected tracking error independent of the other variables in the experiment. As indicated, there are 60 points used for each mean (5 pilots × 2 motion-filter gains × 3 spatial frequencies × 2 scene backgrounds).

All means were in the ±2 ft (±0.6 m) desired performance range about the center of the disk (Table 1). Tracking error degraded as the natural frequency of the filter increased. This is consistent with previous results, which have shown that the distortion introduced by the motion-filter natural frequency reduces the phase margin of the tracking loop, which in turn negatively impacts the closed-loop damping ratio of the pilot-vehicle system.[4,7] More overshoots occur, and larger maximum tracking errors then follow.

Figure 10 shows that the presence of a visual background also influenced tracking error ($p = 0.017$). Although having the stripes span the entire field of view provided extremely precise altitude and altitude rate information, pilots performed slightly worse overall without the background vs with it. Although Ref. 13 showed that perceived speed becomes slower as the stimulus field becomes larger, more than just stimulus field size varied here. As discussed earlier, pilots also received additional altitude and speed cues from having the natural background. In addition, the presence of the horizon line always showing the pilot's height relative to the vertical board was likely a compelling and precise altitude cue.

Tracking Error at Lower Disk

Motion-filter natural frequency was a main effect for the tracking at the lower target. However, in addition, a two-way interaction occurred among motion-filter natural frequency and background presence.

Figure 11 shows the effect of motion-filter natural frequency ($p = 0.003$). Again, tracking error degraded as motion-filter natural frequency increased as with the upper disk. The interaction is shown in Fig. 12 ($p = 0.031$), but the interaction does not appear particularly strong. The error appears to perhaps be worse in going from 0.00 to 0.52 rad/s with the background scene than without the background and vice versa when going from 0.52 to 0.89 rad/s.

One may ask why motion-filter gain did not affect the tracking error in this experiment. The fact that no gain effects were revealed is consistent with previous results in Refs. 4 and 7. Because this was a tracking task in which the pilot generates all of his or her motion, the effect of motion-filter gain is not an influence for vehicles with reasonable control sensitivities. It is when a disturbance rejection task is added, in which the pilot does not generate all of the motion, that motion-filter gain has an effect.[4,7]

As to why spatial frequency did not have an effect on tracking error is unknown. Perhaps a large enough range in spatial frequency was not examined. Or, pilots may have been able to extract sufficient velocity cues using the angular rate of the edges as opposed to using the edge rate of the objects.

The other two objective performance measures in the task were time to ascend and descend between the targets. No statistically significant effects were found in going to the upper target, but a three-way interaction among motion-filter gain, motion-filter natural frequency, and spatial frequency occurred when going to the

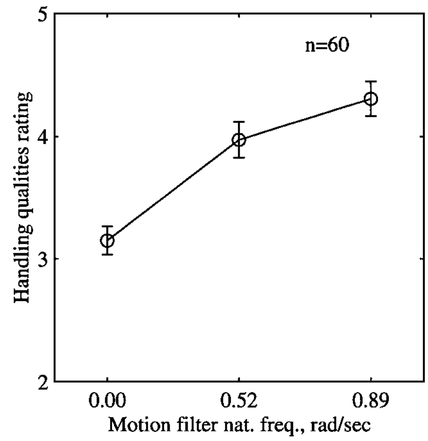


Fig. 13 Motion filter ω_n effect on HQRs.

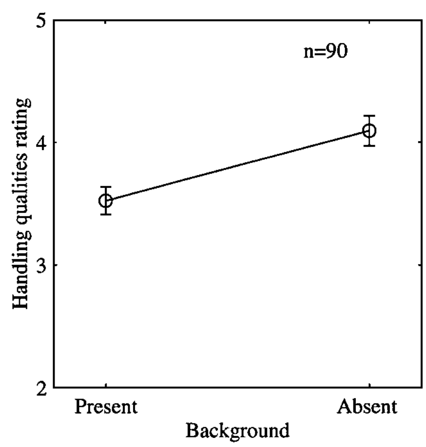


Fig. 14 Effect of scene background on HQRs.

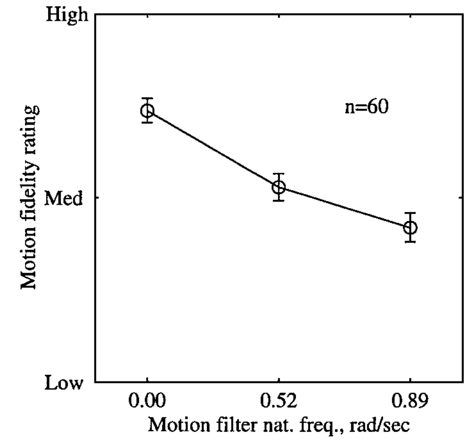


Fig. 15 Effect of motion filter ω_n on motion fidelity rating.

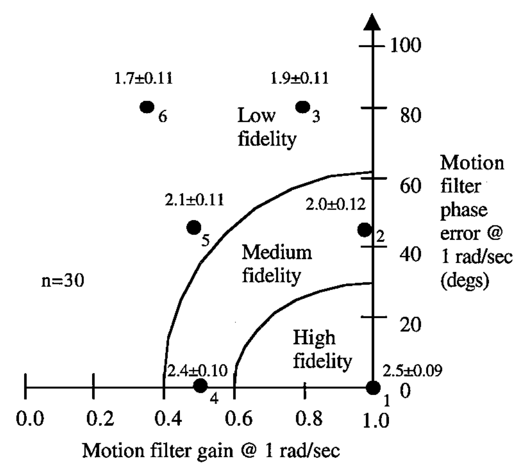


Fig. 16 Predicted vs actual motion fidelity.

lower target ($p = 0.005$). Plots of this complex interaction did not reveal any interpretable trend.

Subjective Performance Data

Handling Qualities Ratings

Motion-filter natural frequency and the visual background again were the main effects. Also, a three-way interaction among motion-filter gain, motion-filter natural frequency, and visual background occurred ($p = 0.032$).

Figure 13 shows that the motion-filter natural frequency affected handling qualities ratings ($p = 0.001$). As the natural frequency increased, the handling qualities degraded one point from just over three to slightly over four. Only the natural frequency of 0.00 rad/s received level 1 ratings on average.

Figure 14 shows that the handling qualities ratings (HQRs) were better with the visual background than without it ($p = 0.014$). However, the mean differences were not as great as the variations caused by motion-filter natural frequency. Because desired performance, on average, was achieved by the tested configurations, the differences in HQRs were attributed to variations in the required pilot compensation.

Motion Fidelity Ratings

As with the HQRs, motion-filter natural frequency and the visual background were the main effects on motion fidelity ratings. Figure 15 shows that motion fidelity degraded as the motion-filter natural frequency increased ($p = 0.002$). A motion-filter natural frequency of 0.00 resulted in a mean rating between high and medium. When increased to 0.52 rad/s, the average rating was medium, and that rating decreased to below medium for the highest natural frequency tested. As discussed when the motion fidelities were predicted in Table 3, motion-filter natural frequency is the primary determinant of motion fidelity for tracking tasks without a disturbance rejection component. For the three natural frequencies tested one would expect the motion fidelities to be nearly high, medium, and low, for 0.00, 0.52, and 0.89 rad/s, respectively. Here, the 0.52-rad/s case was exactly as predicted. The 0.00-rad/s case was on the borderline between high and medium. The 0.89-rad/s case was worse than the 0.52-rad/s configuration, but did not receive average ratings of low, as the criterion would predict.

Figure 16 repeats the criterion shown in Fig. 3 but with the means (and their standard error) of the data for each of the six motion configurations added. These means arise from assigning numbers to the ratings as follows: low = 1, medium = 2, and high = 3. So, for the averages it is reasonable to draw dividing lines between the fidelity regions to be: low ≤ 1.5, $1.5 \leq$ medium ≤ 2.5, and $2.5 \leq$ high. Recall from the discussion of Fig. 3 that the criterion applies to tasks combining tracking and disturbance rejection. If only tracking was performed, as was the case here, then gain variations normally do not affect fidelity. Figure 16 shows this to be the case. Configurations 1, 2, 4, and 5 are in excellent agreement with the preceding discussion (which is effectively consistent with the discussion of Fig. 15). Data for configurations 3 and 6 did not agree with the criterion's prediction, although configuration 6 is nearing low fidelity. Also motion-filter gain may be having a slight effect at this high level of phase distortion. So, it can be plausible to raise the medium-to-low fidelity border near the criterion's y axis in light of these results.

As shown in Fig. 17, the presence of a background improved perceived motion fidelity ($p = 0.046$). This result is somewhat surprising. One might expect no difference between having or not having the natural visual background present, as the rating is a motion fidelity rating. Yet pilots rated the no-background case as having poorer motion fidelity. Perhaps the lack of any real world

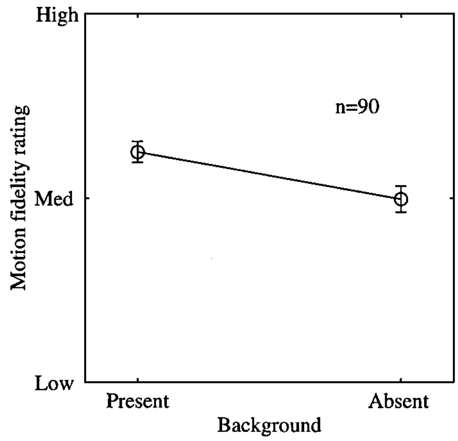


Fig. 17 Background effect on motion fidelity rating.

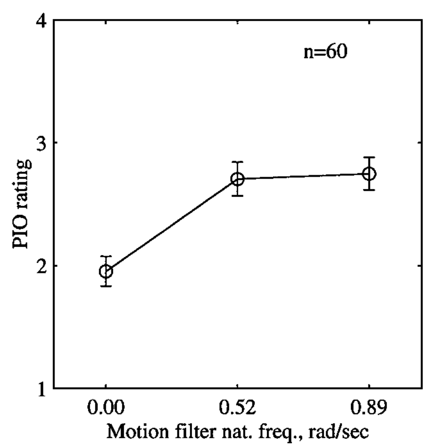


Fig. 18 Effect of motion filter ω_n on PIO rating.

objects (such as the runway) without the background made the determination of how the vehicle was actually moving more difficult. This difficulty may have affected their impression of the motion fidelity.

PIO Ratings

Only motion-filter natural frequency affected this measure, as shown in Fig. 18 ($p = 0.023$). Less of a tendency for a PIO occurred for a motion-filter natural frequency of 0.00 than for either 0.52 or 0.89 rad/s. Platform motion has previously been shown to affect PIO ratings.[26] Here, poorer motion made the configurations more PIO prone.

Conclusions

A piloted simulation evaluated the effects of changes in platform motion, visual-scene spatial frequency, and visual-scene background in an altitude control task for a helicopter. Pilots controlled only altitude and had to accurately move between two points 32 ft (9.7 m) apart within a specified time. Six motion configurations were tested that included one configuration in which the pilot physically moved the full 32 ft required in the task. Three spatial frequencies and the presence or lack of a natural visual background were evaluated.

As motion-filter natural frequency increased, tracking error, HQR, motion fidelity rating, and PIO rating degraded. No statistically significant effects of motion-filter gain changes were found on the preceding measures. These results are consistent with previous data on tracking tasks without disturbances. However, at the highest level of motion-filter phase distortion tested there was some indication the motion-filter gain might be a factor.

When a natural sky-Earth background was included in the visual scene, tracking error, HQR, and motion fidelity rating improved. Motion fidelity changed slightly when the background was added; however, these changes were small compared to the motion-filter effects.

No effects of the spatial frequency variations were found. Because pilots were a fixed horizontal distance from the object on which the spatial frequency variations were made, perhaps they instead used visual flow rate (angular rate) of the elements in the visual scene. For a particular vehicle velocity this flow rate does not change when the spatial frequency changes as long as a fixed distance from the object is maintained.

Overall, the motion fidelity criterion was a good predictor of fidelity including these visual-scene variations. This was especially the case for platform motion filters with low-to-moderate levels of phase distortion. When the motion filter had a high gain and high phase distortion, the criterion underpredicted the fidelity, and adjustment of its boundaries may be warranted.

Recommendations

Three values of spatial frequency were examined in this experiment. Future experiments should evaluate a wider range, perhaps focusing on larger, rather than smaller spatial frequencies. The lowest value tested here was 0.041 cycles/deg, and such values would seem to be easily achievable by any modern flight simulator visual system. Thus, it would seem little value would gained by testing even lower spatial frequency values.

Also, the variation in visual-scene backgrounds here was qualitative rather than quantitative. Additional systematic visual-scene variations should be measured and examined to determine what influence they might have on motion fidelity criteria. These effects should be examined in disturbance rejection tasks and tracking tasks.

References

[1]"Helicopter Simulator Qualification," Federal Aviation Administration, U.S. Department of Transportation, Advisory Circular AC 120-63, Washington, DC, Oct. 1994.

[2]Heffley, R. K., Clement, W. F., Ringland, R. F., Jewell, W. F., Jex, H. R., McRuer, D. T., and Carter, V. E., "Determination of Motion and Visual System Requirements for Flight Training Simulators," U.S. Army Research Inst. for the Behavioral and Social Sciences, TR 546, Alexandria, VA, Aug. 1981.

[3]Sinacori, J. B., "The Determination of Some Requirements for a Helicopter Flight Research Simulation Facility," NASA CR 152066, Sept. 1977.

[4]Bray, R. S., "Visual and Motion Cueing in Helicopter Simulation," NASA TM 86818, Sept. 1985.

[5]Cross, K. D., and Gainer, C. A., "An Enumeration of Research to Determine the Optimal Design and Use of Army Flight Training Simulators," U.S., Army Research Inst. for the Behavioral and Social Sciences, TR 763, Alexandria, VA, Oct. 1987.

[6]Boldovici, J. A, "Simulator Motion," U.S. Army Research Inst. for the Behavioral and Social Sciences, TR 961, Alexandria, VA, Sept. 1992.

[7]Schroeder, J. A., "Helicopter Flight Simulator Motion Platform Requirements," NASA TP-208766, July 1999.

[8]Schroeder, J. A., "Evaluation of Simulation Motion Fidelity Criteria in the Vertical and Directional Axes," *Journal of the American Helicopter Society*, Vol. 41, No. 2, 1996, pp. 44–57.

[9]Young, L. R., "Visually Induced Motion in Flight Simulation," *Piloted Aircraft Environment Simulation Techniques*, CP-249, AGARD, 1978, pp. 16-1–16-8.

[10]Goldstein, E. B., *Sensation and Perception*, Brooks/Cole, Pacific Grove, CA, 1989, pp. 68, 69.

[11]Hess, R. A., and Malsbury, T., "Closed-Loop Assessment of Flight Simulator Fidelity," *Journal of Guidance, Control, and Dynamics*, Vol. 14, No. 1, 1991, pp. 191–197.

[12]Johnson, W. W., and Schroeder, J. A., "Visual-Motion Cueing in the Control of Altitude," *Proceedings of the IEEE International Conference on Systems, Man, & Cybernetics*, IEEE, NY, 1995, pp. 2676–2689.

[13]Denton, G. G., "The Influence of Visual Pattern on Perceived Speed," *Perception*, Vol. 9, No. 4, 1980, pp. 393–402.

[14]Owen, D. H., Wolpert, L., and Warren, R., "Effects of Optical Flow Acceleration, Edge Acceleration, and Viewing Time on the Perception of Egospeed Acceleration," Air Force Human Resources Lab., AFHRL TP-84-4, Williams AFB, AZ, Nov. 1984.

[15]Shinar, D., Rockwell, T. H., and Malecki, J. A., "The Effects of Changes in Driver Perception on Rural Curve Negotiation," *Ergonomics*, Vol. 23, No. 3, 1980, pp. 263–275.

[16]Johnson, W. W., and Awe, C. A., "The Selective Use of Functional Optical Variables in the Control of Forward Speed," NASA TM 108849, Sept. 1994.

[17]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, No. 2, 1990, pp. 295–302.

[18]Diener, H. C., Wist, E. R., Dichgans, J., and Brandt, T., "The Spatial Frequency Effect on Perceived Velocity," *Vision Research*, Vol. 16, No. 2, 1976, pp. 169–176.

[19]Dichgans, J., Wist, E., Diener, H. C., and Brandt, T., "The Aubert-Fleischl Phenomenon: A Temporal Frequency Effect on Perceived Velocity in Afferent Motion Perception," *Experimental Brain Research*, Vol. 23, No. 5, 1975, pp. 529–533.

[20]Schroeder, J. A., Tischler, M. B., Watson, D. C., and Eshow, M. M., "Identification and Simulation Evaluation of a Combat Helicopter in Hover," *Journal of Guidance, Control, and Dynamics*, Vol. 18, No. 1, 1995, pp. 31–38.

[21]Danek, G. L., "Vertical Motion Simulator Familiarization Guide," NASA TM 103923, May 1993.

[22]Cooper, G. E., and Harper, R. P., Jr., "The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities," NASA TN D-5153, April 1969.

[23]Smith, R. E., "Effects of Control System Dynamics on Fighter Approach and Landing Longitudinal Flying Qualities—Volume I," Air Force Flight Dynamics Lab., AFFDL-TR-78-122, Wright–Patterson AFB, OH, March 1978.

[24]Johnson, W. W., and Phatak, A. V., "Optical Variables and Control Strategy in a Visual Hover Task," *Proceedings of the IEEE International Conference on Systems, Man, & Cybernetics*, IEEE, NY, 1989, pp. 719–724.

[25]Myers, J. L., *Fundamentals of Experimental Design*, Allyn and Bacon, Boston, 1972, pp. 167–190.

[26]Schroeder, J. A., Chung, W. W. Y., Tran, D. T., Laforce, S., and Bengford, N. J., "Pilot-Induced Oscillation Prediction with Three Levels of Simulation Motion Displacement," AIAA Paper 98-4333, *Proceedings of the AIAA Atmospheric Flight Mechanics Conference*, AIAA, Reston, VA, 1998, pp. 390–400.