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Effect of Simulator Motion on Pilot Behavior and Perception

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A set of experiments were conducted on the University of Toronto Institute for Aerospace Studies flight research simulator to determine the effects of translational and yaw motion on pilot performance, workload, fidelity, pilot compensation, and motion perception for three helicopter yaw control tasks. The three control tasks were a yaw capture, a disturbance rejection task, and a tracking task. The yaw capture experiment was a duplication of an experiment previously run at a different simulator facility. The results of the yaw capture task were in general agreement with the previous study with the exception that, in the current study, yaw motion had a larger impact on pilot performance than the previous study. The current study found that translational motion improves performance and increases fidelity for all three tasks. Yaw motion increased performance for the yaw capture and disturbance rejection tasks. Translational motion generally improved fidelity and was easier to detect than yaw motion for all three tasks. Finally, if translational motion was present, the addition of yaw motion usually provided little additional benefit to performance, workload, compensation, or fidelity for all three tasks.

Nomenclature

f_x^p = specific force at pilot's location in x-direction of pilot body frame, ft/s^2
f_y^p = specific force at pilot's location in y-direction of pilot body frame, ft/s^2
$\mathrm{HP}_{1\mathrm{st}}(s)$ = first-order high-pass filter transfer function
$\mathrm{HP}_{2\mathrm{nd}}(s)$ = second-order high-pass filter transfer function
K = washout filter gain
L = rotor radius, ft
$\mathrm{LP}(s)$ = second-order low-pass filter transfer function
p = probability that null hypothesis is true, standard repeated measures analysis
p^{**} = probability that null hypothesis is true, mixed model analysis
$S(s)$ = shaping filter transfer function
s = Laplace variable
U_0 = mean velocity of wind, ft/s
w = Gaussian white noise source
δ_p = pedal displacement, in
ζ = washout filter damping ratio
σ = standard deviation of wind velocity, ft/s
ψ = vehicle yaw angle, rad
$\dot{\psi}$ = vehicle yaw rate, rad/s
$\ddot{\psi}$ = vehicle yaw acceleration rad/s^2
$\dot{\psi}_c$ = simulator motion base yaw rate command, rad/s
$\dot{\psi}_s$ = simulator motion base response, rad/s
ω = washout filter break frequency, rad/s

Introduction

PREVIOUS research has demonstrated that for difficult control tasks, motion improves pilot performance [1,2]. The necessity and required fidelity of such motion, however, is still the subject of some debate. Of particular concern in this study is the effect of lateral and yaw motion on helicopter yaw control tasks. Meiry [3] found that the pilot time delay in a yaw disturbance rejection task was reduced by 0.1 s when yaw motion was present. Two later studies by Schroeder [4,5], found that simulator yaw motion had no effect on pilot performance or pilot opinion, particularly when translational motion was present. The first study consisted of a disturbance rejection task and the second a yaw repositioning task. In an attempt to determine the motion requirements for helicopter simulators and address the contradictory findings of the previous yaw studies, Schroeder [6] performed a series of helicopter motion experiments in several degrees-of-freedom using a representative helicopter model. For a yaw capture experiment, simulator lateral motion (which resulted from yawing about a point 4.5 ft behind the pilot) significantly improved pilot control performance, subjective handling qualities rating, and pilot impression of motion fidelity. In contrast, simulator yaw motion showed no significant benefit. In the same study, lateral motion also significantly improved pilot performance, subjective handling qualities, and motion fidelity for a pseudorandom disturbance rejection task and for a 180 deg hover turn. Again, yaw motion showed no significant benefit.

In 2003, Hosman et al. [7] demonstrated that Hosman's descriptive pilot model could generate results that compared well with Schroeder's yaw capture experiment. Furthermore, for the same helicopter model, the descriptive pilot model predicted an improvement in pilot performance with the addition of lateral and yaw motion for a disturbance rejection task. For a disturbance rejection task, Hosman et al.'s predictions and the results of Meiry's experiment appear to be in disagreement with the experimental results of Schroeder; unfortunately, significant differences in vehicle

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Table 1 Motion filter parameters

		No motion		Translational		Yaw		Trans. + Yaw	
		UTIAS	NASA	UTIAS	NASA	UTIAS	NASA	UTIAS	NASA
Lateral filter	K	0	0	0.98	1.0	0	0	0.98	1.0
	Order	——	——	2	2	——	——	2	2
	ω (rad/s)	——	——	0.05	10^{-5}	——	——	0.05	10^{-5}
	ζ	——	——	1	0.7	——	——	1	0.7
Yaw Filter	K	0	0	0	0	0.98	1.0	0.95	1
	Order	——	——	——	——	1	2	1	2
	ω (rad/s)	——	——	——	——	0.01	10^{-5}	0.01	10^{-5}
	ζ	——	——	——	——	——	0.7	——	0.7
Long. filter	K	0	0	0.98	1.0	0	0	0.98	1
	Order	——	——	2	2	——	——	2	2
	ω (rad/s)	——	——	0.2	10^{-5}	——	——	0.2	10^{-5}
	ζ	——	——	0.7	0.7	——	——	0.7	0.7

dynamics, motion base dynamics, and disturbance properties prevent direct comparison of the experimental results. Given the lack of agreement in the literature, an experiment was run to gather additional data on the usefulness of simulator translational and yaw motion.

The purpose of this study is to investigate whether translational and yaw motion in a helicopter simulator produce significant improvements in pilot performance, subjective handling qualities, or perceived fidelity for three different yaw control tasks. Because the study is an extension of Schroeder's experiment, and it is being conducted at a different facility, benchmarking the simulator by repeating the original experiment was considered prudent. Similar findings would increase the reliability of both studies. The first part of the study is therefore a duplication of the yaw capture experiment by Schroeder [6]. The second and third parts of the study are new experiments that examine the effects of motion for a yaw disturbance rejection task and a yaw tracking task.

Experimental Setup

Vehicle Model

The linear vehicle model, describing the yaw response of the helicopter about it center of mass to pedal inputs is

$$\frac{\psi}{\delta_p} = \frac{0.494}{s(s+0.27)} \tag{1}$$

This model is identical to the representative math model for an unaugmented AH-64 Apache helicopter in hover described by Schroeder, when only pedal inputs are considered. The helicopter model only yaws about it center of mass. The pilot location is 4.5 ft in front of the center of rotation so the specific forces at the pilot location in the body frame of the pilot are

$$f_x^p = -4.5\dot{\psi}^2 \qquad f_y^p = 4.5\ddot{\psi} \tag{2}$$

Simulator Motion

The University of Toronto Institute for Aerospace Studies (UTIAS) flight research simulator consists of a multipurpose cab mounted on a CAE 300 series Stewart platform. Grant describes the motion characteristics of the system in detail [8]. For the current study the simulator reference point (the point about which motions are to be simulated) was placed at the pilot's location, thereby allowing pure rotational motion at the pilot's location. Because the bandwidth of the UTIAS system is significantly greater than the NASA VMS system employed by Schroeder, a shaping filter was inserted in series, between the helicopter dynamics and the UTIAS motion system. The lateral and yaw dynamics of the NASA VMS motion system[‖] can be approximated as (see [4])

$$\frac{\dot{\psi}_s}{\dot{\psi}_c} = \frac{11^2}{s^2 + 2(0.6)(11)s + 11^2} \tag{3}$$

Because a reduced -order approximation was not available for the UTIAS simulator, a trial and error procedure was used to find a shaping filter such that the combined response of the UTIAS motion system and shaping filter closely matched the low-order approximation of the NASA VMS. The following shaping filter was selected:

$$S(s) = \frac{10^2}{s^2 + 2(0.6)(10)s + 10^2}\,\frac{0.08s+1}{0.001s+1} \tag{4}$$

This filter was applied to the yaw, lateral, and longitudinal degrees-of-freedom. In the study, second-order high-pass filters were used to filter the lateral and longitudinal vehicle motions before they were sent to the motion system. The filters are given in the Laplace domain as

$$\mathrm{HP}_{2\mathrm{nd}}(s) = K\frac{s^2}{s^2 + 2\zeta\omega s + \omega^2} \tag{5}$$

A first-order high-pass filter was used to filter the yaw degree-of-freedom. The filter transfer function is

$$\mathrm{HP}_{1\mathrm{st}}(s) = K\frac{s}{s+\omega} \tag{6}$$

Four different motion conditions were used for all three tasks in the study: no motion, translational motion, yaw motion, and translational plus yaw motion. The high-pass filter parameters used for all conditions are shown in Table 1. Also shown in Table 1 are the high-pass parameters used by Schroeder in his yaw capture experiment (which employed second-order high-pass filters on all degrees-of-freedom). The small envelope of the UTIAS motion system prevented exact duplication of the NASA filters.

The lateral and yaw UTIAS total describing functions (motion system + shaping filter + high-pass filters) are compared to the NASA Ames VMS total describing functions (low-order approx. + high-pass filters) in Fig. 1. Below 1 rad/s, the additional phase lead from the higher break frequency of the UTIAS lateral filter becomes apparent, leading to approximately 10 deg of lead at 0.3 rad/s. At 6 rad/s the yaw and lateral UTIAS describing functions lag the low-order approximation of the NASA VMS by approximately 14 deg. The longitudinal describing function is not shown because the maximum longitudinal specific force, which occurred during the yaw capture task, was only 30 mg. The maximum longitudinal specific force for the yaw capture task was approximately 150 mg.

Visual Systems

Evans and Sutherland 6500Q image generators drove all three channels of the visual systems used in this study. The system

[‖]At the time of the experiment described in [6].

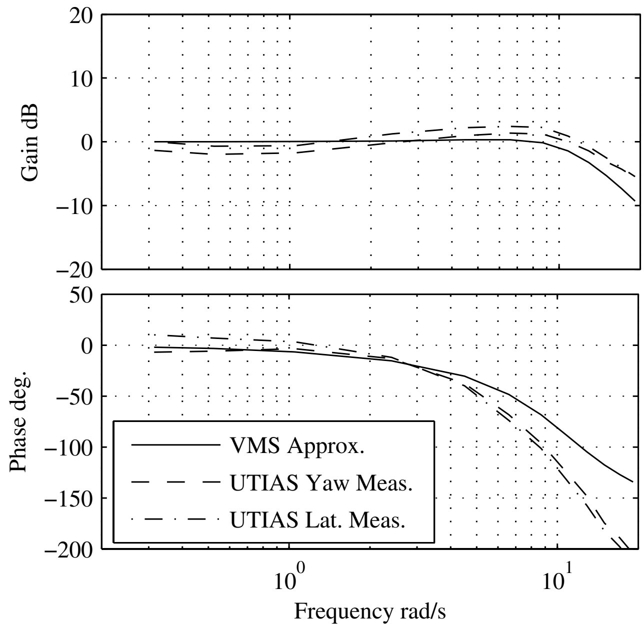

Fig. 1 UTIAS and NASA VMS total describing functions.

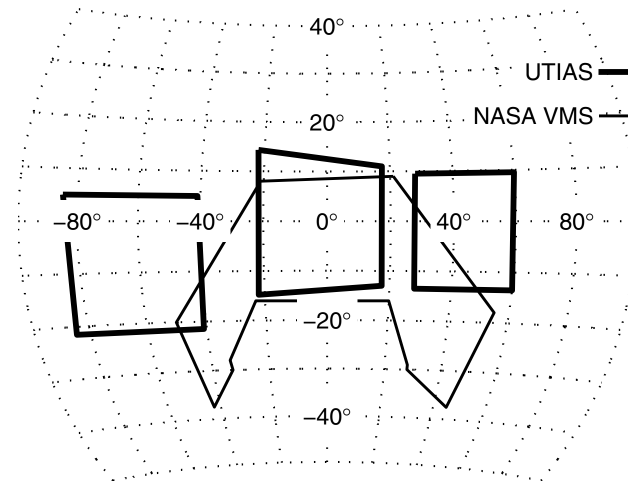

Fig. 2 UTIAS and NASA visual field of views.

refreshed the 1280 H × 1024 V images at 60 Hz noninterlaced, with a transport delay of 58 ms (measured from receipt of data to half the field of view of the visual system.) The Out-the-Window visual system employed Vital II collimated display boxes, driven by 24 in Sony Multi-Scan monitors. The visual system properties for the UTIAS and NASA VMS system used during Schroeder's yaw capture task are summarized in Table 2. Figure 2 provides a more precise description of the field of view for the UTIAS and NASA visual systems.

Rudder Pedals

The feedback force properties of the rudder pedal setup used in this experiment, along with the NASA pedal properties are shown in Table 3. A modest amount of mass, upstream of the UTIAS pedal control loading force sensor, limited the bandwidth of the UTIAS system.

Sound Generation

Cabin noise recorded from a Bell 206 helicopter was played during the experiment at a volume sufficient to mask the noise of the hydraulic actuators.

Pilots

Three pilots participated in the study. Two pilots were experienced helicopter test pilots from the Flight Research Laboratory, Institute for Aerospace Research at Canadian National Research Council. The third pilot was an ex-military pilot and ex-NRC helicopter project pilot with significant simulator test experience.

Yaw Capture

The yaw capture task was a duplication of a study run by Schroeder on the NASA Ames VMS simulator. For this task, the pilot was required to rapidly acquire a north heading from 15 deg east or west of north. Starting from either 15 deg east or west, the desired task performance was to capture the north heading as rapidly as possible and stay within ±1 deg of north with two or less overshoots. Pilots were instructed to stabilize on the north heading for at least 5 s before attempting another capture. The experiment was performed in clear conditions and without turbulence. The repositioning from north to the initial east or west headings were not part of the task, and this was indicated to the pilots. The 2 deg range was demarcated by the sides of a vertical pole, as shown in the pilot's forward field of view in Fig. 3. The pilot's reference for Ownship position was a cross-hair on the helicopter's centerline in front of the pilot at their eye height. Each pilot performed six captures per trial, alternating between initial east and west directions. Pilots performed four trials for each motion configuration leading to 16 runs per subject. The presentation order of the motion conditions (including the four trials) was random. It should be noted that the visual database in Schroeder's experiment only had the center pole.

The subjective information gathered from the pilots was identical to that described by Schroeder. At the end of each trial, pilots were asked to rate the overall level of compensation required for the task using the following descriptors: not a factor, minimal, moderate, considerable, extensive, and maximum tolerable. The descriptors were taken from the Cooper-Harper Handling Qualities scale. Next, the pilots rated the motion fidelity according to the following three categories: 1) Low Fidelity: motion cueing differences from actual flight were noticeable and objectionable, 2) Medium Fidelity: motion cue differences were perceptible, but not objectionable, and 3) High Fidelity: motion cues were close to those of actual flight. Finally, the pilots were asked to report whether they perceived any cockpit translational or yaw motion.

Disturbance Rejection

The disturbance rejection task required the pilots to keep the helicopter pointed towards north for 100 s while the helicopter was subjected to simulated turbulence. The visual database and helicopter cross-hair from the yaw capture task was also used for this task (see Fig. 3). Desired performance for this task required the pilots to keep the helicopter's heading within ±4 deg of north. Satisfactory performance was within ±8 deg of north.

A turbulence model developed by Lusardi et al [9] was used to produce control positions that were added onto the pilot's pedal

Table 2 Visual systems properties

	UTIAS	NASA
Total field of view (FOV), deg	145 H × 30 V	110 H × 50 V
Approx. central pixel resolution, arc-min.	1.8	1.8
Transport delay, ms	58	86
Refresh rate, Hz	60 noninterlaced	60 interlaced

Table 3 Rudder pedal properties

	UTIAS	NASA
Travel, in	±3.5	±2.7
Breakout force, lb	3.0	3.0
Force gradient, lb/in	3.0	3.0
Natural freq., rad/s	11	30
Damping ratio	0.5	0.5

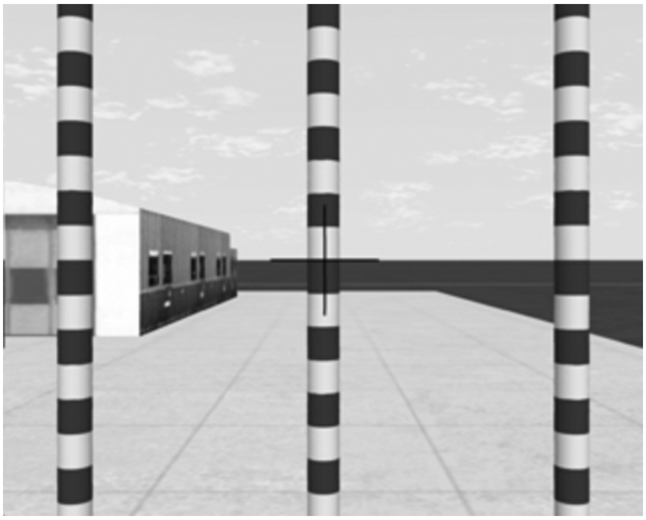

Fig. 3 Pilot's visual scene for yaw capture and disturbance rejection tasks.

inputs. According to the model, the pedal to white noise transfer function for a hovering UH-60 helicopter can be described by

$$\frac{\delta_p}{w}(s) = 0.2341\sigma^{-0.6493}\sqrt{\frac{\sigma^2 U_o}{\pi L}}\left(\frac{1}{s + U_o/L}\right) \tag{7}$$

For the windiest conditions $\sigma = 2.16$ m/s, $U_0 = 8.6$ m/s, and $L = 7.9$ m. The disturbance for this study was generated by summing 60 sinusoids spanning the frequency range from approximately 0.15 to 18 rad/s. The amplitudes of the sinusoids were determined by calculating the gain of Eq. (7), at each frequency and multiplying by 0.51. This resulted in a rms yaw acceleration of 5.27 deg/s^2 when the sinusoids were passed through the AH-64 helicopter dynamics described in Eq. (1). This is the value that would be obtained if Lusardi et al.'s windiest condition was run through the UH-60 vehicle dynamics. The magnitude of the disturbance was therefore representative of real world severe turbulence. The frequencies and corresponding pedal displacements for the sinusoids are shown in Table 4. Random phase angles were assigned to each sinusoid for each experimental trial. The disturbance was linearly faded in over the first 10 s of the trial. An example of the time history of the disturbance is shown in Fig. 4. The square of the amplitude of the sinusoids, which is proportional to power, is plotted against frequency in Fig. 5.

The pilots flew each motion condition four times leading to 16 trials per subject. The order of presentation was random. At the end of each trial, pilots rated the workload, motion fidelity, and motion detection using the same scales previously described for the yaw capture task.

Table 4 Turbulence frequencies and pedal amplitudes

Freq., rad/s	Amp., in	Freq., rad/s	Amp., in	Freq., rad/s	Amp., in
0.140	0.1306	6.423	0.0212	12.776	0.0108
0.419	0.1223	6.772	0.0201	13.125	0.0105
0.768	0.1062	7.051	0.0194	13.404	0.0103
1.047	0.0932	7.400	0.0185	13.753	0.0100
1.396	0.0791	7.749	0.0177	14.032	0.0098
1.676	0.0699	8.029	0.0171	14.382	0.0096
2.025	0.0606	8.378	0.0164	14.661	0.0094
2.304	0.0545	8.657	0.0158	15.010	0.0092
2.653	0.0484	9.006	0.0152	15.359	0.0090
2.932	0.0443	9.285	0.0148	15.638	0.0088
3.281	0.0401	9.634	0.0142	15.987	0.0086
3.560	0.0372	9.913	0.0139	16.266	0.0085
3.910	0.0341	10.263	0.0134	16.616	0.0083
4.259	0.0315	10.542	0.0130	16.895	0.0082
4.538	0.0296	10.891	0.0126	17.244	0.0080
4.887	0.0276	11.170	0.0123	17.523	0.0079
5.166	0.0262	11.519	0.0119	17.872	0.0077
5.515	0.0246	11.868	0.0116	18.151	0.0076
5.794	0.0234	12.147	0.0113	18.500	0.0075
6.144	0.0222	12.497	0.0110	18.850	0.0073

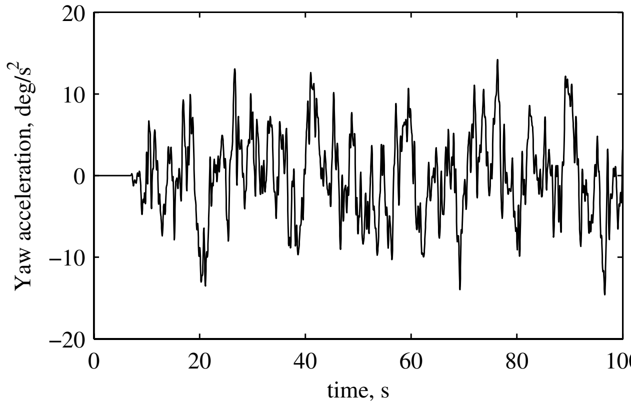

Fig. 4 Yaw acceleration due to turbulence.

Tracking Task

The tracking task required the pilots to track a randomly moving lead helicopter for 100 s. The lead helicopter yawed randomly about the Ownship's center of rotation (4.5 ft behind the pilot in the simulator). A cross-hair was attached to the Ownship's centerline in front of the pilot and a target was attached to the rear of the lead helicopter to provide a tracking error reference, as shown in the pilot's forward field of view in Fig. 6.

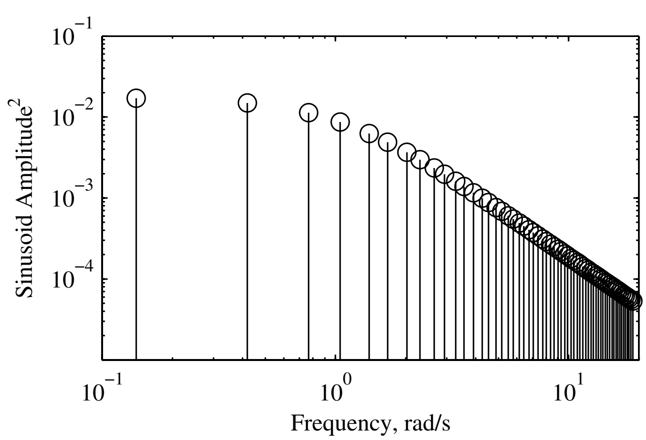

Fig. 5 Spectral content of simulated turbulence.

Fig. 6 Visual scene for tracking task.

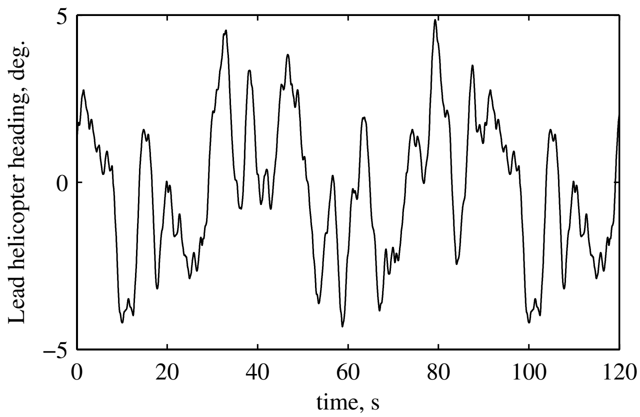

Fig. 7 Lead helicopter heading time history.

The pseudorandom lead helicopter yaw heading was generated by summing 60 sinusoids spanning the frequency range from 0.15 to 18 rad/s. The amplitudes of the sinusoids were calculated by multiplying the gain of a second-order low-pass filter at the given sinusoid frequency by 2. The low-pass filter had the form

$$\mathrm{LP}(s) = \frac{\omega^2}{s^2 + 2\zeta\omega s + \omega^2} \tag{8}$$

with $\omega = 0.8$ and $\zeta = 0.7$. The lead helicopter motion was linearly faded in over the first 10 s. Random phase angles were assigned to each sinusoid, for each experimental trial. Figure 7 shows an example of the lead helicopter motion. A list of the frequencies and amplitudes used in the experiment are provided in Table 5.

Desired performance for this task was to keep the cross-hair within the lead helicopter circular target which spanned ± 1.3 deg of the pilot's field of view. Satisfactory performance was to keep the cross-hair within ± 2.6 deg of the center of the target. The pilots flew each motion condition four times leading to 16 trials per subject for each experiment. The order of presentation was random. At the end of each trial, pilots were asked to rate the workload, motion fidelity, and motion detection using the same scales previously described for the yaw capture task.

Results

Six different measures were analyzed for each task. The first two measures were objective measures of pilot performance and workload and the remaining four were subjective measures of workload, motion fidelity, and detection of yaw and translational motion. The experimental design was a repeated measure, except that each cell was repeated four times during each experiment (each subject flew the same condition four times). The repetition enabled statistical analysis using a mixed model analysis of variance due to the extra degrees of freedom. Subjects were considered a random factor and the remaining factors were considered fixed. With the mixed model, first the factor (or interaction of factors) × Subject was tested. If the null hypothesis was accepted at a relatively high probability (with a $p > 0.3$) then the mean square from that factor(s) × Subject was pooled into the error and the factor was tested (or interaction of factors) against the pooled error term [10]. If the factor(s) × Subject null hypothesis was not accepted (with the relatively high p-value) then the standard repeated measures F ratio was formed for the test.

The advantage of testing against the pooled error (when the data have the described properties) was the large increase in the degrees of freedom in the denominator of the F test, and the subsequent increase in power of the test. For example, in the given experiment, there were 36 degrees-of-freedom in the error and only 2 in any factor(s) × Subject. Unfortunately, it was rarely the case that the factor × Subject interaction was insignificant. In the following discussion, a significant F test using the error term is indicated using p^{**} instead of p. In the following analysis, effects were considered significant when the probability that the null hypothesis is true, is less than 5% ($p \le 0.05$). Effects for which the probability (of the null hypothesis being true) was between 5 and 10% ($0.05 < p \le 0.1$) were considered marginally significant. When an interaction is statistically significant, a simple effects test was used to determine the nature of the interaction. Although in some respects these were post-hoc tests, the 5 and 10% probability levels were used to determine significant and marginally significant effects. Winer et al. [11] discuss the appropriate level of significance for simple effects tests. All the analysis was carried out using the SYSTAT® software package.

Table 5 Lead helicopter frequencies and amplitudes

Freq., rad/s	Amp., deg	Freq., rad/s	Amp., deg	Freq., rad/s	Amp., deg
0.140	1.7788	6.423	0.0276	12.776	0.0070
0.419	1.7241	6.772	0.0248	13.125	0.0066
0.768	1.3212	7.051	0.0229	13.404	0.0063
1.047	0.9044	7.400	0.0208	13.753	0.0060
1.396	0.5581	7.749	0.0190	14.032	0.0058
1.676	0.397	8.029	0.0177	14.382	0.0055
2.025	0.2752	8.378	0.0162	14.661	0.0053
2.304	0.2134	8.657	0.0152	15.010	0.0051
2.653	0.1614	9.006	0.0140	15.359	0.0048
2.932	0.1322	9.285	0.0132	15.638	0.0047
3.281	0.1057	9.634	0.0123	15.987	0.0045
3.560	0.0898	9.913	0.0116	16.266	0.0043
3.910	0.0745	10.263	0.0108	16.616	0.0041
4.259	0.0628	10.542	0.0102	16.895	0.0040
4.538	0.0553	10.891	0.0096	17.244	0.0038
4.887	0.0477	11.170	0.0091	17.523	0.0037
5.166	0.0427	11.519	0.0086	17.872	0.0036
5.515	0.0374	11.868	0.0081	18.151	0.0035
5.794	0.0339	12.147	0.0077	18.500	0.0033
6.144	0.0302	12.497	0.0073	18.850	0.0032

Yaw Capture

Examples of a yaw capture for the yaw motion, translational motion, and yaw plus translational motion conditions are shown in Figs. 8–10, respectively. The motion response data were recorded with a BEI MotionPak® instrument package, and filtered with a zero phase, 10 Hz low-pass fourth-order filter. As seen in Fig. 8 at 70.5 s, the simulator yaw rate temporarily droops relative to the commanded helicopter motion due to nonlinearity in the motion base response resulting from the high velocity command. As the helicopter gets

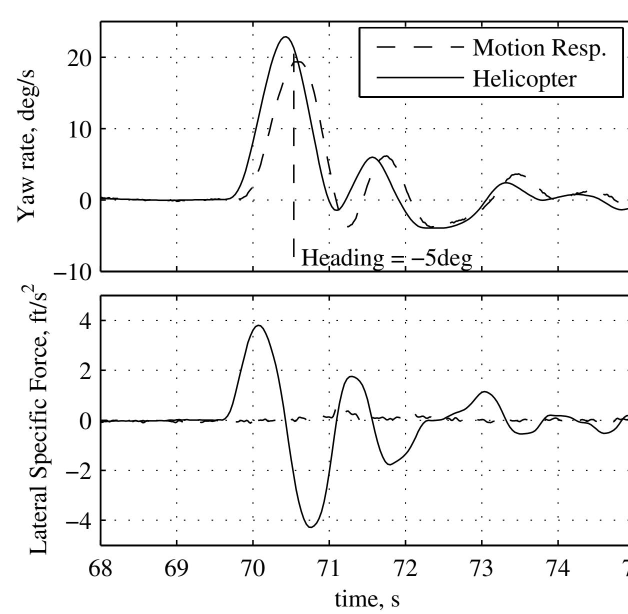

Fig. 8 Helicopter motion and motion base response for capture task. Yaw-only motion case.

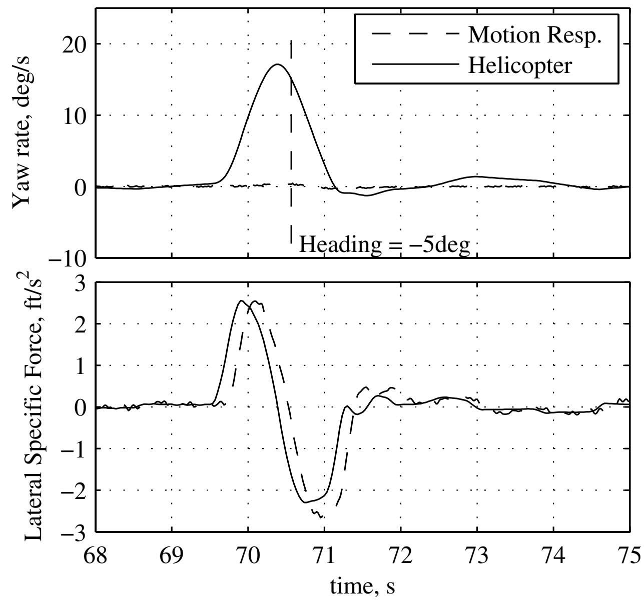

Fig. 9 Helicopter motion and motion base response for capture task. Translational-only motion case.

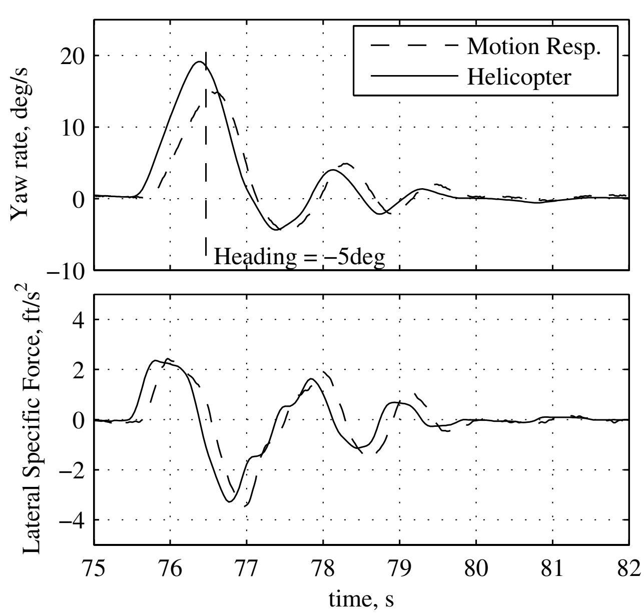

Fig. 10 Helicopter motion and motion base response for capture task. Yaw and translational motion case.

close to the target (shown by the −5 deg heading on the figures), however, the simulator yaw rate recovers. Because the initial pedal input was likely an open-loop input, it is unlikely this change in gain had an impact on pilot performance.

The measure used by Schroeder to evaluate performance was the number of overshoots greater than ±1 deg. To allow direct comparison with Schroeder's results the same measure was used in this study. This measure is unlikely to have a Gaussian distribution due to the fact it is discrete and bounded below by zero; however, the F tests are relatively robust against non-Gaussian distributions.

Figure 11 shows the pilot performance for the four motion conditions for both the current UTIAS experiment and Schroeder's yaw capture experiment (NASA). The bars denote one standard error of the mean. The results from the two experiments are very similar when translational motion is present. In the case of no translational motion, there is more variation among the experiments, particularly when yaw motion is present. The NASA result for yaw motion alone is substantially larger than the UTIAS experiment.

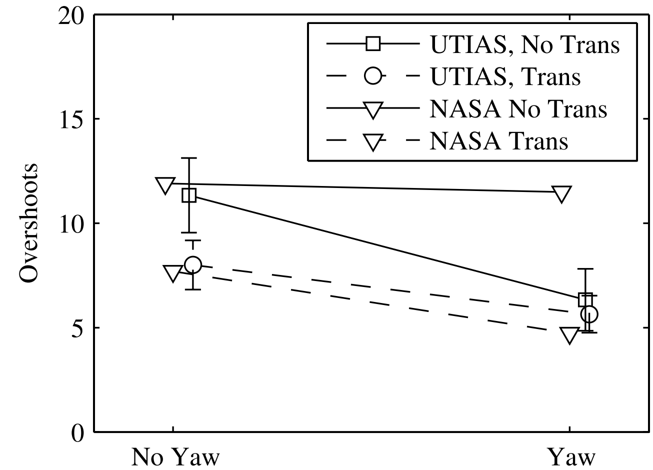

Fig. 11 Performance for yaw capture task.

The residual errors resulting from the standard analysis of variance tended to decrease as the number of overshoots decreased. A square root transformation was therefore applied to the overshoot data to remove this trend. The analysis of variance of the transformed data showed a significant yaw-translational motion interaction ($p = 0.05$). A simple effects test indicated that the reduction in overshoots when yaw motion was added to no motion was significant ($p = 0.027$) and the reduction when translational motion was added to no motion was marginally significant ($p = 0.086$). In other words, the additional benefit of adding the second motion once one was already present (either translational or yaw) is negligible. In contrast, Schroeder found that the reduction in overshoots with the addition of translational motion was significant ($p = 0.039$) and the reduction in overshoots when yaw was added was marginally significant ($p = 0.077$). Six subjects were used in Schroeder's experiment, however, so it had more power than the current experiment. The two experiments mainly differed in the yaw-only results.

The lack of significance of translational motion can be explained by a lack of power (due to the small sample size of three pilots) in the current study. This cannot, however, explain the effect of yaw motion when translational motion was not present. One possibility is that yaw motion in the current study did not occur about the pilot location, or the UTIAS motion system has yaw-translational cross-coupling. Examination of recorded accelerometer data (see Fig. 8) revealed no significant lateral acceleration at the nominal pilot location (<5 mg). Large adjustments in the seat position could lead to offsets of up to 5 in or so, but this would only lead to translational accelerations of less than 14 mg, so this seems an unlikely cause for the effect of yaw motion. It is also possible the differences in the two facilities led to the different result. Although most of the important simulator systems were similar, they were not identical. There were differences in the visual cues (FOV, transport delay, number of vertical poles in database), motion cues and pedal dynamics, but it is difficult to see how the small differences could only affect the yaw-only motion case. The increased scatter between the experiments when yaw motion was present remains largely unexplained.

As discussed by Schroeder, pedal rate is often associated with pilot workload, with a higher rate being indicative of higher workload. For this study, the rms pedal rate was calculated from the first time the ±1 deg threshold was crossed until the threshold was crossed again for repositioning for the next capture. Figure 12 shows the average rms pedal rates for the four motion conditions for both the UTIAS experiment and Schroeder's experiment (NASA).

Once again, the two experiments are in close agreement when translational motion is present. For the analysis of variance, a square root transformation was applied to the pedal data to improve the distribution of the residuals. For the UTIAS experiment there was a marginal interaction between yaw and translational motion ($p = 0.067$). Simple means tests showed that the reduction in pedal rate when translational motion was added to no motion was marginally significant ($p = 0.048$; but this test was a post-hoc test

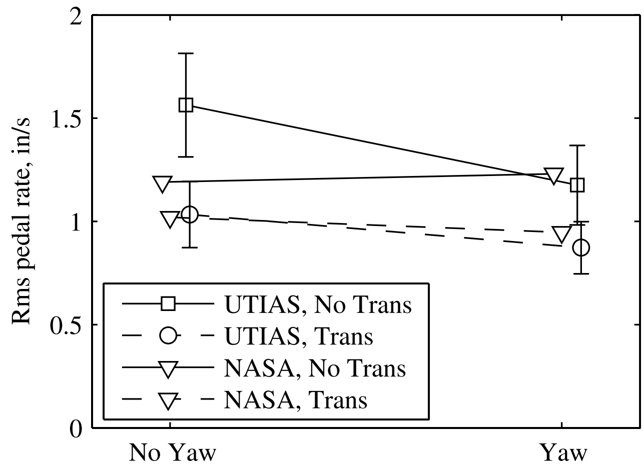

Fig. 12 Pedal rate for yaw capture task.

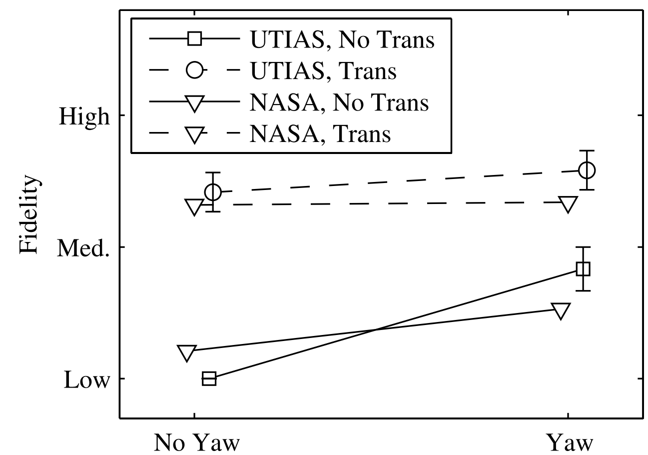

Fig. 14 Subjective fidelity for yaw capture task.

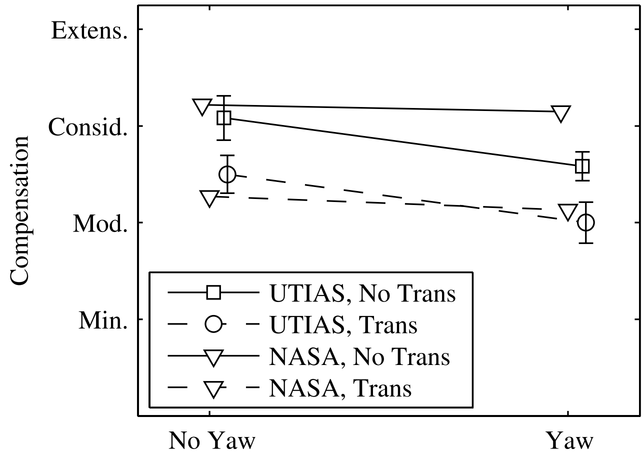

Fig. 13 Compensation for yaw capture task.

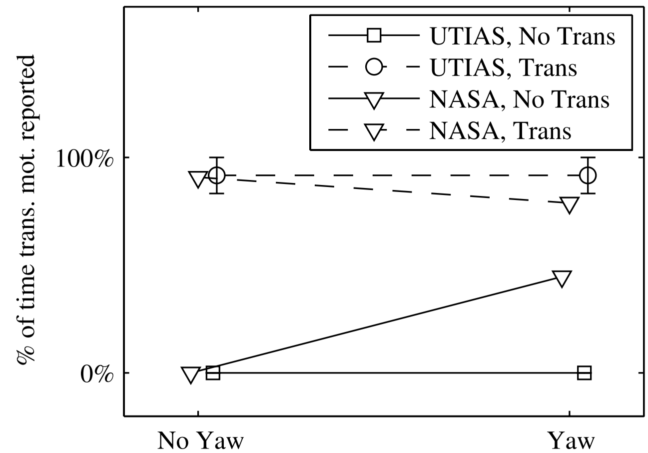

Fig. 15 Translational motion perception for yaw capture task.

done on a marginal effect so we will consider it marginal). Schroeder found that the addition of translational motion significantly reduced the pedal rate ($p = 0.013$). The lack of significance in the current study may be explained by the small sample size (three pilots).

Figure 13 shows the compensation results for the four motion conditions for the UTIAS and Schroeder's experiment (NASA). An analysis of variance for the UTIAS study showed no significant effects of motion on pilot rated compensation. Schroeder found that the addition of translational motion significantly reduced compensation ($p = 0.047$). The addition of translational motion alone had a large reduction in compensation in Schroeder's experiments and only a modest impact in the UTIAS experiment. The addition of yaw motion resulted in a modest reduction in compensation in the UTIAS experiment (although it was not significant) and almost no impact in Schroeder's experiment. The results may be influenced by the ability of the subjects to detect the motion. As will be shown later, pilots were able to detect yaw motion more reliably in the UTIAS experiment than in Schroeder's experiment.

Figure 14 shows the subjective fidelity results for the four motion conditions for the UTIAS and the NASA experiment. The two experiments are in general agreement, with a larger improvement in perceived fidelity from the addition of translational motion than from yaw. For the UTIAS experiment there was a significant interaction between yaw and translational motion ($p = 0.015$). A simple effects test revealed that translational motion was always significant regardless of yaw motion ($p < 0.035$) and yaw motion was only marginally significant when there was no translational motion ($p = 0.063$). Schroeder found similar results; when translational motion was added there was a significant increase in fidelity rating ($p = 0.039$). The two experiments are therefore in general agreement; translational motion has a larger and more consistent impact on perceived fidelity than yaw motion.

Figure 15 depicts whether or not pilots reported lateral translational motion to be present for the four motion conditions. Before discussing the results, it should be noted that the pilots in the UTIAS experiment were aware of the four different motion conditions, whereas the pilots in the NASA experiment were given no information regarding the different motion conditions. The results from UTIAS and NASA experiments are quite similar considering the pilots in the UTIAS study had only to decide whether or not full translational motion was present. For the UTIAS experiment, translational motion significantly increased the reporting of translational motion ($p = 0.002$). For Schroeder's experiment the yaw-translational motion interaction was significant ($p = 0.003$). The addition of yaw motion appears to have increased the reporting of translational motion, but results from a simple effects test were not available to test the significance of this increase. Schroeder hypothesized that a small offset from the center of yaw rotation may have led to the relatively high percentage of reporting of translational motion when only yaw motion was present. This effect was not present in the UTIAS experiment, as pilots only had to decide if full translational motion was or was not present.

Figure 16 depicts whether or not pilots reported yaw motion to be present for the four motion conditions for both the UTIAS and NASA experiments. The results from the two experiments are very similar, except for the frequent reporting of yaw motion when only translational motion was present in Schroeder's experiment. The analysis of variance for UTIAS experiment indicated there was a strong interaction between yaw and translational motion ($p < 0.001$). A simple effects tests indicated that the addition of yaw motion always significantly increased the reporting of yaw

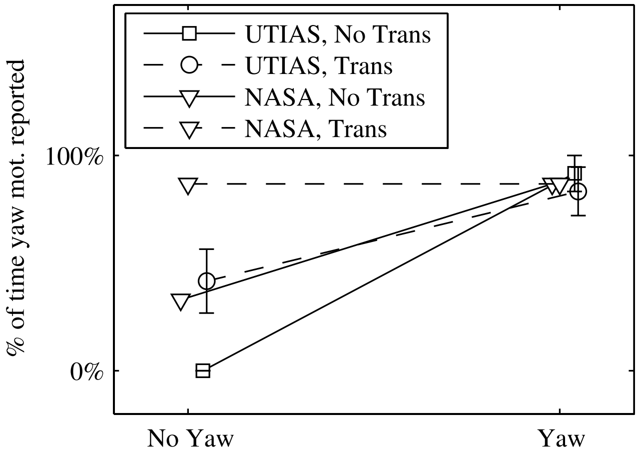

Fig. 16 Yaw motion perception for yaw capture task.

motion ($p < 0.038$). It also indicated that the addition of translational motion to no motion significantly increased the reporting of yaw motion ($p = 0.038$). Schroeder found a significant yaw-translational motion interaction as well ($p = 0.023$); however, simple effects tests were not done.

It is interesting to note that even though the UTIAS pilots knew that the yaw motion was either full or none, there was still an increase in yaw reporting with the addition of translational motion (although it was not significant). The lower percentage reporting of yaw motion when only translational motion was present in the current study (compared to Schroeder's experiment) can be explained by the knowledge the UTIAS pilots had regarding the four motion conditions. Schroeder hypothesized that the translational motion increased the rotational vection effect leading to the increased reporting of yaw motion.

Disturbance Rejection

The motion base response for the disturbance rejection task was very similar to the yaw capture results shown in Figs. 8–10, except that the gain reduction associated with the very high peak yaw velocities did not occur for the disturbance rejection task. This is because the peak accelerations, velocities, and displacements were significantly smaller for the disturbance rejection task than for the yaw capture task.

For the disturbance task, rms heading error was used as the measure of pilot performance. The first 10 s of a trial were excluded from the analysis to allow the pilot to stabilize the helicopter. The heading error results are shown in Fig. 17 for all four motion conditions.

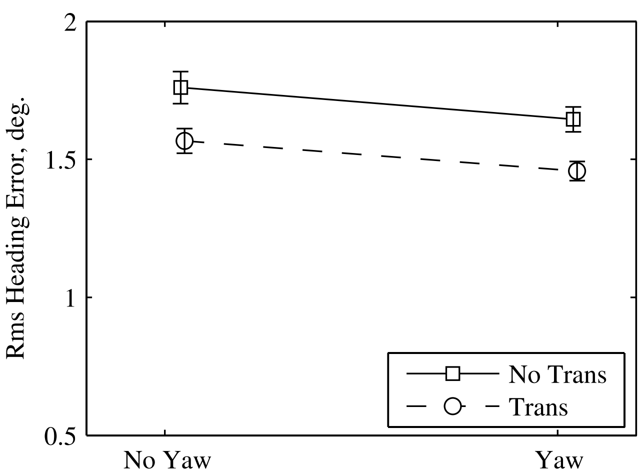

Fig. 17 Performance for disturbance task.

Both translational and yaw motion significantly improved pilot performance ($p^{**} = 0.0$ and $p^{**} = 0.05$, respectively). Although the improvements were small, they were consistent.

The pedal rates for the four motion conditions used in the disturbance task are shown in Fig. 18. Translational motion may have significantly reduced the pedal rates ($p^{**} = 0.01$), but this conclusion is dubious as the Translational $\times$ Subject effect that was pooled into the error term to obtain this p-value was less than 0.3 ($p = 0.24$).

The pilot rated compensation is shown in Fig. 19. The reduction in compensation when translational motion was added was marginally significant ($p = 0.082$).

The motion fidelity for the four motion conditions during the disturbance task are shown in Fig. 20. The increase in fidelity with the addition of translational motion was significant ($p = 0.028$) and the increase in fidelity with the addition of yaw motion was marginally significant ($p = 0.069$).

The reporting of translational motion for the disturbance task is shown in Fig. 21. The reporting of translational motion when translational motion is added is significant ($p = 0.0$). The pilots were perfect in their detection of translational motion; again the knowledge of the four possible motion conditions almost certainly contributed to this perfect reporting.

The reporting of yaw motion for all four motion conditions of the disturbance task are shown in Fig. 22. The addition of yaw motion significantly increased the reporting of yaw motion ($p = 0.034$). Translational motion did not significantly affect the reporting of yaw motion as was found for the yaw capture task. Perhaps the smaller high frequency displacements did not lead to strong vection, and hence the addition of translational motion had a smaller impact.

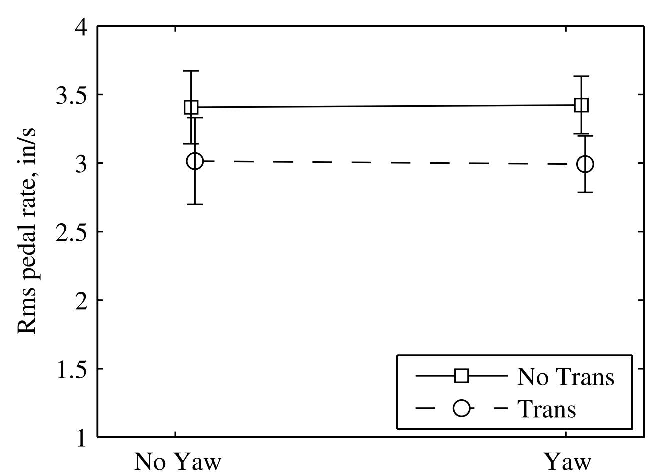

Fig. 18 Pedal rate for disturbance task.

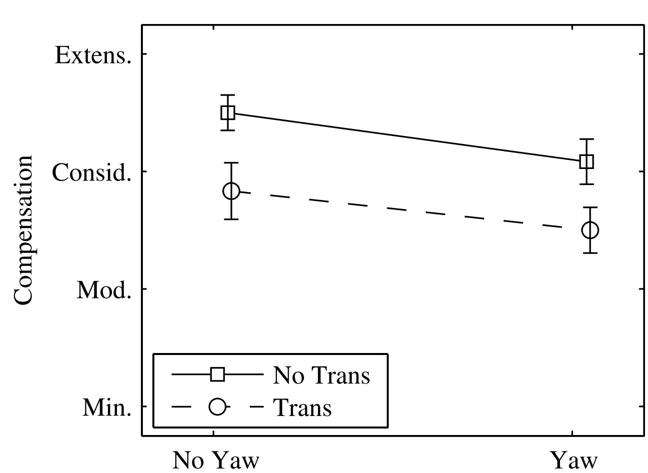

Fig. 19 Compensation for disturbance task.

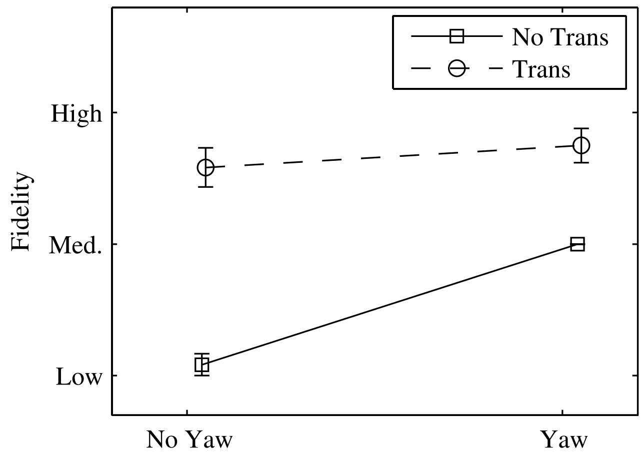

Fig. 20 Motion fidelity for disturbance task.

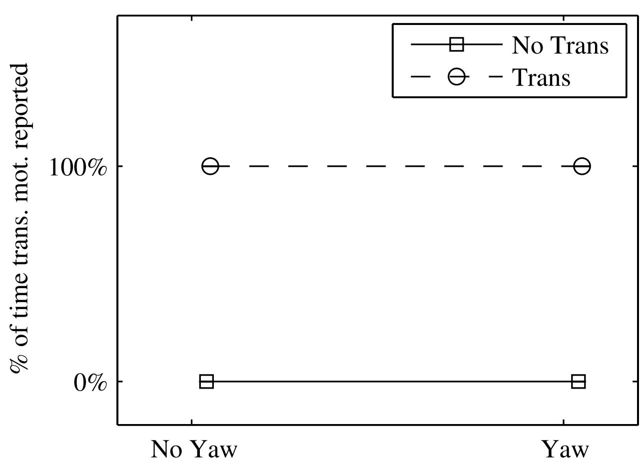

Fig. 21 Translational motion perception for disturbance task.

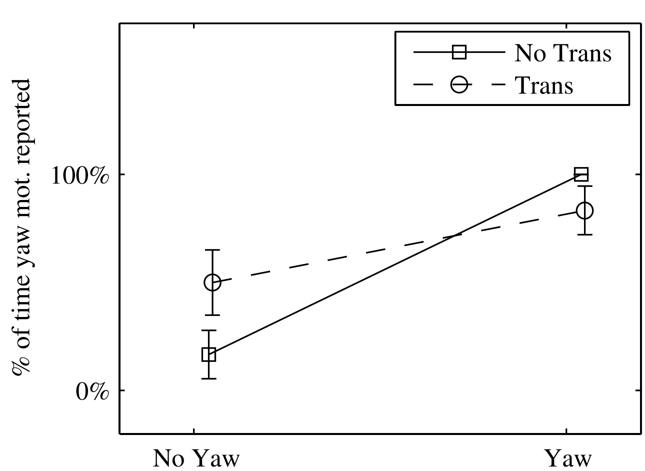

Fig. 22 Yaw motion perception for disturbance task.

Tracking Task

The motion base response for the tracking task was very similar to the yaw capture results shown in Figs. 8–10, except, as with the disturbance rejection task, the gain reduction associated with the very high peak yaw velocities did not occur. The peak accelerations, velocities, and displacements were significantly smaller for the tracking task than for the yaw capture task.

For the tracking task, rms tracking error was used as the measure of pilot performance. The first 10 s of a trial were excluded from analysis to allow the pilot to stabilize. Pilot performance for the four motion conditions used in the tracking task are shown in Fig. 23. There was a significant interaction between yaw and translational motion ($p = 0.004$).

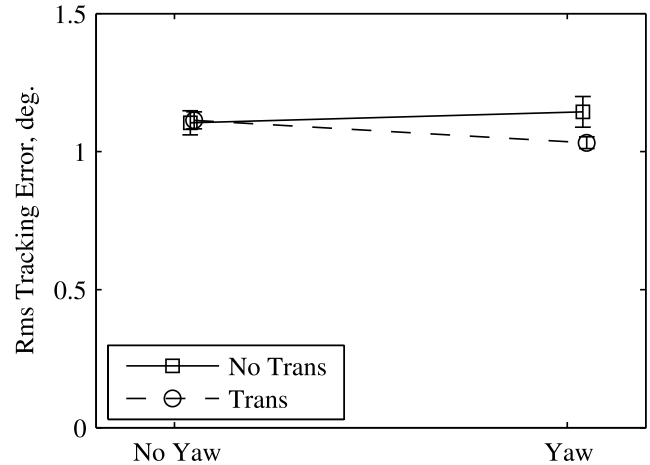

Fig. 23 Performance for tracking task.

A simple effects test indicated that the increase in performance with the addition of translational motion, when yaw was present, was statistically significant ($p = 0.01$). The increase in performance with the addition of yaw motion when translational motion was present was marginally significant ($p = 0.1$). It appears that yaw motion and lateral motion may improve tracking performance, but only marginally.

The rms pedal rates for the tracking task are shown in Fig. 24. The analysis of variance indicates no effects of motion on pedal rate. The subjective pilot compensation ratings are shown in Fig. 25. There were no significant effects of motion on rated compensation. The rated fidelity of the four motion conditions for the tracking task is shown in Fig. 26. The results are in general agreement with the yaw capture and disturbance rejection tasks. The increase in fidelity with the addition of translational motion was marginally significant ($p = 0.069$).

The reporting of translational motion is shown in Fig. 27. The results are very similar to the yaw capture and disturbance tasks. The increase in reporting of translational motion when translational motion was added was statistically significant ($p = 0.02$).

The reporting of yaw motion is shown in Fig. 28. Once again, the results from this task agree with the yaw capture and disturbance rejection tasks. The increase in reporting of yaw motion when yaw motion was added was significant ($p^{**} = 0.01$).

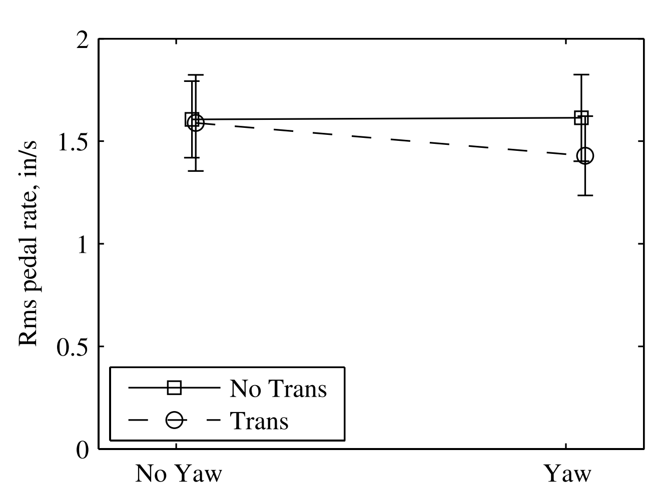

Fig. 24 Pedal rate for tracking task.

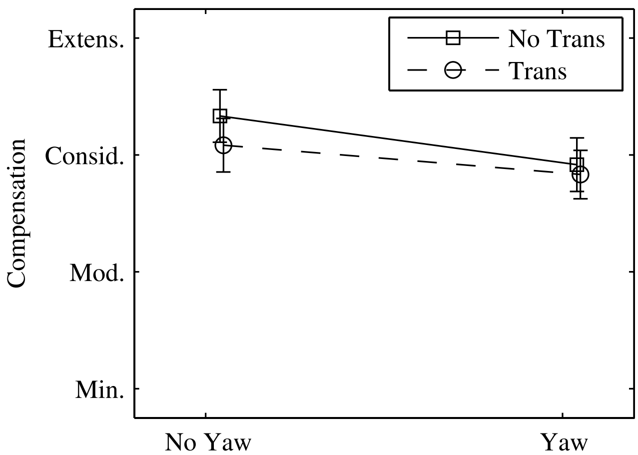

Fig. 25 Compensation for tracking task.

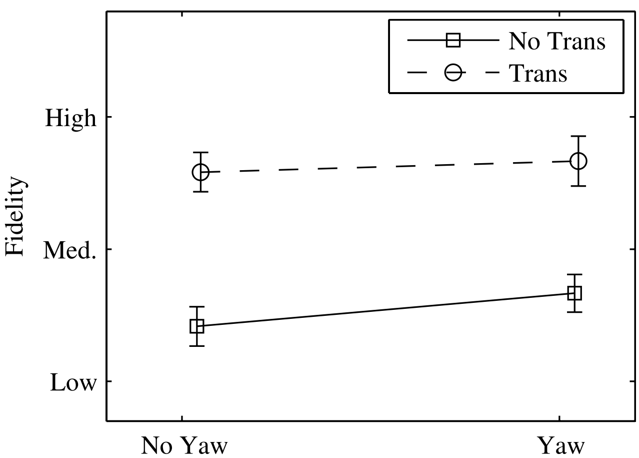

Fig. 26 Fidelity for tracking task.

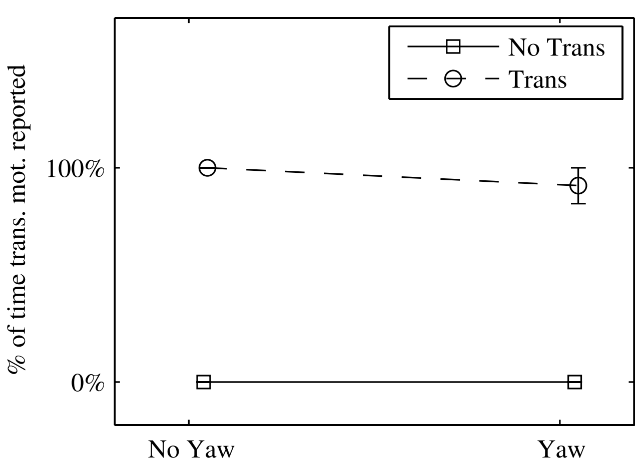

Fig. 27 Translational motion perception for tracking task.

Discussion

The results of the analysis of variance for the yaw capture experiment are summarized in Table 6. Examination of the table shows the current yaw capture results are in general agreement with Schroeder's yaw capture experiment. For pilot performance (overshoots), however, there is a difference. Schroeder found translational motion had a more significant effect than yaw on performance, whereas the current study found yaw motion had the more significant effect on performance. There are a number of potential causes for this difference. First, the small number of pilots could have contributed to each study finding (different) subsets of the set of all significant effects. If the studies had more power, both yaw and translational motion may have significantly affected performance. Second, it is possible that the differences in the two simulators led to the difference in results between the current study and Schroeder's study. Although most of the important simulator systems were similar, they were not identical. There were differences in the visual cues (FOV, transport delay, number of vertical poles in database), motion cues, and pedal dynamics. Perhaps the sum total of the small differences led to the significant differences in pilot behavior. Finally, the two groups of pilots may not be a random sample of the test pilot population. Pilots tend to be recruited in groups and may therefore have common piloting styles.

A summary of the analysis of variance for the disturbance and tracking tasks is shown in Table 7. As seen from Tables 6 and 7, there is general agreement between all tasks and studies on the effects of translational and yaw motion on fidelity; translational motion usually leads to improved fidelity whereas yaw motion rarely leads to improved fidelity. There is also general agreement between all tasks and studies on the effects of yaw and translational motion on the reporting of each. Translational motion always leads to increased reporting of translational motion and yaw motion often leads to increased reporting of yaw motion. For the disturbance task, both translational and yaw motion improved pilot performance. This is in agreement with Hosman et al.'s predictions [7]. For the tracking task, motion did not have a consistent effect on performance. Again, this is in general agreement with Hosman et al.'s predictions.

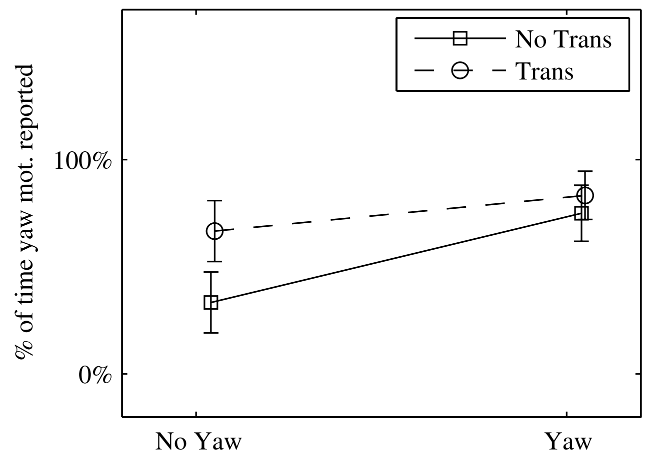

Fig. 28 Yaw motion perception for tracking task.

Table 6 Comparison of ANOVA results from NASA and UTIAS yaw capture experiments

	Experiment	Yaw	Trans.	Yaw × Trans.
Overshoots	UTIAS	c	d	a
	NASA	b	a	——
RMS pedal rate	UTIAS	——	d	b
	NASA	——	a	——
Compensation	UTIAS	——	a	——
	NASA	——	——	——
Fidelity	UTIAS	d	a	a
	NASA	——	a	——
Trans. motion reported	UTIAS	——	a	——
	NASA	e	e	a
Yaw motion reported	UTIAS	a	c	a
	NASA	e	e	a

[a]Significant main effect ($p \leq 0.05$)
[b]Marginally significant main effect ($0.05 < p \leq 0.1$)
[c]Significant when other motion not present ($p \leq 0.05$)
[d]Marginally significant when other motion not present ($0.05 < p \leq 0.1$)
[e]Unknown, simple effects test not performed

Table 7 ANOVA results for disturbance rejection and tracking task

	Task	Yaw	Trans.	Yaw × Trans.
RMS heading error	Disturbance	[a]	[a]	——
	Tracking	[d]	[c]	[a]
RMS pedal rate	Disturbance	——	——	——
	Tracking	——	——	——
Compensation	Disturbance	——	[b]	——
	Tracking	——	——	——
Fidelity	Disturbance	[b]	[a]	——
	Tracking	——	[b]	——
Trans. motion reported	Disturbance	——	[a]	——
	Tracking	——	[a]	——
Yaw motion reported	Disturbance	[a]	——	——
	Tracking	[a]	——	——

[a]Significant main effect ($p \leq 0.05$)
[b]Marginally significant main effect ($0.05 < p \leq 0.1$)
[c]Significant when other motion present ($p \leq 0.05$)
[d]Marginally significant when other motion present ($0.05 < p \leq 0.1$)

Conclusions

The effect of simulator translational and rotational motion on pilot performance, workload, compensation, perceived fidelity, and motion perception were determined for a yaw capture task, a yaw disturbance rejection task, and a yaw tracking task. The yaw capture task was a repetition of a study previously run at the NASA VMS facility.

The repetition of Schroeder's yaw capture study [6] on the UTIAS facility produced very similar results with a rather surprising difference. The current study found that yaw motion alone benefited pilot performance, whereas Schroeder found almost no benefit from yaw motion. When translational motion was present, however, the additional improvement in performance from yaw motion was small. Similarly, the current study found translational motion improved performance, but unlike Schroeder's study, there was little additional benefit from translational motion when yaw motion was present. There are many possible explanations for the different results of the two studies, but to date none of these has been verified. Of particular concern for simulation researchers is the possibility that the differences in the two facilities lead to the different results. A large effort was made to closely match the main cueing systems in the current study to those in the original NASA study. If the remaining modest differences led to the different results, then generalization of simulation results is troublesome at best. The study also demonstrates the difficulty in repeating experiments at different facilities. It is a large effort and there are often simulator differences that cannot be eliminated.

A number of general conclusions from the current motion study are noteworthy. For the three yaw tasks, the study found that translational motion had a larger impact on fidelity than yaw motion, and was usually easier to detect. For a representative disturbance task, both yaw and translational motion were of benefit to performance, as well as fidelity; although the benefit from translational motion was larger. For the tracking task there was a small but significant effect of translational motion on performance and a small, marginally significant effect of yaw motion on performance. Hosman et al.'s descriptive pilot model [7] proved useful at determining the tasks that were studied in the simulator.

Acknowledgments

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