Effects of Motion Cueing on Components of Helicopter Pilot Workload

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ABSTRACT

Research into the effect of motion cueing on workload in flight simulation has resulted in conflicting conclusions. Some researchers provide evidence that motion cueing technology affects pilot workload (Schroeder 1999), whereas others found no effect ((Go, Burki-Cohen, and Seja 2000). This study examined data from a recent helicopter flight simulation experiment to determine how different motion cueing technologies affected the components of workload. 24 Canadian Forces pilots performed eight Aeronautical Design Standard –33E mission task elements and 3 emergency manouevres in a simulated medium-weight helicopter configurable with a 6 degree-of-freedom motion platform, a motion cueing seat, or no motion cueing. Each pilot performed all the manouevres in two of the three motion cueing conditions. Detailed workload measures (NASA TLX) captured after each manouevre will be examined to determine how the individual components of workload are differentially affected by the different cueing technologies. The results are important in that they suggest that pilots may perform and potentially learn the task differently, depending on the motion cueing technology employed in the simulator.

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The use of proprioceptive motion cueing in flight simulation predates World War I (Ullrich 2008), yet its proper role in simulation training continues to be debated (US Department of Transportation 2010). However, two recent reviews concluded that motion cueing does not appear to have any effect on the transfer of training (McCauley 2006; Bowen, Oakley, and Barnett 2006).

The lack of evidence of an effect of motion cueing on transfer of training could be attributed to differences in effort or workload when a pilot is forced to perform or learn a task in the absence of motion cues. Hall (1989) explains that there are four main ways that pilots sense and perceive motion: vestibular organs, touch, kinesthetic sensors and visually. Vestibular organs are responsible for a pilot's sense of balance; or their ability to feel if they are traveling flat and level (i.e. lined up with the horizon), or if they are flying on an angle to the horizon. Touch refers to a pilot's ability to sense both tactile and pressure changes. Most commonly, these sensations are keenly felt during a quick acceleration. Kinesthetic sensors help a pilot distinguish between the aircraft's motion and the motion of their own body by providing muscular feedback (i.e. how hard their muscles are working) and orientation (i.e. knowing that the aircraft is moving forward while the pilot is looking left). Finally, external visual cues allow the pilot to comprehend motion, especially by detecting changes in the environment (i.e. landscape changing) and the rate of change (i.e. acceleration/ deceleration). Hall (1989) argues that when one or more of the sensory inputs of flight are missing, the pilot expends more effort, but achieves the same level of performance. Schroeder (1999) provides some supporting evidence, reporting that pedal input rates (used as a marker of workload) decreased when translation motion was added to a helicopter simulator. Rotational motion had no effect on pedal inputs, however.

The present study addresses the possibility that pilots in simulators without motion cueing bear a greater workload to achieve the same level of task performance as pilots of simulators equipped with motion cueing systems. The data were collected in a recent helicopter flight simulation experiment to assess the effect of different motion cueing technologies on learning and performance (Grant 2011). Canadian Forces pilots performed various flight manoeuvres in two of the three motion cueing conditions: no motion, motion seat, and full motion platform (6 degrees of freedom).

Workload was assessed using the NASA Task Load Index (TLX) (Hart and Staveland 1988) to provide a more fine-grained characterization of workload and to facilitate comparisons with future studies. The NASA TLX provides an overall workload score, which will determine if the different motion cueing technologies lead to different workload during the flight. The TLX also provides scores for components of workload. The components of workload scores were examined to determine if and how the components of workload are differentially affected by the different motion cueing technologies. It could be that the overall workload remains the same, but the nature of the workload changes with cueing provided. For example, Hancock and Caird (1993) had subjects perform a target sequence task and measured workload using the NASA TLX (Hart and Staveland 1988) and the Subjective Workload Assessment Technique (Reid and Nygren 1988). Both measures of workload revealed that changes to task conditions affected some workload components differently from others.

METHOD

Subjects

In the conduct of the experiment, 24 Canadian Forces (CF) rotary wing pilots flew the FTD. They were drawn from all CF rotary wing fleets. Their rotary wing flight experience ranged from 110 to 6500 hours.

Apparatus

The flight training device (FTD), located at the Carleton University Visual and Simulation Centre, represented a three-engine, medium–weight helicopter equipped with an automatic flight control system. The system, depicted in Figure 1, is a research device and was developed to evaluate motion cueing options for future devices (Grant 2011).

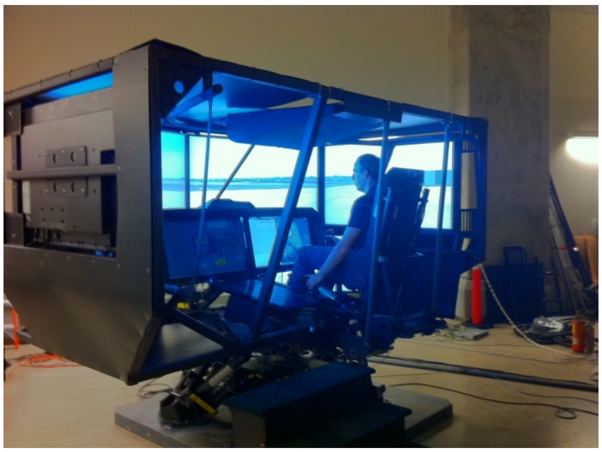

Figure 1 The Flight Training Device

The FTD accommodates a single pilot in the right-hand seat of a cockpit mock-up. Although medium-weight helicopters typically operate with two pilots, the payload of the motion platform restricted operation to one occupant. In this experiment, the non-flying pilot was a confederate located at an instructor console. The instructor console was equipped with voice intercom, flight data displays, and systems controls that allowed the confederate to support the flight manoeuvring and emergency procedures included in this experiment.

The FTD has three different motion cueing configurations. In the first configuration, the FTD employed a Moog six degree of freedom (6DOF) motion platform that provided approximately ±22° of rotation around each axis and approximately ±25 cm of translation along each axis. In the second configuration, the No Motion condition, the motion platform was not activated. In the third configuration the seat on the motion platform was replaced by a motion cueing seat provided by Acme Worldwide Enterprises. In this Motion Seat condition, the seat provided cues to aircraft vibration, rotation and translation by movement of the seat back and pan.

Other aspects of the FTD were identical across conditions. Wittenstein flight controls provided force-feedback cueing to the pilots. The visual display consisted of six LCD flat panel monitors driven by a six channel image generator running Genesis RTX software. The flight dynamics for the simulator were derived from the RotorLib software from RT Dynamics.

Procedure

The pilots completed two sessions in the FTD, first with one type of motion cueing (No Motion, Motion Seat, or 6DOF), then with one of the other technologies, as depicted in Table 1.

Table 1. Motion Cueing per Session

First Session	Second Session
No Motion	Motion Seat
No Motion	6DOF
Motion Seat	No Motion
Motion Seat	6DOF
6DOF	No Motion
6DOF	Motion Seat

In each session the pilot performed 4 repetitions of 8 different mission task elements (MTEs) defined in the US Army ADS-33E standard (US Army 2000) followed by 3 repetitions of 3 emergency manoeuvres defined in cooperation with subject matter experts and summarized in Table 2. The MTEs are precision manoeuvres used to evaluate the handling qualities of helicopters, whereas the emergency manoeuvres are compositions of multiple manoeuvres that form more complex vignettes. Aircraft location, velocities, accelerations, and flight control inputs were recorded at 60 Hz.

Table 2. Emergency Manoeuvres

Emergency	Description
Tail Rotor Failure	During forward flight the tail rotor fails, fixing the pitch of the rotor. The pilot must regain control of the aircraft and perform a run-on landing at a nearby runway.
Automatic Flight Control System Failure	During a night approach to a ship, a dual generator failure disables the automatic flight control system. The pilot must maintain controlled flight until the system is restarted.
One Engine Inoperative, confined area off-level landing	During a hoisting operation in a confined area, one engine fails and the pilot must perform an immediate off-level landing.

After performing each MTE or emergency manoeuvre block, the pilot completed the NASA TLX (Hart and Staveland 1988) to assess the workload experienced while performing the manoeuvres. The TLX captured the pilots' mental demand, physical demand, temporal demand, performance attained, effort expended, and frustration experienced. At the end of the experiment, they compared the relative importance of these sources of workload.

RESULTS

Analysis of the performance of the ADS-33E Mission Task Elements revealed that the pilots performed similarly regardless of motion cueing technology. In general, their performance was satisfactory, showing that they were able to meet the ADS-33E criteria for "adequate" performance by utility and cargo helicopters. The exceptions were the time to achieve hover in the hover MTE, position and altitude in the Hover Turn MTE, and track error in the Depart / Abort MTE. These are depicted in Figure 2.

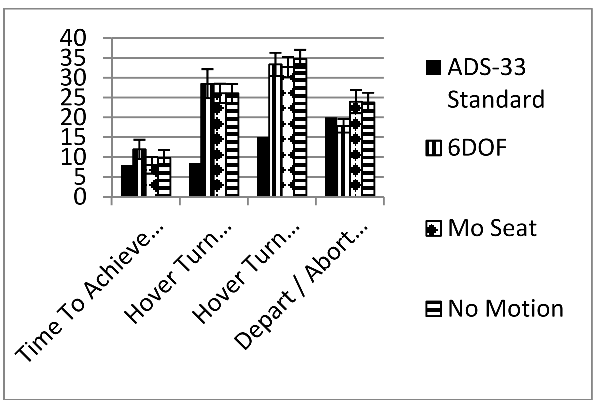

Figure 2 90% Confidence Intervals for ADS-33E MTEs showing differences amongst motion cueing types

The time needed to achieve hover in the Hover MTE exceeded the standard in all motion cueing conditions. The standard was within the 90% lower confidence interval of the No Motion and Motion Seat conditions, but not the 6DOF condition. In the Hover Turn MTE, the pilots, regardless of type of motion cueing technology used, could not meet the altitude or position standards. The performance standards were not within 90% confidence limits around their mean performances. Considering the Depart / Abort MTE, only the pilots using the 6DOF system achieved a mean level of performance that kept their flight track within the margin of error called for by the standard. The 90% confidence limit around the mean performance of the Motion Seat and No Motion did not include the performance standard.

To determine whether the type of cueing technology affected performance on the ADS-33E MTEs, a series of planned comparisons were performed. The decision criterion was set at α =.10 (uncorrected for multiple comparisons). On 11 of the 17 dependent measures, there was no difference amongst the different cueing conditions. Six comparisons did detect a difference, but the differences did not follow a pattern. Hover MTE altitude errors and Depart / Abort MTE track position errors in the 6DOF condition were smaller than in the other conditions. However, Hover MTE heading error and Hover Turn MTE position error were larger in the 6DOF condition than in the No Motion condition. As well, Landing MTE position error was lower in the Motion Seat condition than in the No Motion condition. Finally, pilots in the No Motion condition were able to achieve a higher Slalom MTE speed than pilots in the other conditions. For more detailed treatment, see Grant (2011).

Given that the task performance using the different motion cueing technologies were generally acceptable and equivalent, the workload scores were examined to determine if this comparable performance was being achieved under unequal workload. The unweighted workload component scores and the scaled sum of components workload data were analyzed using a series of 3 (cueing technology) x 11 (manoeuvre type) repeated measures analyses of variance. All analyses were performed with the per-comparison Type I error rate set to α =.10. Mean ratings are presented in Table 3.

Table 3 Mean Component Workload Ratings

Workload Component	Mean Rating		
	No Motion	Motion Seat	6DOF
Mental	51.03	46.54	49.14
Physical	42.46	39.60	41.89
Temporal	44.12	42.01	42.14
Performance	43.68	44.68	44.14
Effort	54.50	50.59	53.77
Frustration	38.41	37.23	37.30
Overall	48.30	46.16	46.73

The analysis of the overall workload scores showed that while some manoeuvres were harder than others ($F_{10, 474}$ = 20.76; p < .00001), the type of motion cueing technology had no effect on the overall workload experienced by the pilots ($F_{2,474} = 1.02$; $p > .1$). There was no interaction of motion cueing technology and manoeuvre ($F_{20,474} = 0.90$; $p > .10$).

The analysis of the mental demand found a significant effect of both manoeuvre ($F_{10,474} = 11.60$; $p < .00001$) and motion cueing technology ($F_{2,474} = 2.69$; $p < .1$), but again, no significant interaction ($F_{20,474} = 0.68$; $p > .10$). Planned comparisons of the different motion cueing technologies revealed that the mental workload experienced while using the motion seat was significantly lower than the No Motion condition. The ratings in the 6DOF condition did not differ significantly from the other conditions.

The analysis of the physical demand found a significant effect of manoeuvre ($F_{10,474} = 7.79$; $p < .00001$), but neither for cueing technology ($F_{2,474} = 1.72$; $p > .1$), nor the interaction ($F_{20,474} = 0.59$; $p > .1$).

The temporal demand data showed only an effect of manoeuvre ($F_{10,474} = 23.55$; $p < .00001$). The effect of cueing technology ($F_{2,474} = 0.67$; $p > .1$) was not significant, nor was the interaction ($F_{20,474} = 0.73$; $p > .1$). Likewise with the performance component of workload, where the effect of manoeuvre was significant ($F_{10,474} = 14.80$; $p < .00001$) whereas the effects of motion cueing technology ($F_{2,474} = 0.12$; $p > .1$) and the interaction ($F_{20,474} = 1.04$; $p > .1$) were not.

The effort component of workload showed significant main effects for manoueuvre ($F_{10,474} = 13.54$; $p < .00001$) and motion cueing technology ($F_{2,474} = 2.58$; $p < .1$), and no interaction ($F_{20,474} = 0.76$; $p > .1$). Planned comparisons revealed that the effort component of workload was lower in the Motion Seat condition than in the No Motion condition. The 6DOF condition was not significantly different from the other two conditions.

Finally, the manoeuvring task affected the Frustration component of workload ($F_{10,474} = 14.28$; $p < .00001$), but the motion cueing technology did not ($F_{2,474} = 0.19$; $p > .1$), nor was there an interaction ($F_{20,474} = 0.83$; $p > .1$).

DISCUSSION

Helicopter pilots performed a series of flight manoeuvres using different motion cueing technologies: a six degree of freedom motion platform, a motion cueing seat, and a fixed base condition, where the motion cueing systems were switched off.

The pilots achieved an acceptable level of performance, the effect of motion cueing had few effects, and those differences did not consistently favour one technology over another.

When the workload measures were considered, there was no overall difference in workload amongst the different motion cueing conditions. However, when the individual components of workload were examined, pilots experienced significantly lower mental workload and lower effort when using the motion seat as opposed to the other cueing technologies.

This result is interesting in two regards. First, the motion cueing seat provided the lowest workload. Under the common, but untested, assumption that the lowest workload equates to the best or highest fidelity cueing, the obtained result contradicts the view that a motion seat is an intermediate solution between a fixed base system and a full motion platform. Perhaps the motion cues provided by motion seats bear greater fidelity to those experienced in real systems, or perhaps those cues are more important to task performance.

Second, this result provides some support for the assertion that motion cueing technologies affect workload (Hall 1989). If the present result is replicated by future studies, the implication is that the components of workload should be considered when assessing the effect of motion cueing on task performance. The same implication would apply to studies of transfer to live systems. The repeated failures to find any effect of motion cueing on transfer of training would be bolstered by data showing that operators were not compensating for impoverished cueing with increased workload.

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