L38

N82-13703

THE INFLUENCE OF SHIP MOTION ON MANUAL CONTROL SKILLS

By Peter McLeod, Christopher Poulton

MRC Applied Psychology Unit, 15 Chaucer Road, Cambridge CB2 2EF, England

Howard Du Ross

RAE, Farnborough, Hants, England

and Wynn Lewis

WSL, Stevenage, Herts, England

SUMMARY

The effects of ship motion on a range of typical manual control skills were examined on the Warren Spring ship motion simulator driven in heave, pitch and roll by signals taken from the frigate HMS Avenger at 13 m/s (25 knots) into a force 4 wind. The motion produced a vertical r.m.s. acceleration of 0•024g, mostly between 0•1 and 0•3 Hz, with comparatively little pitch or roll. A task involving unsupported arm movements was seriously affected by the motion; a pursuit tracking task showed a reliable decrement although it was still performed reasonably well (pressure and free-moving tracking controls were affected equally by the motion); a digit keying task requiring ballistic hand movements was unaffected. There was no evidence that these effects were caused by sea-sickness.

The differing response to motion of the different tasks, from virtual destruction to no effect, suggests that a major benefit could come from an attempt to design the man/control interface on board ship around motion resistant tasks.

INTRODUCTION

Ship motion typically consists of a narrow band of high amplitude, low frequency movement with a wider band of low amplitude motion at higher frequencies superimposed on it. The degrading effects of the low amplitude, high frequency motion (i.e. vibration) on manual control skill are well known (for reviews, see Guignard and King 1972, Collins 1973, or Drennen et al. 1977) and much is known about the tendency of low frequency movement to induce nausea (e.g. O'Hanlon and McCauley 1974). But very little is known about the effects of the high amplitude, low frequency components of ship motion on manual control skills This is presumably due, at least in part, to the high cost of building simulators to reproduce the high amplitude of the low frequency components.

The only studies of the effects of ship motion on control skills are Jex et al. (1976) and O'Hanlon et al. (1976). Jex et al. simulated the motion of a 2000 ton surface effect ship at a variety of speeds and sea-states. Sailors spent up to 2 days in the cabin performing a range of tasks including tracking, vigilance, navigational plotting, keyboard operation and mechanical assembly. The various conditions simulated produced a range of r.m.s. vertical acceleration values between 1 and 3m/s^2. (Note: r.m.s. acceleration is the standard deviation of the accelerations experienced during the run. For those who find it easier to appreciate acceleration magnitude in terms of g, 1m/s^2 is almost exactly equal to 0·1g.)

The study reported here is similar to the Jex et al. study in using ship motion in three dimensions: heave, pitch and roll. However, the level of accelerations is considerably lower, in fact at a level where Jex et al. predict there will be no effects of ship motion on manual control skill. A range of manual control skills was studied: tracing (unsupported movements of the while arm); tracking, using either a pressure or a free moving control, (continuous fine hand movements with the arms supported); keyboard digit punching (ballistic movements with unsupported hands). An attempt was made to separate the effects on performance of motion itself and the effects caused by feelings of sickness induced by the motion.

METHOD

2.1. The motion

The experimental cabin was mounted on the ship motion simulator at the Department of Industry laboratory at Warren Spring, Stevenage, England (see Appendix). This was driven in heave, pitch and roll by signals recorded from the helicopter deck of the 2040 ton frigate HMS Avenger moving at 25 knots (13 m/s) into a force 4 wind Under these conditions virtually all the motion is in heave (i.e. vertical movement): the r.m.s. accelerations in heave, pitch and roll were 0·24 m/s^2, 1·35°/s^2 and 0·46°/s^2 respectively. Given that the subject's head was about 1·7 m above the centre of rotation of the cabin the two latter figures correspond to approximately 0·045 m/s^2 and 0·015 m/s^2. These values are so low that we have only correlated performance with the vertical accelerations.

The peak to peak vertical motion was 2·5m. The average vertical r.m.s. acceleration for the hundred 7 s periods used for the tracking task was 0·31 m/s^2 --slightly higher than the average over the whole run. The average rate of displacement zero crossings for the whole period of the experiment corresponded to a frequency of 0·17 Hz.

Figure 1 shows the amplitude spectrum for the heave input. It can be seen that the bulk of the energy lies between 0·1 and 0·3 Hz. Figure 2 shows a typical period of 110s motion in heave. The upper trace shows the displacement signals recorded on HMS Avenger which were used to drive the experimental cabin. The superimposition of high frequency low amplitude components on the low frequency waves is clear. The centre trace shows the vertical acceleration of the cabin while being driven by the upper trace. It can be seen that a jolt, a brief period of higher than average acceleration, sometimes followed the start of an upward movement by the cabin. The average duration of the jolts was 0·28s, range 0·12 to 0·38s. The average

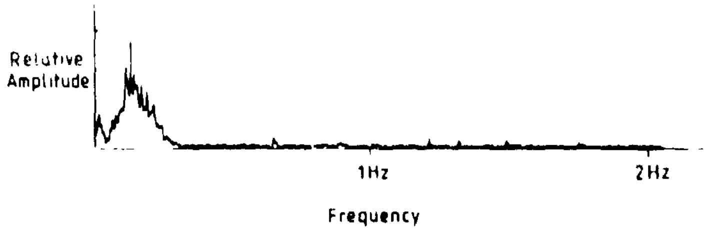

Figure 1. Amplitude versus frequency plot for the heave displacement input.

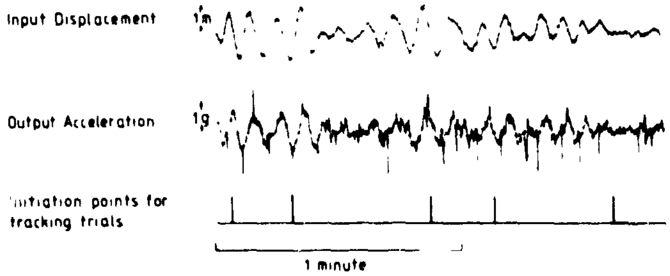

Figure 2. A 110 s period of heave motion. The upper plot shows the displacement input to the cabin. The centre plot shows the vertical acceleration of the cabin. The bottom line shows the points at which tracking runs were initiated during this part of the motion.

peak acceleration was 0·16m/s^2, range 0·1 to 0·2m/s^2. This non-linearity introduced by the simulator was unfortunate but not disastrous. For the tracking task it was possible to examine the effect of the jolts by comparing performance on those trials where they occurred with those where they did not.

2.2. Motion sickness

As figure 1 shows, the motion used lies mainly between 0·1 and 0·3 Hz. This is the region which is most efficient at inducing motion sickness (O'Hanlon and McCauley 1974). (It should be noted that their data were obtained with single sinusoids: quantitative data for complex motion do not exist.) The r.m.s. acceleration value used is slightly less than that which would be expected to produce vomiting in 5% of young men after 2 hours exposure (0·33m/s^2) at the most nauseogenic frequency (0·167 Hz). However, since feelings of nausea are likely to degrade performance, it is important to try and separate these from any biomechanical effects of motion. Reason and Graybiel (1969) have reported the commonest subjective sensations which precede nausea. These sensations are a change in general well-being, dizziness, stomach awareness, headache, salivation, sweating and blurred vision. Before, during and after motion subjects rated their feelings on each of these dimensions. The subjects were given a booklet with a line 100 mm long on each page corresponding to one of the sensations with the two end points appropriately marked, e.g. 'fine' and 'awful' for the general well-being scale. They placed a mark on each line to indicate how they felt. Changes in the position of the marks were used as an indication of which subjects felt nauseous.

2.3. The experimental cabin

A cabin measuring 2·3 m × 1·85 m with a curved roof, minimum height 1·85m was mounted on the moving platform. This was enclosed so there were no visual cues to motion for the subjects. During an experimental run the subject was strapped to a modified Sea King helicopter seat facing a console holding the CRT display for the tracking task and the LED display for the number punching task (see figure 3). Forearm restraints, the joystick and a numerical keyboard were attached to the deck of the console; the subject used the forearm restraints for the tracking task but not for the key punching task. An emergency button to stop the rig, a vomit bag and the booklets for subjective ratings were also attached to the console. The patterns for the tracing task were pinned to the back wall of the cabin.

Communication between subject and experimenter was via headphones; the subject was observed throughout the experiment by a closed-circuit TV camera mounted over the console.

2.4. The tasks

2.4.1. Tracing task.

The subjects stood upright and tried to trace along a variety of patterns drawn on a sheet of paper pinned to the wall at shoulder height. The subjects stood at approximately arm's length from the wall and were not allowed to steady themselves by holding onto the cabin or to try and support their writing arm on the wall. They performed a set of six tracings twice over on each occasion. Measures taken were accuracy and

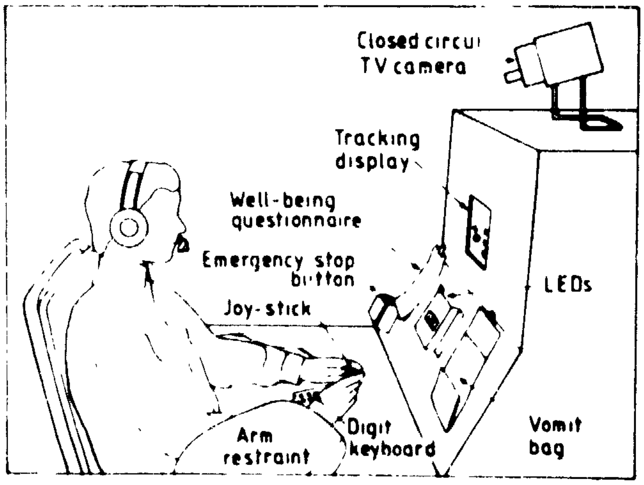

Figure 3. The console in the experimental cabin

time to complete each set of six. The accuracy was measured by sampling the perpendicular distance from the tracing to the line the subjects were trying to follow at 31 points distributed across the six patterns. Figure 4 shows four attempts to follow the tracing patterns, the upper two static and the lower two made under motion.

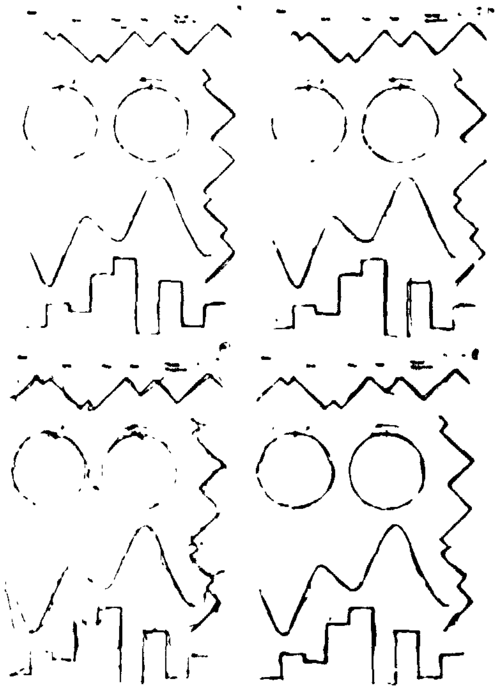

Figure 4 Four attempts to follow the tracing pattern. The upper two were done with the cabin stationary. The lower two while it was under motion. They show the approximate range from best to worst under both conditions

2.4.2. Tracking task. This was a pursuit task, with each trial lasting 7s. The seated subjects face a 100 mm × 80mm screen at a viewing distance of about 600mm. Their forearms were supported by arm restraints. Each trial was preceded by the word READY on the screen for 1s. Then the target, a circle radius 2•5mm, and a cross (arm length 5 mm) which was controlled by the subject appeared on the screen. The cross and circle started in random positions with the proviso that the circle was inside a central area measuring 50 mm by 40 mm and the cross was outside this area. Throughout each trial the circle continued to move at random within this inner area. The algorithm used to control the movement of the circle was that every 300ms its vertical and horizontal velocities were changed independently by a random amount with a random sign up to a maximum in either direction of 0•75cm/s. The subject's task was to place the cross inside the circle as quickly as possible and keep it there for the remainder of the trial.

There were two groups of subjects, four men and one woman in each. One group tracked with a pressure control (i.e. a joy-stick which does not move, but which gives an output proportional to the force applied to it); the other tracked with a spring-centered free-moving joy-stick, the output of which was proportional to its displacement from the central point. The relation of the position of the cross on the screen to the output of the joy-stick was

$$P_c = P_j + 3\int P_j dt + \int\int P_j dt$$

where P_c is the position of the cross and P_j the output from the joy-stick. The control, therefore, was basically a velocity control, with small components of position and acceleration.

The performance measures taken were the time to acquire the target and the modulus mean error after acquisition. "Acquisition' was defined as holding the centre of the cross within 5 mm of the centre of the circle continuously for 1 s.

The tape driving the cabin lasted for 22 min. During this time there were 50 tracking trials occurring at fixed positions at intervals of 20-30s. During an experimental run of 100 trials the subject experienced the tape twice through separated by a static period of about 25 s. The cabin went through the same motion on any particular trial for every subject.

2.4.3. Digit keying task. The subjects were presented with a series of 50 four digit numbers which they entered on a conventional calculator keyboard. Their arms rested on a horizontal surface but were not restrained. The keys were 9 mm square with a vertical and horizontal inter-key spacing of 6·5mm. In pre-motion training the numbers were spoken aloud by the experimenter. Under motion they appeared on the LEDs in front of the subject (see figure 3). In both cases the subjects were required to say the number aloud and then enter it as a group of four keystrokes. They were instructed to go as fast as was compatible with error free performance. Entry time of each key stroke and any errors were recorded.

2.5. Experimental design

2.5.1. Pre-motion practice. The subjects practiced the three tasks over a period of 3 months before going to the motion simulator. On eight separate days they performed a block of 20 tracking trials. They performed the tracing task twice and also had two blocks of 50 numbers on the digit keying task on each of two days.

2.5.2. Motion. Each subject performed the tasks under motion on two consecutive days. The complete session including stationary control trials, filling in well-being questionnaires and taking transmissibility measures lasted about 2·5 hours. The experimental design for the motion sessions is shown in table 1.

2.6. Subjects

The subjects were eight men and two women from the Applied Psychology Unit staff. They all claimed not to be prone to sea-sickness. They were right-handed, and their ages ranged from 23 to 60 years. For the tracking task they were divided into two groups of four men and a women, one group using the pressure control and the other the free-moving control.

Table 1. The order of tasks during a motion session.

Cabin	Task	Approximate duration (min)
Stationary	20 tracking trials	15
	Well-being ratings	2
	2 tracings	2
Moving	100 tracking trials	50
	Well-being ratings	2
	2 tracings	2
Stationary	15 tracking trials	10
	Well-being ratings	2
	2 tracings	2
	5 min break outside cabin	
Motion	Transmissibility measures taken from subject	15
	Well-being ratings	2
	Key-punching task	20
	Well-being ratings	2
	Transmissibility measures taken from subject	10
Stationary	Well-being ratings	2

RESULTS

3.1. Nausea

None of the subjects actually vomited. However, there was a small but reliable drop in the feeling of well-being. Comparing the estimate made immediately prior to motion with that made at the end of the first motion session (see table 1) gives a drop of 9% in the scale going from 'Fine' to 'Awful, about to vomit'. Pooling across days and subjects this is reliable, $p<0{\cdot}05$, Wilcoxon test, 2-tail. None of the individual indices (dizziness, sweating, headache, stomach awareness, salivation or blurred vision) showed a reliable change when pooled across subjects and days. At the end of the second motion session the position was very similar. Compared to the pre-motion ratings, 'well-being' pooled across subjects and days showed a reliable 7% decline ($p<0{\cdot}05$, Wilcoxon test, 2-tail). But none of the other individual indices showed a reliable change. Table 2 shows the detailed ratings.

3.2. Tracking task

Figure 5 shows the basic performance data for the tracking task. The two left hand graphs show the performance of the group who tracked with the pressure control; the right-hand side shows the performance of the group with the free-moving control. The two upper graphs show the acquisition time (in seconds); the two lower graphs show the average modulus mean error after acquisition (in millimetres). (It should be noted that the minimum possible acquisition time is greater than zero, approximately 2s, but the minimum possible error is zero.) In each graph the average performance on the 20

Table 2. Mean subjective judgments between 100 = fine and 0 = awful.

Judgment	Pre-motion	Motion	Change for worse	Post-motion
Well-being	91	82	9*	88
Dizziness	90	89	1	89
Sweaty	64	55	9	61
Headache	89	86	3	88
Stomach awareness	90	83	7	88
Salivation	43	48	−5	46
Blurred vision	94	92	2	94

$^{*}p<0{\cdot}05$.

pre-motion trials and the 15 post-motion trials is shown separately, before and after the 100 motion trials. The 100 motion trials have been broken down into ten consecutive groups of ten.

The main effect, that tracking is worse under motion, is immediately obvious. Taking the mean of the pre-motion and post-motion trials as a control, every subject in both groups takes longer to acquire the target under motion ($p<0{\cdot}01$, sign test). (Pressure control--acquisition time: control = 2•8 s, motion = 3•1s; error: control = 1•3 mm, motion = 1•8 mm; free-moving control--acquisition time: control = 3•0 s, motion = 3•2s; error: control = 1•9 mm, motion = 2•2 mm.) If this effect were caused by onset of nausea the size of the motion decrement would increase over the 100 trials (about 50 min of motion). Figure 5 shows that this is not the case. None of the four performance indices show a reliable correlation with time on task (the largest of the four correlations is 0•06). In other words the decrement caused by motion appears as soon as the cabin starts moving and is no worse after 50 min motion. Therefore we can say with confidence that there is a degradation in tracking performance caused by the biomechanical effects of this relatively small degree of motion even for subjects who are strapped to a chair and whose forearms are restrained.

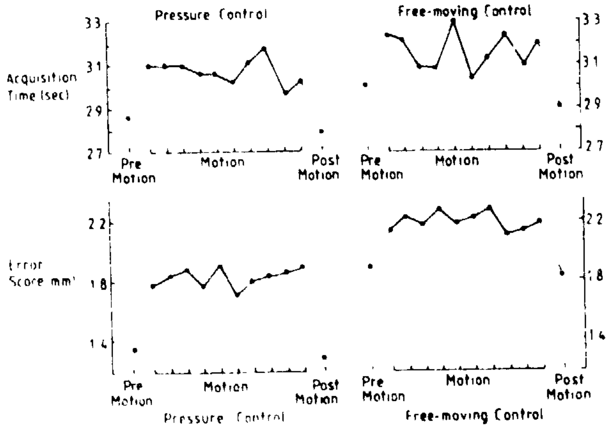

Figure 5 The results of the tracking experiment. The two left-hand graphs show the data from the pressure control. The free-moving results are on the right. The two upper graphs show the acquisition time; the two lower ones show the error score.

It was mentioned in §2.1 that the simulator introduced some jolts, brief periods of relatively high acceleration, into the movement. It is possible to see whether the tracking decrements were caused by the jolts rather than the normal motion by comparing the performance on trials where there was a jolt with that on trials where there was not.

For both pressure and free-moving controls the presence of a jolt after acquisition made no difference to the error score. (Pressure control: error--with jolt = 1·8 mm, no jolt = 1·8 mm; free-moving control: error--with jolt = 2·2 mm, no jolt = 2·2 mm.) Clearly the motion decrement in the error score cannot be attributed to the jolts.

The presence of a jolt did produce slower acquisition by the free moving group (mean acquisition time with jolt = 3·3s, no jolt = 3·1s; $p>0{\cdot}02$, Mann-Whitmey test). There was an effect in the same direction for the pressure group which failed to reach significance (mean acquisition time with jolt = 3.1s, no jolt - 3.0s; $p=0.125$, Mann-Whitney test). Part of the reduction in acquisition time under motion is caused by the jolts rather than the real ship motion. However a comparison of acquisition time on no jolt trials with the pre- and post-motion control trials shows that every subject in the free-moving group was slower on the jolt-free motion trials. Therefore, as with the error measure, it is clear that the motion does produce a reliable, if small, change in the acquisition time.

It is possible to examine the extent to which the two controls are affected by the roughness of the 'sea' by correlating the average group performance on each no-jolt trial with the mean modulus vertical acceleration on each trial. The range of mean modulus acceleration experienced ranged from 0.03 to 0.45 m/s^2. Both performance measures for both controls show positive correlations as would be expected but they were not particularly large, nor were the differences between the correlations for the two controls reliably different. (Free moving: acquisition time, $r_s=0.48, p<0.01$; error, $r_s=0.28$, $p<0.1$; pressure: acquisition time, $r_s=0.39, p<0.025$; error, $r_s=0.25, p<0.1$.) There seems to be little difference in the effects of roughness on these two controls although the rather small range of 'roughness' examined should be noted.

There seems to be little ground for deciding that either control is superior under motion. They show a similar response to both jolts and roughness. The pressure control is superior on both performance indices under motion but the same is true of the non-motion conditions. This may reflect a difference in tracking ability between the rather small groups, or a genuine superiority of the pressure control for this particular combination of task and control law.

3.3. Tracing task

The tracing patterns produced under motion were compared with those produced immediately before and after motion. The increase in error was large and shown by every subject. (Mean error: no motion=0.7mm; motion=1.9mm, $p<0.01$, sign test.) There was a small increase in the time to complete each tracing under motion, but pooled across days and subjects this was not reliable. (Mean time to completion: control=46.8s; motion=48.5s; $p=0.2$, Wilcoxon test, 2-tail.)

Figure 4 shows four tracings; the upper two were produced with the cabin stationary and the lower two under motion. The lower two demonstrate the range of tracings produced under motion from the very bad (which is typical of about half the tracings produced under motion) to one which is as accurate as the worst tracing produced when the cabin was stationary.

3.4. Digit keying task

The subjects keyed in a string of 50 four digit numbers, twice under motion and twice static. The data given for each condition are for the middle 20 four digit numbers on each of the days, pooled across the two days. The standard deviations are the means of the standard deviations for the individual subjects.

Time to enter a four digit number (static)=1069ms(S.D. 218ms)
Time to enter a four digit number (motion)=1102,s(S.D. 249ms)

The difference in mean keying time is due to chance. Half the subjects are faster under motion, half are slower. The increase in variability approaches reliability (p=0.075, Wilcoson test, 2-tail). There was a small increase in errors (0.5 to 1.0%) which approaches reliability across subjects (p=0.07, Wilcoxon test, 2-tail).

CONCLUSIONS

We have examined three manual control tasks requiring movement of the unsupported arms, continuous fine movement with restrained arms or ballistic hand movement with unsupported arms. The extent of degradation in these tasks caused by a comparatively mild ship motion is very different.

The tracing task, involving continuous whole arm movement was very seriously affected. The average error increased by a factor of three and many of the individual records were so bad that without the target tracing visible it would be difficult to guess what the subjects' intended drawing had been. The tracking task, which involved continuous fine movements of the supported arms, was reliably worse under motion, but performed with reasonable conpetence. The average error and the time to acquire the target increased by about 20%. The digit keying task, requiring a group of four pre-programmed ballistic movements, was virtually unaffected.

The changes in performance were not primarily due to nausea. Firstly, the motion was below the threshold at which 5% of people vomit after an exposure somewhat longer than the duration of the motion in the experimental period. Secondly, the subjects reported little change in their own feelings of well-being. Thirdly, in the tracking task there was no change in performance over a period of about an hour. Were nausea an important factor, performance would decline with time as nausea increased.

This study is clearly preliminary. It involves the dynamic response of only one sort of ship to one sea-state. However, in general, it confirms the findings of Jex et al. with a very different sort of ship under much rougher conditions. They found very little change in performance of a desk-top calculator task, a consistent 20-40% drop in tracking performance and breakdown in a task requiring unsupported arm movements. The major point of difference between the studies is that Jex et al. dismiss motion under $1 m/s^2$ r.m.s. as unlikely to affect performance. It is clear from our study that there are reliable changes in performance well below $1 m/s^2$ r.m.s.

There has been remarkable little work to date on the influence of ship motion on manual control skills. It seems necessary to demonstrate two conditions before it is worth investing a major human factors effort in designing the man/control interface on board ship to minimize the effects of motion. Firstly it needs to be shown that some tasks are much more affected by motion than others, otherwise there would be no scope for optimizing the design around tasks which are relatively unaffected by motion. Secondly, it is necessary to show that nausea is not the major determinant of the decrement. If it were, this would indicate a job for a pharmacologist rather than an ergonomist. This paper has demonstrated that both these conditions can be met.

As an example of the importance of these results we might consider the design of a system to allow an observer to identify a point of interest on a radar display on board ship. A recommendation from existing human factors wisdom, which all derives from land based experiments, would suggest, other things being equal, that a light-pen was preferable, a joy-stick controlled cursor next best and a keyboard entry specifying the appropriate matrix point on the display the least efficient. It is clear from the results of our experiments that the results of land based experiments cannot simply be transferred to ships, for a light pen would be the most affected by ship motion and keyboard entry the least. Of course, this does not mean that light pens must not be used in moving environments. But it does mean that a proper programme of research should be mounted to investigate the effects of likely movements to be met under operational conditions on the tasks in question before devices which involve unrestrained limb movement are used in moving environments.

ACKNOWLEDGMENTS

The authors wish to thank Harry Hughes and the staff of the Warren Spring simulator, who did so much to make this work possible. The research was funded by the Office of the Senoir Psychologist (Naval) and coordinated by Hugh Stockbridge. The authors received considerable help in running the experiments and analysing the data from Bob Edwards, Dave Howarth and Bob Olsson. Geoff Allen helped with some of the technical analysis. Finally, we would like to thank the members of the APU staff who volunteered to act as subjects.

APPENDIX

Description of the Warren Spring ship motion simulator

The WSL ship's motion simulator is a counter-balanced gimbal mounted platform system with a heave displacement capability of 3•2m and out-to-out angular motion of 14° in both roll and pitch axes.

The heave motion is derived from a servo-controlled hydraulic motor and reduction gear which drives the payload and counterbalance platforms up and down each side of a central supporting mast structure. The two platforms are coupled by a chain which hangs over the drive sprocket on the main shaft at the top of the mast. Thus the platforms are operated as a balanced system and backlash is minimised. Auxiliary free running cables and pulleys are also provided as a safety measure in the event of mechanical failure in the main chain.

Roll and pitch motions are obtained by servo-controlled hydraulic piston actuators acting against the gimbal mounted platform. These are double acting pistons which move through ± 76mm (3 in) to give the out-to-out displacement of 14°.

The motions of the simulator are controlled (1) by locally generated sine-wave signals from which it can be programmed for either single or combined motions and (2) by external signals which includes recorded ship's motion data or synthesized random data. Operation by sine-wave signals allows individual control of frequency, amplitude and phase relationship for all three motions. To prevent possible damage to the simulator, external signals are connected through a low-pass filter and attenuator to limit signals to within safe operating capability of the simulator.

Collins, A. M., 1973, Decrements in tracking and visual performance during tracking. Human Factors, 15, 379-393.

Drennen, T. G., Curtin, J. G., and Warner, H. D., 1977, Manual control in tracking tasks as a function of control type, task loading and vibration. McDonnel Douglas Astronautics Company--Report No: MDC E1713.

Guignard, J. C., and King, P. F., 1972, Aeromedical aspects of vibration and noise. AGARD-AG-51.

Jex, H. R., O'Hanlon, J. F., and Ewing, C. L., 1976, Simulated rough water operations during long cruises in a 2000-ton surface effect ship, phases 1 and 1A. Systems Technology, Ins., Technical Report, 1057-2.

O'Hanlon, J. F., and McCauley, M. E., 1974, Motion sickness incidence as a function of the frequency and accelaration of vertical sinusoidal motion. Aerospace Medicine, 45, 366-369.

O'Hanlon, J. F., Miller, J. C., and Royal, J. W., 1976, Simulated rough water operations during long cruises in a 2000-ton surface effect ship--Phase 2. Human Factors Research, Inc., Technical Report, 1757-2.

Reason, J. T., and Graybiel, A., 1969, Changes in subjective estimates of well-being during the onset and remission of motion sickness symptomatology in the slow rotation room. NASA-NAMI joint report: NAMI-1083.