Thresholds to Roll Motion in a Flight Simulator

A. J. Gundry*
R.A.F. Institute of Aviation Medicine, Farnborough, U.K.

Providing effective motion cues requires that we first identify the role of motion in flight simulation, and second describe the amount and type of motion necessary to fulfill that role. One of the first tasks is to define the sensory threshold to motion in a flight simulator. Data on roll motion thresholds measured in a small flight simulator are presented. During the normal use of a simulator, the pilot does not have the sole task of detecting motion. He also has to fly the simulator. Data also are presented on the effects of a concurrent task upon motion thresholds, which were found to increase as the cognitive task became more demanding. It is concluded that the classical method of threshold measurement may produce data that are misleading if used as the basis of motion system drive laws.

Introduction

IN flight, the pilot of an aircraft is subjected to the effects of a dynamic force environment. The effects of this environment on his control of the aircraft can be classified as advantageous or disadvantageous. Disadvantageous effects can arise from the forces on the pilot caused by turbulence and maneuvering. These cause spatial disorientation, motion sickness, or the physiological effects of '*g*'. On the other hand, advantageous effects can arise which can be identified as providing the pilot with veridical information about the motion of the aircraft. These are, in general, transient motions resulting from turbulence or from malfunctions, and those motions that are the result of the pilot's own control activity. A simple distinction can be drawn between advantageous and disadvantageous effects of motion. Disadvantageous effects of motion, in principle, will be suffered by all persons in the aircraft, whereas the advantageous effects of motion can be observed only when the pilot is part of the aircraft control loop.

On the whole, the disadvantageous effects of motion are not intentionally included in flight simulation. However, simulators with motion systems do attempt to reproduce the advantageous effects of motion. These are of two types, which are distinct enough to be given two separate names. Motion cues arising external to the pilot control loop can be called disturbance motion. This results from turbulence and any failure of a component of the airframe, equipment, or engines which results in aircraft motion that is unexpected by the pilot. Motion cues arising within the control loop can be called maneuver motion. This motion results from the pilot initiating a change in the motion of the aircraft in order to achieve a different heading, height, or attitude. All simulators that have motion systems will provide maneuver motion, and those that have turbulence generators will provide disturbance motion in addition.

A number of experiments have found the presence of both types of motion to result in more accurate pilot performance than static stimulation (Beck,[1] Bergeron and Adams,[2] Buckhout et al.,[3] Gerathewohl,[4] Guerico and Wall,[5] Matheny et al.,[6] Ruocco et al.,[7] Sadoff and Harper[8]). What might appear to be a clear picture, showing that motion produces a better performance than no motion, is clouded by the results of Brown et al.[9] and Matheny et al.,[10] who found that cockpit motion did not produce any better performance than no motion, and by the conclusions of some authors that cockpit motion only benefits the performance of some tasks (Brown and Collins,[11] Graham,[12] Perry and Naish,[13] Williges et al.[14]). Further, some authors conclude that the benefit made by motion to performance and training depends upon the experience level of the pilot (Brown et al.,[9] Graham,[12] Newton,[15] Muckler et al.[16]).

Further evidence concerning the effects of motion cues comes from studies of the pilot's control activity. Douvilier et al.,[17] Matheny et al.,[10] Perry and Naish,[13] and Tremblay et al.[18] report a change in the control activity of operators who tracked a simulated turbulence input in a simulator with and without motion. When motion was provided, there was an increase in the occurrence of high-frequency/low-amplitude control movements. These changes served to make the control activity in the moving simulator appear more like that observed during flight than that recorded in the static simulator. Douvilier et al.[17] and Tremblay et al.[18] actually conducted this comparison using the same subjects in a simulator and an aircraft.

Changes in control activity when motion cues are present have been investigated, using the human operator transfer function measures of how hard the pilot needs to work. Experiments by Shirley,[19] Dinsdale,[20] Meiry,[21] and Stapleford et al.[22] used the set-up shown in Fig. 1 to investigate the effects of roll motion upon compensatory tracking. The presence of motion was found to reduce phase lag, increase the midfrequency gain and cross-over frequency, and reduce the size of the remnant. A measure of overall performance, such as root-mean-square error, also showed a decrease when motion was provided. The conclusion is that roll motion cues provide the operator with information that he can use in order to track the disturbance input more accurately. This information is used to generate lead in the output, especially at frequencies above 0.5 Hz (Shirley[19]).

It is clear that one of the reasons why motion results in quicker and more accurate control during simulated turbulence is because it provides more lead information about the disturbance of the vehicle than can be obtained visually. However, motion may play another role, that of giving the

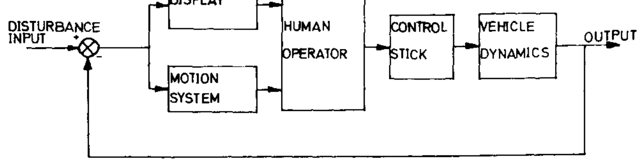

Fig. 1 Block diagram for compensatory tracking task with disturbance and maneuver motion.

Presented as Paper 76-1717 at the AIAA Visual and Motion Simulation Conference, Dayton, Ohio, April 26-28, 1976; submitted April 29, 1976; revision received Jan. 24, 1977.

Index categories: Simulation; Human Factors.

*Junior Research Fellow, Flight Skills Section.

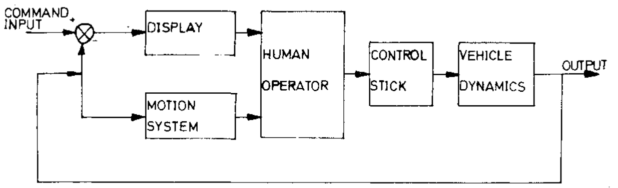

Fig. 2 Block diagram for compensatory tracking task with maneuver motion.

pilot additional information about the consequences of his control actions on the aircraft. This is the role of maneuver motion. Besco[23] studied the effects of heave maneuver motion in the compensatory task, using the set-up shown in Fig. 2, as did Newell[24] and Stapleford et al.[22] for roll. Only Besco[23] found that the presence of maneuver motion aided control. In contrast, Sadoff et al.,[25] using a pursuit task to investigate maneuver motion in pitch, found that it was important only when the simulated vehicle was unstable. Similar findings were reported by Meiry,[21] who required that subjects stabilize a simulator, set up as an inverted pendulum in roll. Meiry[21] altered the dynamics of the vehicle from stable to unstable. When the simulator dynamics were stable, the presence of maneuver motion did little to improve control, but as the vehicle became more unstable, its presence allowed the operator to exercise control, even in regions where control by visual cues alone would be impossible. The conclusion from these experiments is that motion again helps the pilot to generate lead information, and this is especially useful when an unstable vehicle is simulated (see also Young[26] and Bray[27]).

The next question concerns the degree to which disturbance and maneuver motion need to be simulated. There is some experimental evidence that motion can be degraded without too drastic a change in the simulator operator's behavior. Bergeron[28] had operators performing a two-axis compensatory tracking task with varying degrees of motion. With the full pitch and yaw motion of the simulator, tracking error was normalized to be 1.0. With 50% motion, error was also 1.0. With only 25% motion, error was 1.2, compared to error values of 1.75-2.2 when there was no motion. Matheny et al.[10] conducted a similar experiment; however, they varied the frequency response of the motion system to disturbance and maneuver motion. Altering the bandwidth of the frequency response over a range from full motion to no motion did not alter the operator's error in compensatory tracking. Nevertheless, there were differences in the control activity power spectra. These are somewhat complicated, but essentially it was found that a wide bandwidth frequency response produced control activity no different from narrow bandwidth response.

These two experiments indicate that motion cue sophistication may be reduced without too great an effect upon operator performance. However, in these experiments the main task was tracking a disturbance input. Some authors have proposed that, although the simulation of disturbance motion may be accomplished adequately at a rudimentary level, maneuver motion may need to be simulated as realistically as possible (Bray,[27] Cohen,[29] Perry and Naish[13]). It is obvious that the complexity of a motion system will be determined by the most sophisticated requirement. Hence, the degree to which maneuver motion needs to be simulated will determine the sophistication of the motion system. This degree of sophistication can be determined by experiments similar to those of Bergeron[28] and Matheny et al.[10] which use a command input producing maneuver motion.

Once a decision has been made about what sort of cues a simulator should provide, the provision of these cues ought to be implemented with some regard to the motion sensing capabilities of the human. One of the most important of these is the absolute threshold. This threshold to motion is the least value of a motion stimulus which can be identified correctly as present or absent over a large number of presentations, with a stipulated accuracy, normally 75%. Some authors use a correct identification of direction of motion in 75% of the stimuli as determining the threshold. Absolute motion thresholds are important in flight simulation for two reasons. First, these thresholds need to be measured so that one can be certain that a motion system provides onset cues in excess of their values. Secondly, the magnitude of washback motion ideally should be below the threshold value, so that it cannot be sensed by the simulator operator.

The human senses a force environment by means of the mechanoreceptors of the joints, muscles, and skin, and the specialized vestibular apparatus of the inner ear. The mechanoreceptors of the skin, joints, and muscles are sensitive to movement of the body members in relation to one another, and to changes in the forces in contact with the body. Within the vestibular system, the otolith organs of the utricle and saccule respond to linear accelerations, whereas angular acceleration is the adequate stimulus for the semicircular canals. However, as Guedry[30] has explained, for acceleration stimuli having frequencies in the same bandwidth as natural head movements, the output of the semicircular canals, and eventually sensation, copies the stimulus angular velocity. Since motion system response is within the bandwidth of natural head movements, it is clear that the magnitude of angular motion cues should be expressed in terms of stimulus velocity.

Figure 3 presents results of a number of experiments that have tested whether angular motion thresholds are determined similarly by angular velocity. Clark and Stewart,[31] Van Egmond et al.,[32] Fennessey,[33] Guedry and Richmond,[34] and Meiry[21] presented angular acclerations over a range of magnitudes (the abscissa) to subjects, who had to indicate when they could sense motion or identify its direction. The response latency is shown on the ordinate. Doty[35] used a forced-choice staircase procedure in which fixed durations of angular acclerations were varied in magnitude to reach threshold value. Insofar as the values from each experiment lie on a line with a slope of minus one (that is, are parallel to the line marked $aT=k$), the product of acceleration magnitude and duration is a constant. This constant is the velocity threshold to rotational motion for stimuli up to 10-sec duration. From Fig. 3, the velocity threshold lies between 1.6 and 9 deg/sec^{-1} (27.9-157.1 mrad/sec^{-1}). Hence, when dealing with angular motion cues of the sort of frequencies generated by flight simulators, both the dynamic response of the sensory system and the threshold values of that system are determined by the change in angular velocity.

Although estimates of the magnitude of thresholds to angular motion in an operational simulator are desirable,

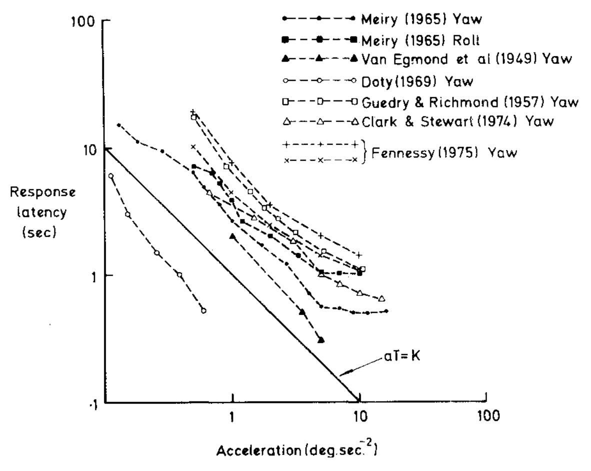

Fig. 3 Experimental results for time to perceive angular motion as a function of acceleration magnitude.

there are a number of problems in taking laboratory threshold data and extrapolating them to the simulator:

1) There is a lack of data on thresholds for rotation about anything other than an earth-vertical axis. Huddleston[36] identifies roll and pitch as the two most important simulator axes, and in the simulator these involve rotation about an earth-horizontal axis. Clark[37] reviews rotational threshold data from 25 sources, of which 23 are for yaw motion about earth-vertical axes, and one is for pitch about an earth-horizontal axis. Only one source (Meiry[21]) concerns roll motion, and this is about an earth-vertical axis, as were Clark and Stewart's[38] investigations of acceleration thresholds about all three body axes. Kirkpatrick and Brye,[39] however, investigated thresholds for pitch motion about an earth-horizontal axis in a simulator. In summary, for earth-horizontal rotation axes, there are two sources of pitch threshold data, and no sources of roll threshold data. The difference between rotation about earth-vertical and earth-horizontal axes is that in the latter case motion detection may well depend upon the sensitivity to tilt. Since static tilt involves reorientation of the otoliths to gravity, sensitivity can be expressed in terms of the change in linear acceleration. Sensitivity to changes in linear acceleration has been measured in blindfolded subjects between 0.03 and 0.2 m/sec^{-2} by Walsh,[40,41] using oscillatory stimuli, and estimated at 0.06 m/sec^{-2} by Meiry,[21] using constant accleration profiles. Sensitivity to the oculogravic illusion (when subjects' eyes were open) is calculated from Graybiel and Patterson's data at 0.25 m/sec^{-2} (see Guedry,[30] p. 82), higher than the majority of sensation threshold data.

2) In the simulator motion cues occur in more than one axis at once; some may be superimposed on others, such as simulated turbulence, and the amplitude/time function of the motion is different to that typically studied in the laboratory.

3) The third reason why thresholds to motion cues in operational flight simulators may be different from those measured in laboratories is considered by some authors to be the most important (Guedry,[30] Staples,[42] Stewart[43]). These authors identify a potentially important difference: in the laboratory, the subject usually is required to sit with eyes closed, or look at a spot of light, and concentrate on detecting the presence/absence or direction of motion. In the operational simulator, however, things are very different. The operator has a complex cognitive and perceptual-motor task to perform in flying the simulated aircraft. Authors often have asked for threshold data under more realistic conditions such as these. An indication of the effect of a concurrent task upon absolute thresholds is given by Kirkpatrick and Brye.[39]

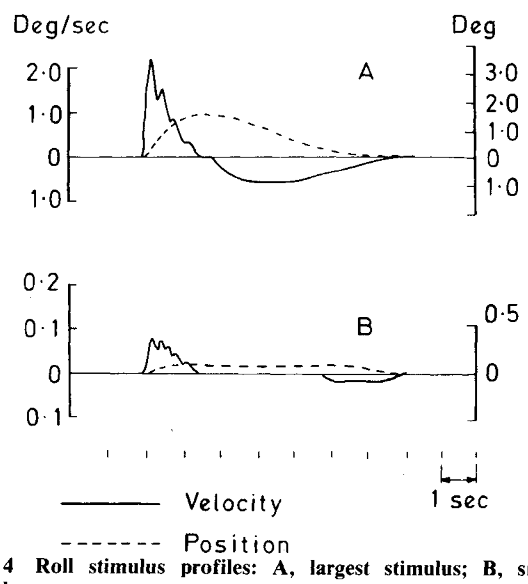

Fig. 4 Roll stimulus profiles: A, largest stimulus; B, smallest stimulus.

Thresholds to pitch, heave, and surge motion in a simulator were determined in the presence and absence of a one-axis visual steering task, akin to driving down a road in the presence of crosswinds. For surge motion, the task raised thresholds only for acceleration in the aft direction. There was no effect for heave motion, and only limited indication of decreased sensitivity for pitch acclerations. On the whole, therefore, the data are suggestive only of threshold elevation in the presence of a perceptual-motor task. However, the perceptual-motor task is only one aspect of the simulator operator's workload, there is, in addition, a demanding cognitive information-processing element. It is sensible to ask whether introducing a cognitive task during threshold measurement would elevate threshold levels.

The overall aim of the experiment was to obtain threshold values for motion stimuli under conditions that were more representative of those of an operational flight simulator than had been obtained by other authors. The experiment investigated the effects of a concurrent cognitive task on thresholds to angular motion. For the reasons outlined previously, the motion axis was roll about an earth-horizontal axis, and the motion device used was a flight simulator. The amplitude/time course of the motion waveform was that which normally was produced by the simulator in response to a brief aileron deflection. The magnitudes of the motion stimuli were scaled in angular velocity terms.

Method

Apparatus

Motion stimuli were presented to subjects sitting in a Redifon 101 flight simulator. The simulator was 'on the ground,' with the engines and instruments off. The pitch system of the simulator was frozen throughout the experiment. Roll motion cues were obtained by a signal from a PDP-12 computer, which was equivalent to a brief (0.25-sec) full-scale aileron input to the left or right. This caused the simulator to reach peak velocity in 0.25-0.3 sec. The simulator's washout returned this to zero in a further 1.7 sec, and the washback returned it to the upright position in a further 5 sec (see Fig. 4). Different magnitudes of the motion cue were controlled by the computer via an independent circuit. Calibration of the motion cues was in terms of the peak velocity. Figure 4a shows the largest stimulus magnitude used in threshold measurement, and Fig. 4b shows the smallest.

Subjects

Ten subjects were used. Four were female students and assistants, whose ages ranged from 19-40 years, none of whom had had any previous flying or simulator experience. Of the six male subjects, there were three trainee pilots with about 100-hours of jet experience and a little simulator experience, one engineer with little flying and simulator experience, one transport pilot with extensive flying and simulator experience, and one chief technician with little flying but extensive simulator experience. Their ages ranged from 22-34 years. All were in good health and had never suffered from inner ear disorder. All subjects sat in the left-hand seat of the simulator, and all but one were strapped in normally. All wore a headset throughout the experiment.

Procedure

Psychophysical Procedure

The psychophysical procedure that was adopted was a forced-choice double random staircase. A PDP-12 computer controlled the sequence of trials, the presentation of stimuli, and the printing and calculation of results. The program was written so that the procedure used would be virtually identical to that described by Clark and Stewart.[44] There were only three differences in procedure from that described by these authors: 1) an estimated midpoint above and below which the stimulus steps ranged, was not measured individually for each subject, but remained the same for all subjects; 2) threshold was calculated as the mean of 40 trials after the staircases had crossed; 3) subjects received knowledge of results (the number of incorrect responses) after each block of 8 trials, and 5-min rest periods were enforced after 8 and 24 trials after crossover.

The structure of each trial was as follows. Subjects held on their laps a small box on which were mounted a "warning" light, a "stimulus-ceased" light, and two response buttons, "left" and "right." A trial began with the "warning" light illuminating for 0.5 sec. One second later the motion stimulus was presented at the appropriate level, a roll to either left or right. After 8 seconds, when the simulator was back in the upright position, the "stimulus-ceased" light started flashing. Subjects extinguished this light by pressing either the "left" or "right" button, depending upon their judgement of the direction of roll. After 10-30 sec, the warning light came on for the next trial.

Cognitive Loading Task

The requirements for the cognitive task were that it should be capable of computer control, easily started and stopped, and should engage the subject in cognitive activity as completely as possible when it was present. A task that fits these requirements is that of adding three to aurally presented numbers. Performance on the task during simulator piloting has been used successfully as an index of pilot workload (Green[45]), showing that it has cognitive demands in common with the task of piloting a simulator. A further advantage was that, simply by issuing different instructions, the separate components of the task (auditory, verbal, and cognitive) could be assessed for their effect on thresholds.

The aural material consisted of random numbers in the range 0-9, read onto a tape recorder at 1.5-sec intervals. In order to present this material to the subject, the computer operated a tape recorder by means of the latter's remote pause facility. The numbers started when the "warning" light came on, and ceased when the "stimulus-ceased" light came on. In this fashion, the numbers were presented over the subject's headset concurrently with the motion stimuli. The four conditions of the mental loading task were as follows.

Task 1: No numbers were presented. Subjects were engaged solely in the task of detecting the direction of roll motion.

Task 2: Numbers were presented as described previously. However, subjects were told to ignore them and concentrate solely on the task of detecting motion.

Task 3: Numbers were presented as described previously. Subjects were told to shadow the numbers, that is, to repeat back each number as it arrived. Although subjects also had to perform the motion detection task, they were told to devote as much attention to the number task as was necessary to prevent them missing numbers.

Task 4: Numbers were presented to subjects who were required to add three to each number as it arrived and reply. Again, subjects were told that they must not miss numbers, even though they had the motion detection task to do.

During tasks 3 and 4, the experimenter monitored subject's output and, if necessary, during interblock pauses, chastized subjects for missing numbers. In fact, this was rarely necessary.

All subjects took part in a practice and familiarization session prior to the experimental sessions. During the initial stages of this session they were given verbal knowledge of results about the correctness of each response. The four tasks were presented, explained, and subjects were allowed to practice them. Each subject performed all four tasks, each task occupying a 1-hr experimental session. The order of tasks was counterbalanced within two groups of four subjects, with the remaining two subjects having the same order as the first two. Most subjects had one session (including the practice session) a day on consecutive days, except for three subjects,

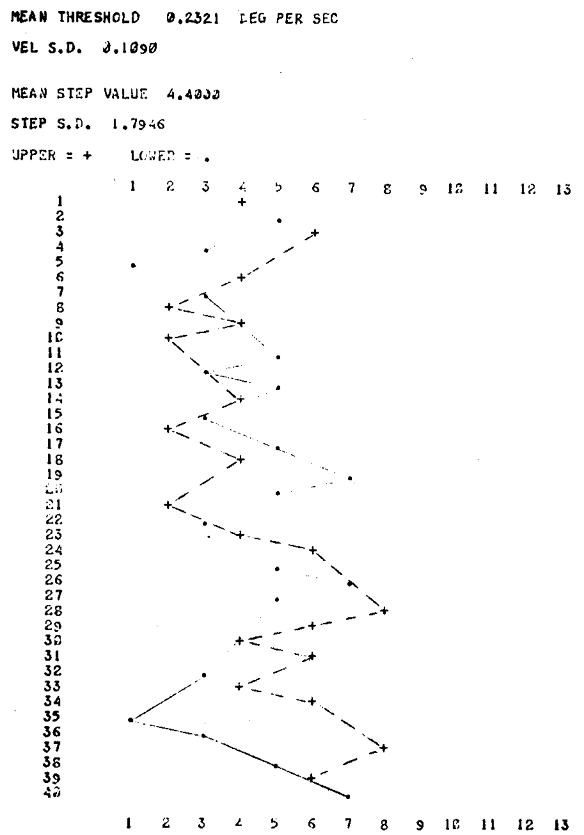

Fig. 5 Computer output for one subject showing results of double-random staircase procedure. Horizontal axis is stimulus magnitude, vertical axis is trial number. The points have been joined up by hand.

who served in sessions in the morning and afternoon of the same day.

Results

Figure 5 shows typical output from the computer for a subject engaged in task 4. The horizontal axis represents increasing peak velocity magnitude, from left to right, and the vertical axis gives the trial number. Threshold was taken as the mean of the steps presented to subjects. In addition, the standard deviation of the staircase was calculated in order to provide a measure of the variability of the subject's performance under each of the four task conditions. The data, averaged over 10 subjects, are shown in Table 1 and Fig. 6.

Differences between tasks were investigated by means of t-tests. Threshold angular velocity was significantly lower under task 1 than task 4 ($t=2.58$, $df=9$; $t_{0.05}=2.26$), and also lower under task 2 than task 4 ($t=2.82$, $df=9$; $t_{0.05}=2.26$). Threshold angular velocity under task 3 did not differ significantly from that under tasks 1, 2, or 4. Staircase standard deviation did not differ significantly between tasks.

Discussion

Task Effects

One reason for conducting the present experiment was to investigate whether a cognitive task had any effect upon thresholds to motion in a flight simulator. The results clearly indicated that there was an effect. For tasks 1 and 2, in which the subject was not required to perform any information processing in addition to detecting motion, thresholds were identical. These thresholds were numerically smaller than those observed when the subject was engaged in shadowing, and significantly smaller than the thresholds observed when subjects had to perform a demanding task of adding three to rapidly-occurring numbers. It seems clear that, as the processing demands of the tasks increased, the threshold was raised.

Table 1 Mean roll threshold, mean staircase standard deviation, and between-subject standard deviations for the four tasks, values in deg-sec $^{-1}$

	Task 1	Task 2	Task 3	Task 4
Mean threshold	0.12	0.12	0.15	0.17
S.D. (between subjects)	0.032	0.042	0.041	0.07
Mean staircase standard deviation	0.107	0.102	0.107	0.109
S.D. (between subjects)	0.017	0.015	0.018	0.02

It is appropriate to ask why threshold was raised. It is unlikely that a change in threshold was brought about by changes in the neural mechanisms involved. In the lower levels of the auditory pathway of animals, Wicklegren[46] has shown no change in neural activity consequent upon the activity or state of the animal. Hence, it appears that a change in threshold was brought about by a change in the amount of capacity that could be devoted to the output of motion detection mechanisms. Norman and Bobrow[47] provide the terminology to explain why motion detection should be affected by a mental loading task. The motion detection process itself is primarily 'data-limited,' in that performance depends most upon the quality of the motion stimulus (i.e., its amplitude, duration, presence of noise, etc). However, a portion of the motion detection task is 'resource-limited,' in that a minimum amount of processing capacity is necessary. Normally this minimum requirement is available, but when performance of the cognitive task takes up much of the total processing capacity, that which can be allocated to the motion detection task falls below its minimum requirement.

There are two explanations of what can happen to an attentional channel when there is insufficient processing capacity allocated to it. These are the attenuation and blocking hypotheses of attention (Moray[48]). The distinction is between an attenuation of all signals on a particular attentional channel, or the total blocking of some signals on that channel. In many laboratory tasks the net result of these two processes would be identical. An increase in error on a task of 40% could result from all signals being attenuated by 40%, or 40% of the signals being blocked. However, in the threshold situation it was possible to distinguish between these two hypotheses.

In order to distinguish between the attenuation and blocking hypotheses, a simple computer model was set up of the subject's behavior in a two-alternative forced-choice threshold procedure. This model said that for any stimulus there was a probability (g) of the subject having to guess his response, because the output of the motion detector was blocked. If the subject had to guess, then the probability of a

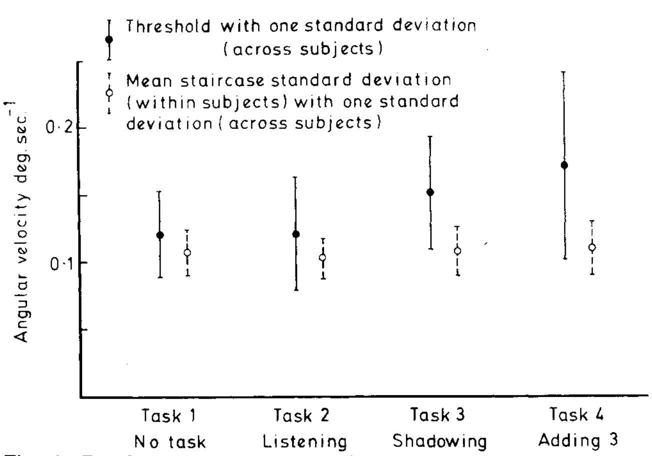

Fig. 6 Results of experiment showing angular velocity thresholds under four task conditions, together with the standard deviation of the staircase.

correct response was 0.5. However, if the subject did not guess (probability 1-g), then whether the stimulus was above or below a value necessary to provoke a critical level of sensory excitation (S) determined his output. If the stimulus was above S, the response was correct. If the stimulus was below S, the subject guessed his response, with a probability of 0.5 of being correct. [The threshold aspect of this model is that of high-threshold theory. More properly, according to signal detection theory (Green and Swets[49]), S is stochastic in nature, and influences the probability of correct 'guessing.' However, this does not invalidate the present simple model as long as the distribution of S remains independent of the probability of stimuli being blocked.] The model therefore had two parameters, g and S, which could be varied independently. An attenuation model of attention would predict an increase in S with no change in g. However, a blocking model would predict no change in S, but an increase in g, because stimuli were being blocked. The output of this model was a simple correct/incorrect decision about each stimulus, and this output was fed into the computer program, which controlled the double-random forced-choice staircase procedure.

The results of this stimulation were unambiguous. With S increasing and g constant, the staircase mean increased, but the standard deviation of the staircase remained constant. Holding S constant and increasing g caused an increase in staircase mean together with an increase in the staircase standard deviation.

The results of this simulation can be compared with the experimental data shown in Table 1. It is clear that, whereas measured threshold increased with increasing mental loading, the mean standard deviation of the staircase did not. Hence thresholds to motion appear to suffer from attenuation rather than blocking in the presence of a concurrent task. The exact nature of such an attenuation process is a matter open to discussion, and is beyond the scope of this paper. However, all sensory information is subjected to stages of analysis and storage before it forms the basis for decisions, and attenuation probably is best regarded as a reduction in the processing performed on the motion stimulus.

Threshold Determination

A further aim of this experiment was to determine thresholds for roll motion in the Redifon 101 flight simulator. An unexpected outcome of the experiment was the magnitude of the angular velocity thresholds, which averaged 0.12 deg/sec^{-1} (2.1 mrad/sec^{-1}) under no-task conditions. Measurements by previous authors for thresholds to angular rotation about an earth-vertical axis, shown in Fig. 3, are in the range 1.6-9 deg/sec^{-1} (27.9-157.1 mrad/sec^{-1}). The obvious explanation for the present finding of very small threshold values for angular velocity is that subjects were detecting tilt or radial and tangential linear acclerations, because that they were some distance from an earth-horizontal rotation axis. The calculated value of tilt at threshold value with no task was 0.024 m/sec^{-2} and calculated tangential and radial accelerations were 0.028 and 0.000014 m/sec^{-2}, respectively. The tilt and tangential accelerations were slightly lower than the lowest previous estimate of threshold to linear accelerations of 0.03 m/sec^{-2} (Walsh[41]).

The fact that the actual threshold values were smaller than those previously estimated led to the suggestion that the actual linear acceleration environment in the simulator cab might have been somewhat different from the calculated one. This would be true if there was significant jerk as the simulator rolled, due to stiction in the roll motion jack. Accordingly, linear accelerations were measured in the earth-horizontal and earth-vertical plane. Figure 7 shows horizontal linear acceleration, measured through a 10-Hz low-pass filter, by an accelerometer mounted on the instrument panel coving in front of the pilot at average head height. The upper curve in

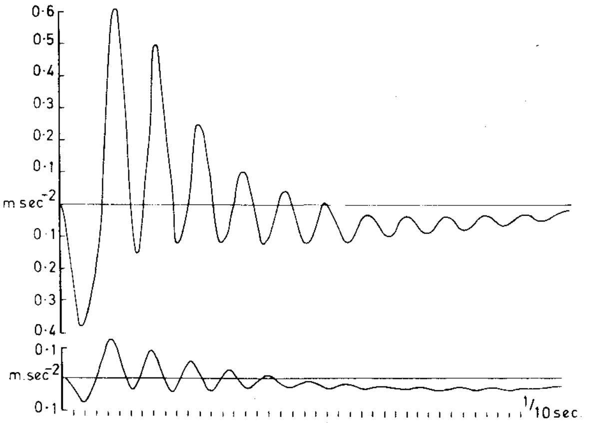

Fig. 7 Horizontal linear acceleration of simulator at head height: upper, at largest stimulus value; lower, at threshold value.

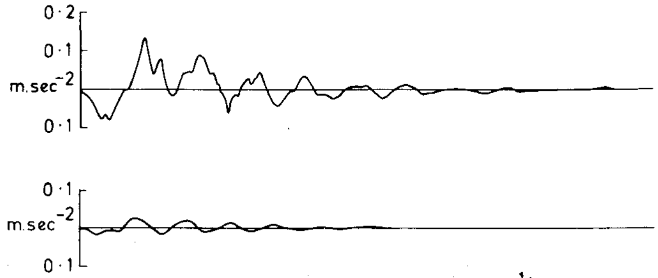

Fig. 8 Vertical linear acceleration of simulator at head height: upper, at largest stimulus value; lower, at threshold value.

Fig. 7 shows the acceleration when the simulator was set to roll with a velocity equal to the largest stimulus value used in the experiment, and the lower curve shows it with a velocity equal to the mean no-task threshold value. Accelerometer records for a point in the simulator level with the pilot's seat were identical in shape, with linear acceleration magnitude reduced by a factor of 0.6 to 0.8. Figure 8 shows readings for earth-vertical linear acceleration measured under the same conditions as those shown in Fig. 7.

The record of horizontal linear acceleration at threshold velocity value (Fig. 7 lower) shows a decaying series of jerks with frequency of about 2 Hz. At pilot head height, the largest peak was an acceleration of 0.14 m/sec $^{-2}$, and at pilot seat height of 0.11 m/sec $^{-2}$. Although there are no data for threshold to linear acceleration along the y body-axis for 2-Hz oscillation, the present values are greatly in excess of Walsh's data[41] for y-axis thresholds at 0.66 Hz, which averaged at 0.054 m/sec $^{-2}$. Since all subjects but one were strapped into the pilot seat, and since studies of transmissability of y-axis oscillation from the seat to the head of unstrapped subjects have shown gain of about unity in the region of 2 Hz[50,51] it seems likely that the magnitude of the motion stimulus reaching the skull was in excess of previously measured threshold values. Therefore, it can be advanced that the threshold value in the present experiment was determined by otolith activity. The only evidence against this is anecdotal; subjects spontaneously reported that they had detected motion by means of pressure changes on the buttocks and back as the simulator rolled. Whether this was true across the whole range of stimulus magnitudes is not clear.

The present experiment has demonstrated that the magnitude of thresholds to motion stimuli depend upon the amount of processing resources available for motion detection. This was demonstrated by applying a loading task to the subject to manipulate the availability of processing resources. In the operational flight simulator, presence of resources for motion detection depends not only upon the effects of task loading, but also upon the voluntary allocation of resources to motion detection. The latter is simply another term for directing attention to the motion stimuli, and the sum of the effects of task loading and direction of attention produce the phenomenon that motion cues are largely unnoticed when flying the simulator. Although it would be possible to investigate many more types of task loading per se, it is arguable that threshold measurement studies never can produce data that are relevant to the simulator. The problem is raised because this experiment has demonstrated a clear effect of resource availability on motion thresholds. What influences resource availability is not only the workload aspect of flying a simulator, but the effect of the priority of tasks within the simulator on the voluntary directing of attention. In the simulator, detection of motion is likely to have minimal priority. However, any conventional threshold-measuring technique, even in the presence of a realistic task, requires the subject being instructed to give motion detection near-maximum priority. Hence, it entirely alters the priority that the subject places upon detecting motion from that which exists in the operational flight simulator. The mere act of measurement renders the experiment unrealistic. In order to determine those threshold levels to motion which are in principle present during flight simulations, a procedure must be used which does not involve the subject attending to motion cues to an unrepresentative extent.

Such a procedure would be to investigate the operator's use of motion cues during tracking. This was recommended earlier as a procedure for determining motion requirements for flight simulation. It is clear that a type of threshold data can be supplied by this technique. All that is required is to look for a minimum value of motion in any axis that has an effect upon the operator's control activity or tracking performance. Once this minimum value has been established, it can be treated as an effective threshold to motion. Further, it is immaterial whether the operator can perceive motion cues at levels that influence his control behavior. Use of effective thresholds to motion cues means that such threshold data would reflect the use that the operator makes of motion cues. This seems to be an advantage over using data that reflect whether the operator can sense the cues, if asked.

Arguments presented in this paper make it clear that there is much to recommend abandoning the sensory threshold to motion as a useful concept for flight simulation, and to use instead values of an effective threshold to motion, which are determined by observing an operator's control behavior. However, it is questionable whether the concept of effective threshold itself is of any practical significance for simulator design. The concern with motion system research is that simulator motion system response can support pilot control behavior, which is acceptably similar to that which is observed in flight. Earlier in this paper it was proposed that motion system parameters should be determined by scaling down motion system response (reducing magnitude of onset rates and raising magnitude of washout rates) while observing control activity. Such data would provide a quantitative base for decisions about motion cue sophistication. This approach is similar to that outlined in the ASUPT research proposals (Kron[52]). In light of such data concerning the acceptable levels of onset and washout rates, it is arguable that data on thresholds to motion (be they traditional sensory thresholds or the effective thresholds proposed here) are largely irrelevant. The problems with sensory thresholds have been outlined previously. An effective threshold to motion provides no more data on motion system sophistication than do data on acceptable levels of response, and bears no quantified relationship to either onset or washout rates. Hence, it is not a parameter that can be incorporated in motion system drive profiles, although presumably it will be similar in magnitude to the maximum acceptable washout rate. Nonetheless, an effective threshold to motion may be useful, because it would be a relatively stable descriptor of human response to motion, whereas a set of parameters describing that simulator motion able to support acceptable control behavior would be more equivocal in nature, and perhaps less universal in its application across a range of simulators.

Conclusions

The discussions and data presented in this paper argue that sensory threshold data may be largely irrelevant for motion cue design, and that the use of effective thresholds is to be preferred. Further, it is argued that motion system parameters that will support acceptably flight-like control activity are more relevant than any form of threshold data. If we identify a continuum in these arguments, with concern for human sensory characteristics at one end, passing through a region of concern for the within-cab behavior of the pilot, it may be salutary to consider the other end of the continuum, where the concern is for the evaluation of motion cues, contributing to the goal of a training system. Recent evidence[53] suggests that the training role of motion cues is not clearly identifiable.

References

[1] Beck, L. J., "The Effect of Spurious Angular Acceleration on Tracking," *Human Factors*, Vol. 16, Aug. 1974, pp. 423-431.

[2] Bergeron, H. P. and Adams, J. A., "Measured Transfer Functions of Puring Two-Axis Tasks with Motion," NASA – TD-N-2177, 1964.

[3] Buckhout, R., Sherman, H., Goldsmith, C. T., and Vitale, P. A., "The Effect of Variations on Motion Fidelity During Training on Simulated Low-Altitude Flight," Wright-Patterson Air Force Base, Ohio, AMRL-TDR-63-108, 1963.

[4] Gerathewohl, S. J., "Fidelity of Simulation and Transfer of Training: A Review of the Problem," FAA Office of Aviation Medicine, Washington, D. C., Rept. AM 69-24, 1969.

[5] Guerico, J. G. and Wall, R. L., "Congruent and Spurious Motion in the Learning and Performance of Compensatory Tracking Tasks," *Human Factors*, Vol. 14, June 1972, pp. 259-269.

[6] Matheny, W. G., Dougherty, D. J., and Willis, J. M., "Relative Motion of Elements in Instrument Displays," *Aerospace Medicine*, Vol. 34, Nov. 1963, pp. 1041-1046.

[7] Ruocco, J. N., Vitale, P. A., and Benfari, R. C., "Kinetic Cueing in Simulated Carrier Approaches," U.S. Naval Training Device Center, Port Washington, NAVTRADEVCEN-1432-1, 1965.

[8] Sadoff, M. and Harper, C. W., "Piloted Flight-Simulator Research: A Critical Review," *Aerospace Engineering*, Vol. 21, Sept. 1962, pp. 50-63.

[9] Brown, J. L., Kuehnel, H., Nicholson, F. T., and Futterweit, A., "Comparison of Tracking Performance in the TV-2 Aircraft and the ACL Computer/AMAL Human Centrifuge Simulation of this Aircraft," U.S. Naval Air Development Center, Johnsville, NADC-MA-6016, 1960.

[10] Matheny, W. G., Lowes, A. L., and Bynum, J. A., "An Experimental Investigation of the Role of Motion in Ground-Based Trainers," Naval Training Equipment Center, Orlando, Fla., NAVTRAEQUIPCEN-71-C-0075-1, 1974.

[11] Brown, J. L. and Collins, C. C., "Air-to-Air Tracking During Closed Loop Centrifuge Tracking," *Journal of Aviation Medicine*, Vol. 29, Nov. 1958, pp. 794-804.

[12] Graham, D. K., "A Rationale for Moving-Base Flight Simulation and a Preliminary Statement of Motion Requirements," Boeing Aircraft Co., Doc. No. D6-57148, 1968.

[13] Perry, D. H. and Naish, J. M., "Flight Simulation for Research," *Journal of the Royal Aeronautical Society*, Vol. 68, Oct. 1964, pp. 645-662.

[14] Willigеs, B. H., Roscoe, S. N., and Williges, R. C., "Synthetic Flight Training Revisited," *Human Factors*, Vol. 15, Dec. 1973, pp. 543-560.

[15] Newton, J. M., "Training Effectiveness as a Function of Simulator Complexity," U.S. Naval Training Device Center, Port Washington, NAVTRADEVCEN-458-1, 1959.

[16] Muckler, F. A., Nygaard, J. E., O'Kelly, L. I., and Williams, A. C., "Psychological Variables in the Design of Flight Simulators for Training," Wright-Patterson Air Force Base, WADC Tech Rept. 56-TR-369, 1959.

[17] Douvilier, J. G., Turner, J. L., McClean, J. D., and Heinle, D. R., "Effects of Flight Simulator Motion on Pilots' Performance of Tracking Tasks," NASA-TN-D-143, 1960.

[18] Tremblay, H. G., Brown, J. L., and Futterweit, A., "Application of Harmonic Analysis in a Study of Tracking Performance in the TV-2 Aircraft and in Centrifuge and Stationary Simulations of that Aircraft," U.S. Naval Air Development Center, Johnsville, NADC-AC-6406, 1964.

[19] Shirley, R. S., "Motion Cues in Man-Vehicle Control," M.I.T. Man-Vehicle Laboratory, Cambridge, Mass., MVT-68-1, 1968.

[20] Dinsdale, P. B., "Relative Effects of Roll and Yaw Motion Cues in Manual Control, M.I.T., Man-Vehicle Laboratory, Cambridge, Mass., MVT-68-4, 1968.

[21] Meiry, J. L., "The Vestibular System and Human Dynamic Space Orientation," M.I.T. Man-Vehicle Control Laboratory, Cambridge, Mass., T-65-1, 1965.

[22] Stapleford, R. L., Peters, R. A., and Alex, F. R., "Experiments and a Model for Pilot Dynamics with Visual and Motion Inputs," NASA-CR-1325, 1969.

[23] Besco, R. O., "The Effects of Cockpit Vertical Accelerations on a Simple Piloted Tracking Task," North American Aviation Inc., Los Angeles, NA-61-47, 1961.

[24] Newell, F. D., "Human Transfer Characteristics in Flight and Ground Simulation for the Roll Tracking Task," Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, AFFDL-TR-67-30, 1968.

[25] Sadoff, M., McFadden, N. M., and Heinle, D. R., "A Study of Longitudinal Control Problems at Low and Negative Damping and Stability with Emphasis on Effects on Motion Cues," NASA-TN-D-348, 1961.

[26] Young, L. R., "Some Effects of Motion Cues on Manual Tracking," *Journal of Spacecraft and Rockets*, Vol. 4, Oct. 1967, pp. 1300-1303.

[27] Bray, R. S., Lead Discussion on K. J. Staples' Paper, "Motion Visual and Aural Cues in Piloted Flight Simulation," Advisory Group for Aerospace Research and Development, Neuilly-sur-Seine, France, AGARD-CP-79-70, 1970.

[28] Bergeron, H. P., "Investigation of Motion Requirements in Compensatory Control Tasks," *I.E.E.E. Transactions on Man-Machine Systems*, Vol. MMS-11, June 1970, pp. 123-125.

[29] Cohen, E., "Is Motion Needed in Flight Simulators used for Training?" *Human Factors*, Vol. 12, Feb. 1970, pp. 75-79.

[30] Guedry, F. E., "Psychophysics of Vestibular Sensation," *Handbook of Sensory Physiology*, Vol. V1/2, *Vestibular System Part 2: Psychophysics, Applied Aspects and General Interpretations*, edited by H. H. Kornhuber, Springer-Verlag, Berlin, 1974.

[31] Clark, B. and Stewart, J. D., "Effects of Angular Acceleration on Man: Choice Reaction Time Using Visual and Rotary Motion Information," *Perceptual and Motor Skills*, Vol. 38, June 1974, pp. 735-743.

[32] Van Egmond, A. A., Groen, J. J., and Jongkees, L.B.W., "The Mechanics of the Semicircular Canal," *Journal of Physiology*, Vol. 110, Dec. 1949, pp. 1-17.

[33] Fennessy, P. A., Report in Preparation, R.A.F. Institute of Aviation Medicine, Farnborough, Hampshire, U.K., 1975.

[34] Guedry, F. E. and Richmond, G., "Differences in Response Latency with Different Magnitude Angular Accelerations," United States Army Medical Research Laboratory, Forth Worth, Ky., Rept. 201, 1957.

[35] Doty, R. L., "Effects of Duration of Stimulus Presentation on the Angular Acceleration Threshold," *Journal of Experimental Psychology*, Vol. 80, May 1969, pp. 317-321.

[36] Huddleston, H. F., "Cockpit Motion Requirements for Flight Simulation," R.A.F. Institute of Aviation Medicine, Farnborough, Hampshire, U.K., Rept. 363, 1966.

[37] Clark, B., "Thresholds for the Perception of Angular Accelerations in Man," *Aerospace Medicine*, Vol. 38, May 1967, pp. 443-450.

[38] Clark, B. and Stewart, J. D., "Thresholds for the Perception of Angular Acceleration about the Three Major Body Axes," *Acta Otolaryngologica*, Vol. 69, April 1970, pp. 231-238.

[39] Kirkpatrick, M. and Brye, R. C., "Man-Systems Evaluation of Moving Base Vehicle Simulation Motion Cues," NASA – CR-120706, April 1974.

[40] Walsh, E. G., "The Perception of Rhythmically Repeated Linear Motion in the Horizontal Plane," *British Journal of Psychology*, Vol. 53, Nov. 1962, pp. 439-445.

[41] Walsh, E. G., "The Perception of Rhythmically Repeated Linear Motion in the Vertical Plane," *Quarterly Journal of Experimental Physiology*, Vol. 49, Jan. 1964, pp. 58-65.

[42] Staples, K. J., "Motion Visual and Aural Cues in Piloted Flight Simulation," Advisory Group for Aerospace Research and Development, Neuilly-sur-Seine, France, AGARD-CP-79-70, 1970.

[43]Stewart, J. D., "Human Perception of Angular Acceleration and Implications in Motion Simulation," *Journal of Aircraft*, Vol. 8, April 1971, pp. 248-253.

[44]Clark, B. and Stewart, J. D., "Comparison of Three Methods to Determine Thresholds for Perception of Angular Acceleration," *American Journal of Psychology*, Vol. 81, June 1968, pp. 207-216.

[45]Green, R. G., "Auditory Communication and Workload," *Paper to ASMP Meeting, Stuides of Pilot Workload*, Cologne, Germany, April 1977.

[46]Wicklegren, W. O., "Effects of State of Arousal on Click Evoked Responses in Cats," *Journal of Neurophysiology*, Vol. 31, Sept. 1968, pp. 757-769.

[47]Norman, D. A. and Bobrow, D. G., "On Data-Limited and Resource-Limited Processes," *Cognitive Psychology*, Vol. 7, Jan. 1975, pp. 44-64.

[48]Moray, N., *Listening and Attention*, Penguin Books, Middlesex, Eng., 1969.

[49]Green, D. M. and Swets, J. A., *Signal Detection Theory and Psychophysics*, Wiley, New York, 1966.

[50]Hornick, R. J., Boettcher, C. A., and Simons, A. K., "The Effect of Low Frequency High Amplitude, Whole-Body, Longitudinal and Transverse Vibration upon Human Performance, Final Report," Bostrom Research Laboratories, Milwaukee, Wis., Contract No. DA-11-022-509-ORD-3300, July 1961.

[51]Woods, A. G., "Human Response to Low Frequency Sinusoidal and Random Vibration," *Aircraft Engineering*, July 1967, pp. 6-14.

[52]Kron, G. J., "Advanced Simulation in Undergraduate Pilot Training: Motion System Development," Air Force Human Resources Laboratory, Brooks Air Force Base, Texas, AFHRL-TR-75-59(II), Oct. 1975.

[53]Hagin, W. V., "Platform Motion in Flight Simulators: Critical or Nice," *Proceedings First International Symposium for the Society for Applied Learning Technology*, Washington, D. C., July 1976.