Effects of Lags on Human Operator Transfer Functions with Head-Coupled Systems

RICHARD H. Y. SO, and MICHAEL J. GRIFFIN, Ph.D.

SO RHY, GRIFFIN MJ. *Effects of lags on human operator transfer functions with head-coupled systems.* Aviat Space Environ Med 1995; 66:550–6.

The effects of operator learning and target velocity on head tracking performance with and without lags has been studied. Five lags (0, 40, 80, 120, 160 ms) between head movement and target image movement, and three target velocities (2, 3.5, 5° · s^{-1} r.m.s.) were investigated with eight male subjects and band-limited random target motions. Head tracking transfer functions, tracking error spectra, mean radial tracking error, and subjective difficulty ratings were obtained. Head tracking performance was significantly degraded by lags greater than, or equal to, 40 ms (in addition to a system lag of 40 ms). Both the input-correlated tracking error and the uncorrelated tracking error increased with increasing lag. No significant improvement in head tracking performance was found through practice with an 80-ms lag. As the lag increased, operators increased their gains at frequencies above about 0.5 Hz and reduced their phase lags at low frequencies (about 0.1 Hz) but failed to fully compensate for the increased display lag. The increased human operator gain was associated with increased operator phase lag at higher frequencies (above 0.5 Hz). To improve head tracking performance in the presence of lags, a lag compensation technique is needed to prevent undesirable changes in tracking strategy.

A HELMET-MOUNTED display (HMD) enables an image to be presented in the line-of-sight of an observer regardless of head orientation. A helmet-pointing system (HPS) is a device which measures the angular orientation of the head. When the two devices are combined to form a head-coupled system, an operator can designate a target by making head movements to place the target behind an aiming reticle that is presented on the HMD. Target cuing and other information may also be displayed (3).

Head-coupled systems can also be used to present computer-generated visual simulations for research, training, or in-flight assistance. The objective is to be able to present images appropriate to the instantaneous line-of-sight of the head. However, problems arise due to the inevitable lag between the moment at which the head orientation is sampled and the moment at which the correctly oriented image is presented on the HMD. This is subjectively disturbing and may result in degraded performance. For example, Allen and Hebb (1) reported that lags due to sampling the head pointing direction and generating the graphics made a space stationary object appear to "swim" during the start and finish of head motions. Woodruff et al. (10) reported that during an investigation of helmet-mounted visual displays for flight simulation, more than one-third of the pilots who attempted the task were unable to obtain satisfactory results. This was considered to indicate failure to adapt to the shortcomings of the simulation (the simulator was sensitive in pitch and roll and there was a lag in the visual display). Such lags represent the dynamic response of the entire visual field of the head-coupled system to head movement and will hereafter be referred to as "display lag." Within the context of this paper, the aiming reticle is not part of the visual field subject to display lag; it was permanently displayed at the center of the HMD.

Previous work by the present authors (8,9) indicates that a display lag greater than, or equal to, 40 ms can be sufficient to cause a significant increase in head tracking error (these lags were in addition to an inherent 40-ms system display lag). The lags caused images to be presented at incorrect positions on the HMD. It was shown that a simple predictive algorithm, based on a constant velocity extrapolation, partially compensated for the lags and that the remaining position error could be corrected by deflecting the image on the display in the opposite direction to the head movement. To further optimize this lag compensation technique it was necessary to understand the mechanism behind the performance degradation caused by lags. Two experiments have been conducted to investigate the effect of operator learning and the effect of target velocity on head tracking performance with and without display lags.

From the Human Factors Research Unit, Institute of Sound and Vibration Research, University of Southampton, England.

This manuscript was received for review in August 1993. It was revised in March and August 1994. It was accepted for publication in August 1994.

Address reprint requests to Michael J. Griffin, Ph.D., Human Factors Research Unit, Institute of Sound and Vibration Research, University of Southampton, Southampton, S017 1BJ, England.

MATERIALS AND METHODS

Apparatus

The general arrangement of experimental apparatus is summarized in Fig. 1. The helmet-pointing system (HPS) was a Ferranti SPASYN system type 101, capable of detecting helmet movement in the pitch, yaw, and roll axes. The system was manufactured by Ferranti plc., Edinburgh, Scotland. Output in digital form was updated every 20 ms. This position sensor was mounted on a United States Air Force flying helmet carrying a collimated helmet-mounted display model SD/HMD-001, manufactured by Hughes Aircraft Company, Culver City, CA. The field-of-view of the display was 17° × 17° with a pixel resolution of 260 (horizontal) by 168 (vertical). The display projected collimated images to the right eyes of the subjects. This head-coupled system had an inherent pure lag of approximately 40 ms between head movements and the corresponding movements on the display. This 40-ms lag included: a) a 20-ms lag in the HPS; b) a 3.5-ms computation time; c) a 0–16.7 ms presentation delay for an image to appear on the raster scan system of the HMD; and d) a 0–16.7 ms lag introduced by the asynchronization between the HPS, updating at 50 Hz, and the HMD system, refreshing at 60 Hz.

Methods of Generating the Lag

As shown in Fig. 1, the HPS was connected to the host computer where the head position was stored in a buffer before being used to update the video output. The length of the buffer was proportional to the required lag. This simulated the pure lags involved in graphics generation within simulators.

Model and Hypotheses

A pursuit tracking system is characterized by the display of an aiming reticle and a target (Fig. 2A). The task is to move the reticle so as to follow the target. Subjects have direct control over the reticle position. In a compensatory tracking system, only the error (i.e., the relative displacement between the target and the reticle) is displayed (Fig. 2B). The task is to reduce the error. Unlike a pursuit task, a subject does not have sole control over a marker on the display.

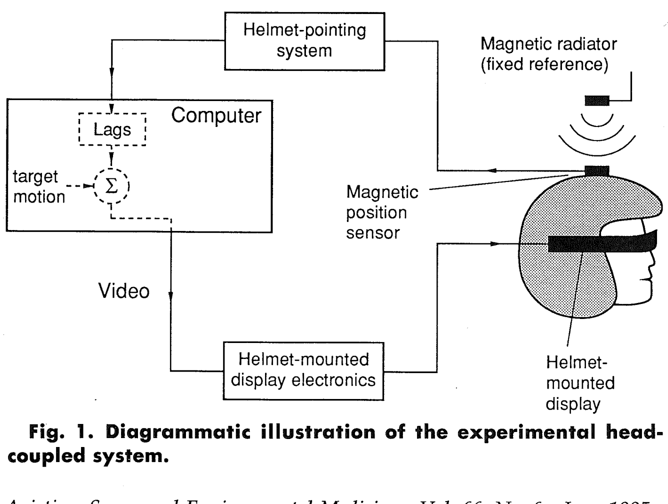

Fig. 1. Diagrammatic illustration of the experimental head-coupled system.

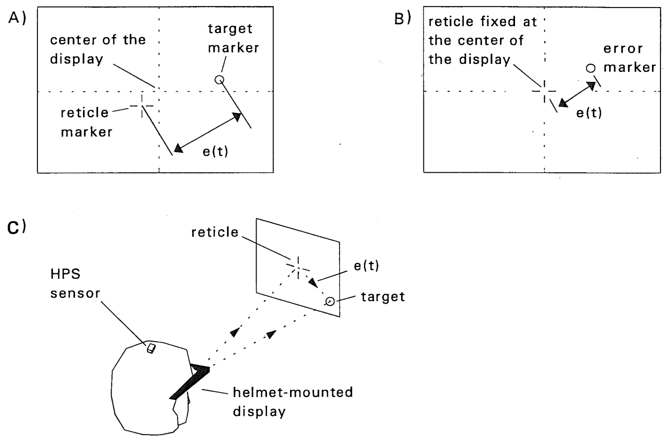

Fig. 2. Information presented in A) pursuit, B) compensatory, and C) head tracking tasks [A,B are adapted from Krendel and McRuer (5)].

Fig. 2C illustrates the reticle and target information during a tracking task with a head-coupled system. The reticle is permanently projected at the center of the HMD which moves with the subject's head. The subject, therefore, has direct control over the reticle position. The task is to follow the target with the reticle, which is similar to pursuit tracking. The quasi-linear model of a head tracking system shown in Fig. 3 is a pursuit model with the structure adapted from Lewis and Griffin (6). Within the frequency range of interest (0–2 Hz), the frequency response of the helmet-pointing system had a unity gain and a 20-ms lag. The 20 ms has been included as part of the 40-ms system lag. The presence of lags [i.e., $H_{sys}(f)$ and $H_{lag}(f)$] delayed head position measurement and image generation. During a head movement, this caused position errors in displaying head-coupled images. These errors increased linearly with increasing lag and increasing operator head velocity (4). It was hypothesized that: a) the presence of a display lag degrades head tracking performance; b) the human operator changes tracking strategy with an imposed display lag; and c) the effect of a display lag depends upon the target velocity.

Two experiments were conducted to test the above hypotheses. Head tracking transfer functions were de-

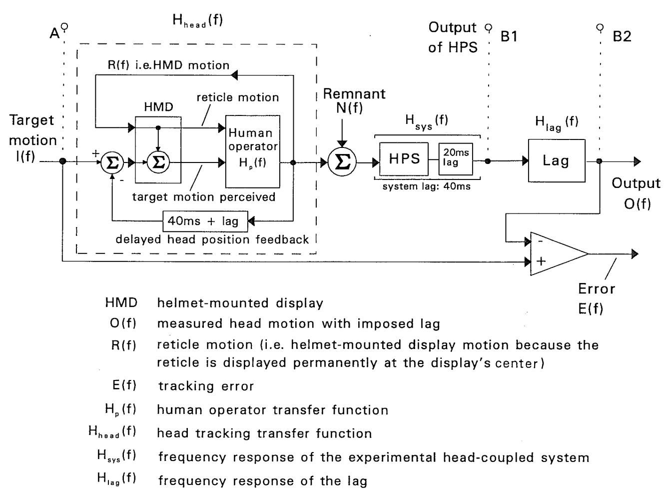

Fig. 3. A quasi-linear model of a head tracking system.

termined to identify factors affecting head tracking performance in the presence of display lags. The two experiments reported in this paper were approved by the Human Experimentation Safety and Ethics Committee of the Institute of Sound and Vibration Research.

Dependent Variables

Tracking performance was measured by means of transfer functions, error spectra, mean radial error, and subjective difficulty rating. From Fig. 3, the transfer function measured between points A and B2 is given by $H_{head}(f) \cdot H_{sys}(f) \cdot H_{lag}(f)$ and may be calculated from $G_{oi}(f)/G_{ii}(f)$, [where $G_{oi}(f)$ is the cross spectrum between the target motion, I(f), and the head motion output at B2, O(f); $G_{ii}(f)$ is the power spectrum of the target motion I(f)]. A transfer function was also measured between points A and B1. This transfer function is given by $H_{head}(f) \cdot H_{sys}(f)$.

The tracking error spectral density $G_{ee}(f)$ has an input-correlated component and a remnant component. The remnant error spectrum was estimated as $G_{oo}(f) \cdot [1 - \gamma_{oi}^2(f)]$, where $G_{oo}(f)$ is the power spectrum of the output, O(f), and $\gamma_{oi}^2(f)$ is the squared coherency function between the output, O(f), and the target motion, I(f). Lags will introduce a bias change in $\gamma_{oi}^2(f)$ (2). In this case the change is small; for example, a 100-ms lag will cause less than 1.5% change in $\gamma_{oi}^2(f)$. However, this doubled the remnant error spectrum at frequencies below 0.1 Hz due to the output motion having most energy around these frequencies.

All power spectral estimations were performed with fast Fourier transform routines. A Hanning window ($\alpha = 2$) with 75% over-lapping ensemble averaging and a spectral resolution of 0.078 Hz were used.

The mean radial tracking error was given by:

$$\frac{1}{N}\sum_{i=1}^{N}(p_i^2 + y_i^2)^{\frac{1}{2}}$$

where p_i is the i^{th} value of the pitch axis error time history; y_i is the i^{th} value of the yaw axis error time history and N is the number of values in the time history.

The subjective difficulty rating of each tracking run in experiment 2 was measured with a six-point (0–5) absolute difficulty rating scale: not difficult, a little difficult, fairly difficult, difficult, very difficult, and extremely difficult.

Experiment 1: Learning with and without Lags

Methods and Design

The target motion in the yaw axis was a normalized random time history integrated once and then low-pass filtered at 0.7 Hz (24 dB/octave) and low-pass filtered at 1 Hz (120 dB/octave). The resulting time history was then reversed in the time domain to form the pitch axis target motion. By this means the pitch and yaw axis target motions had the same frequency content. The duration of each target motion was 120 s and the target velocity was 3.2° s^{-1} r.m.s. in both axes.

Two pure display lags between head movements and corresponding target image movements were used (0 and 80 ms). In addition, there was an inherent system display lag of 40 ms. The experiment was conducted with eight male subjects ranging in age from 19–30 years. They were University researchers and students. All subjects were fully informed about the experiment and their right to withdraw at any time without prejudice during the experiment. The same target motion was used throughout the experiment, with 10 repetitions (i.e., runs) of both lag conditions. In a single experimental session, each subject performed 20 runs, each lasting 120 s. The 0-ms display lag condition was presented first.

Subjects sat inside a dark environment so that the only visible stimuli came from the HMD. A circular target (diameter 1°) was presented on the display at a coordinate derived from the instantaneous target position and the instantaneous orientation of the head. Subjects moved their heads to track the target with an open-cross reticle displayed at the center of the HMD. An initial familiarization run ensured that subjects were able to move their heads freely over the required range.

Results

The mean radial errors for the 10 learning runs with 0-ms and 80-ms display lags were calculated for each subject. Median values of the mean radial tracking errors across the eight subjects are shown in Fig. 4. Head tracking transfer functions in the pitch and yaw axes were measured between points A and B2 in Fig. 3. Head tracking transfer functions in the yaw axis for alternate runs are shown in Fig. 5 for both lag conditions. Data in the pitch axis were similar.

Discussion

Effects of learning: There was no significant change in mean radial tracking error through practice over the 10 runs with either lag condition (Friedman two-way analysis of variance, $p > 0.1$ for both 0 ms and 80 ms). There was also no significant change in the head tracking transfer functions collected for the 80-ms lag condition over the 10 runs. For the 0-ms lag condition, Fig. 5 shows a trend for the gains of the transfer functions to

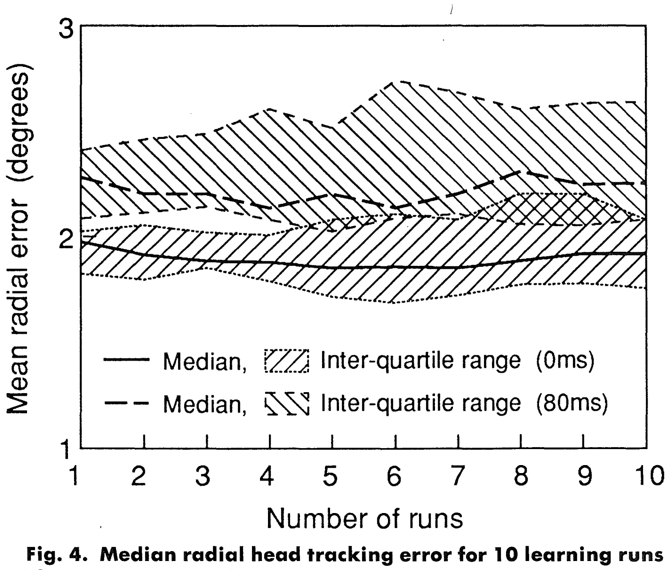

Fig. 4. Median radial head tracking error for 10 learning runs with 0 ms and 80 ms lags (8 subjects).

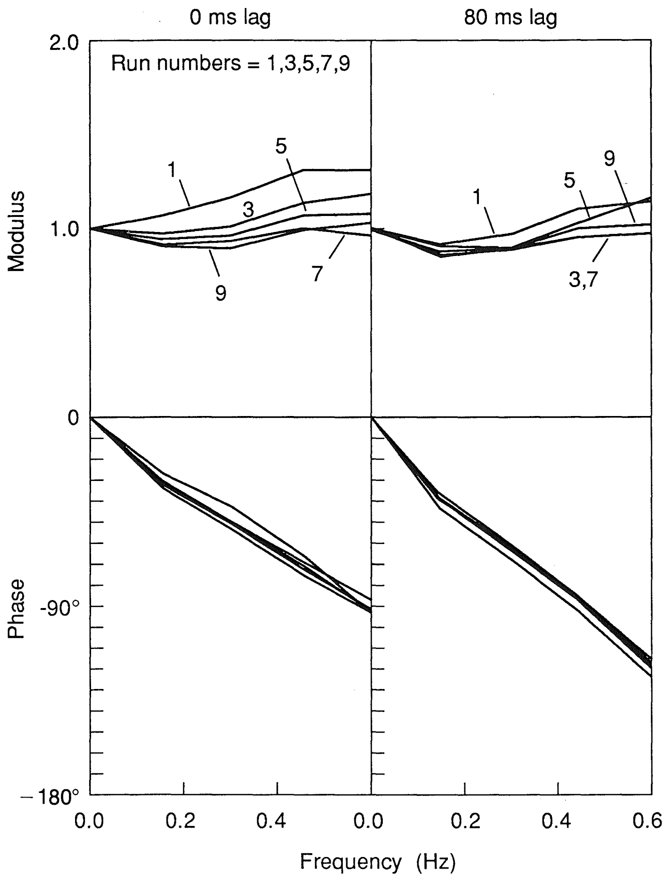

Fig. 5. Mean head tracking transfer functions in the yaw axis for 10 learning runs and 2 lag conditions (only odd number trials are shown: 1,3,5,7,9, data measured between A and B2 in the system block diagram) (0.08 Hz resolution, 72° of freedom).

reduce towards unity in the earlier runs. Since all eight subjects started with the 0-ms lag condition, the trend in Fig. 5 may have been due to learning the general form of the task and the target motion. It is not thought that subjects were able to learn the target motion sufficiently to predict its next move at any moment. For the 0 ms lag condition, Friedman two-way analyses of variance showed that the number of runs (1–10) had a significant effect on the transfer function gains at 0.4 Hz in the yaw axis ($p < 0.001$) and in the pitch axis ($p < 0.05$).

Effects of lag: Wilcoxon matched-pairs signed ranks tests were conducted to compare the two lag conditions. For each of the 10 runs there were significant increases in mean radial tracking error with an imposed display lag of 80 ms ($p < 0.05$). The degraded performance with the 80 ms lag, and the absence of any improvement with learning, suggests that in order to improve head tracking performance in the presence of lags, a lag compensation technique is necessary.

Experiment 2: Effect of Lag and Target Velocity

Methods and Design

The task was the same as in the first experiment except for variations in the lags and the target velocity. Five pure display lags (0, 40, 80, 120, 160 ms) between head movement and target image movement were used with each of three target velocities. There was an inherent system display lag of 40 ms in addition to the above lags.

The target motion used in the first experiment was scaled to give three target velocities: 2.0, 3.5, and $5.0° \cdot s^{-1}$ r.m.s. in both axes. These three target velocities are called V_0, V_1, and V_2, respectively. The corresponding maximum target displacements in both axes were ±9.7, ±16.0, and ±23.5°.

The same eight subjects from Experiment 1 participated in Experiment 2. Similar to Experiment 1, all subjects were fully informed about the experiment and their right to withdraw at any time without prejudice during the experiment. One familiarization run and three practice runs (with no imposed display lag, an 80-ms imposed display lag, and a 160-ms imposed display lag) were presented first to ensure that the subjects understood the tracking task. Three target motions of $3.5° \cdot s^{-1}$ r.m.s. velocity in both axes were used in the practice and these motions were not repeated in the main experiment. These runs were followed by the presentation of 15 runs (i.e., 3 velocities with each of the 5 lags). A randomized block design was employed in which each subject was exposed to all 15 conditions in a random order. At the end of each run, the subjects were asked to assess the task difficulty with a six-point rating scale. Eight target motions with the same frequency content were used so as to minimize any learning and so that, for each condition, the eight subjects were given different target motions. Individual subjects never experienced any target motion more than twice. Subjects performed 19 runs of 120 s in one session.

Results

Mean radial tracking error as a function of display lag and target velocity is shown in Fig. 6. As described above, the maximum target displacements in both axes were proportional to target velocity. With the assumption that an increase in target displacement caused a linear increase in tracking error, the mean radial tracking error data for the conditions V_1 and V_2 were scaled by factors 9.7/16 and 9.7/23.5, respectively. This had the effect of normalizing the tracking error to that with condition V_0. These normalized data are shown in Fig. 6 as broken lines.

For the condition V_1, mean head tracking transfer functions in the yaw axis for the five lag conditions are shown in Fig. 7. Unlike Experiment 1, these transfer functions were measured between points A and B1 instead of between points A and B2. This removed the imposed pure lags and helped to show changes in operator tracking response due to the lags. The mean head tracking error power spectral densities are shown in Fig. 8.

Discussion

Effects of lag: Friedman two-way analyses of variance by ranks were performed separately on the mean radial tracking errors for all three target velocity conditions. Results showed that display lag had a significant effect on tracking performance ($p < 0.001$). Further statistical analysis showed that display lags greater than, or equal to, 40 ms had a significant degrading effect on tracking performance for all three target velocities (p <

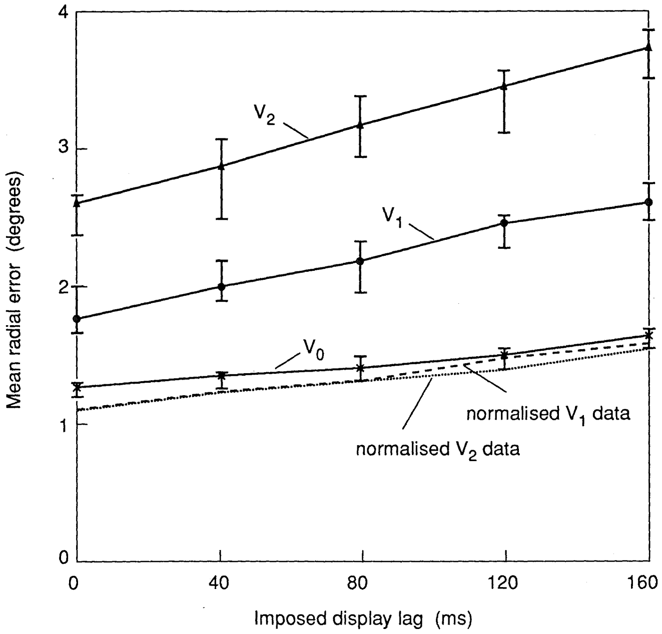

Fig. 6. Mean radial tracking error as a function of lag for three different target velocities (normalized data in broken lines) (8 subjects).

0.05, Wilcoxon matched-pairs signed ranks test). The presence of a significant effect with 40 ms display lag (in addition to the 40 ms system display lag) is consistent with the results of previous studies (8,9).

The head tracking transfer functions in Fig. 7 describe the head tracking characteristics in the presence of display lags, while excluding the direct influence of the imposed lags. There were statistically significant increases in head tracking phase lags and significant increases in gains around 0.8 Hz with increasing display lag (Friedman two-way analysis of variance by ranks, $p < 0.01$). This suggests that the subjects increased their gains in an effort to compensate the lag they observed. This confirms the hypothesis that a human operator will change tracking strategy in the presence of a display lag. The phase lag around 0.1 Hz decreased significantly with increasing display lag (Friedman two-way analysis of variance by ranks, $p < 0.001$). However, the reduction was not enough to compensate for the imposed display lags (Table I). Phase response at 0.1 Hz is important because the target motion had most energy around this frequency. The power spectral density of the target displacement for condition V_1 dropped from 143 degrees^2/Hz at 0.1 Hz to 2 degrees^2/Hz at 0.5 Hz. Because the resolution of the spectral analysis was 0.08 Hz, data around 0.1 Hz have to be interpreted with caution. Future studies with longer tracking time histories are desirable to enable spectral analysis to be undertaken with a finer resolution.

The differences in response at frequencies above and below 0.5 Hz as shown in Fig. 7 suggest that the increased gain may have been associated with a reduction of phase lag at low frequencies and an increase of phase lag at high frequencies: the typical response of a system consisting of a predictive lead-lag filter and a lag (So RHY, Griffin MJ. Unpublished data.) The additional phase lag degraded the subjects' ability to track target motion at frequencies above 0.5 Hz. This reduced the tracking bandwidth. A similar finding has been reported in studies of manual tracking strategies. A model of manual tracking with lead-lag filters has implied that, with the present system, lead generation at low frequencies will be accompanied by increases in response lag at high frequencies and consequent reductions in tracking bandwidth (7).

The transfer function measured between points A and B1 in Fig. 3 is influenced by the human operator transfer function $H_p(f)$. However, due to the head position feedback within $H_{head}(f)$, this transfer function is not linearly influenced by the response of the human operator. Further investigation of how the human operator is affected by lags in such a system is desirable.

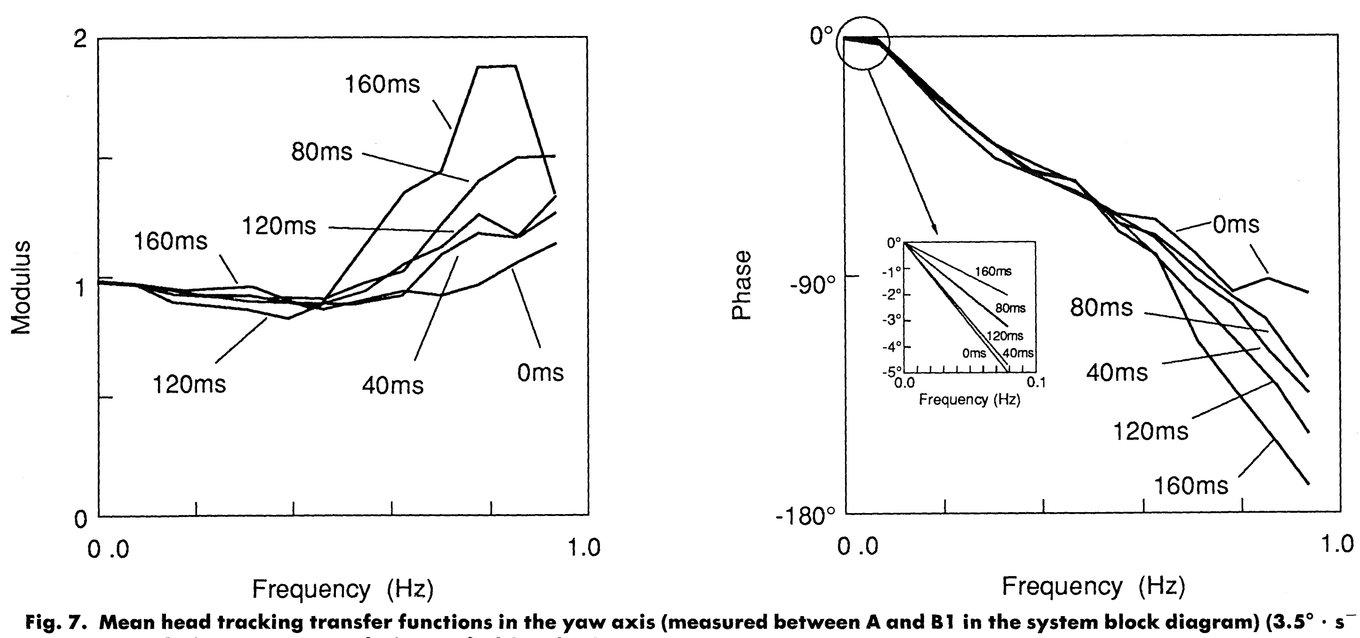

Fig. 7. Mean head tracking transfer functions in the yaw axis (measured between A and B1 in the system block diagram) (3.5° · s^{-1} r.m.s. target velocity, 0.08 Hz resolution, 72° of freedom).

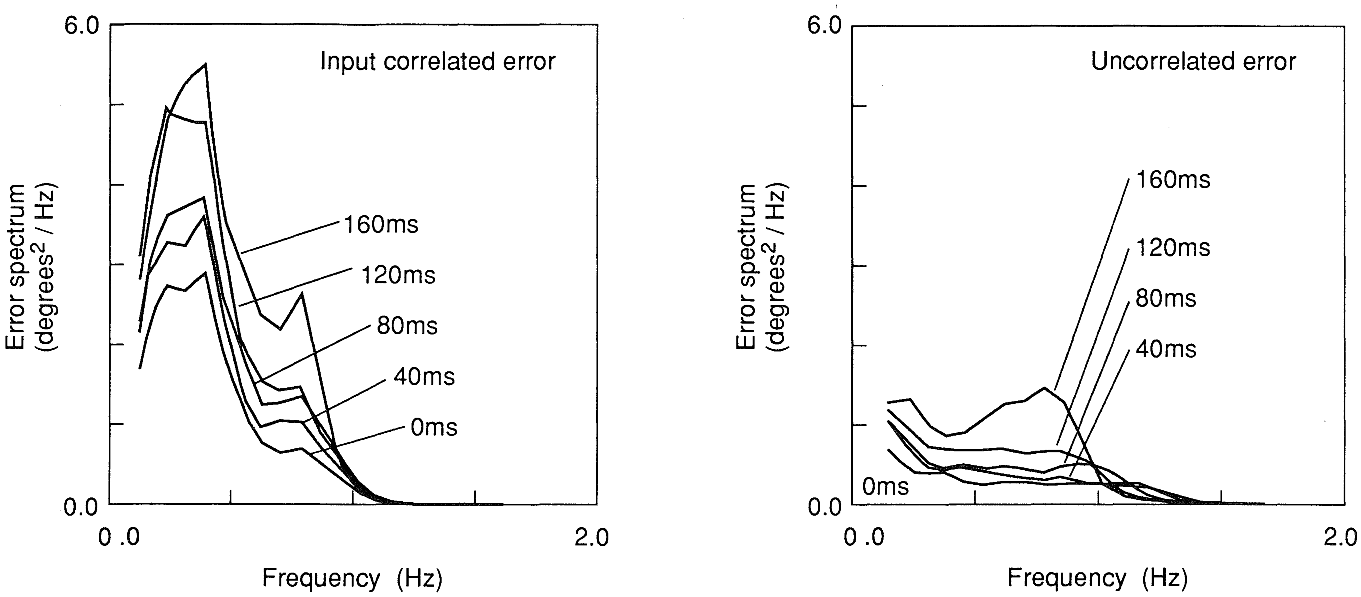

Fig. 8. Mean input-correlated and uncorrelated yaw axis tracking error spectra (measured between A and B2 in the system block diagram) (3.5° · s^{-1} r.m.s. target velocity, 0.08 Hz resolution, 72° of freedom).

TABLE I. TRACKING PHASE RESPONSES AT 0.08 HZ MEASURED BETWEEN POINTS A AND B1 AND BETWEEN POINTS A AND B2 OF FIGURE 3 (MEDIANS OF 8 SUBJECTS).

Lag (ms)	Phase (degrees) A to B1	Phase (degrees) A to B2
0	−4.9° (ranked 1.3*)	−4.9° (ranked 4.5*)
40	−4.6° (ranked 1.9*)	−5.8° (ranked 3.3*)
80	−3.2° (ranked 3.8*)	−5.5° (ranked 3.1*)
120	−3.2° (ranked 3.8*)	−6.6° (ranked 2.0*)
160	−2.0° (ranked 4.4*)	−6.5° (ranked 2.1*)

* Average rank from Friedman two-way analysis of variance by ranks.

Fig. 8 shows that both the input-correlated error and the uncorrelated error (i.e., remnant) increased with increasing lag. This suggests that to improve tracking performance in the presence of a display lag, a lag compensation technique is necessary.

Effects of target radial velocity: As the target velocity increased from 2–5° · s^{-1} r.m.s., the mean radial tracking error also increased ($p < 0.001$, Friedman two-way analysis of variance by ranks). Tracking errors were approximately proportional to the target displacement, since the difference was nearly removed when the mean radial errors were normalized to the same target displacement (Fig. 6). However, for display lags less than 160 ms, statistically significant differences remained between the normalized mean radial errors of the three target velocities (Friedman, $p < 0.05$).

The normalization procedure was used to remove the linear changes of the error due to the target displacement. The ordering of the normalized error magnitudes indicated that as the target velocity increased, tracking performance improved. This suggests that the human operator was not behaving linearly over these ranges of target displacements and display lags. This behavior might be explained by the hypothesis that as target velocity increased, the task became more difficult and subjects tried harder. Not surprisingly, the difficulty rating increased significantly with increasing target velocity for all display lags (Friedman, $p < 0.0001$).

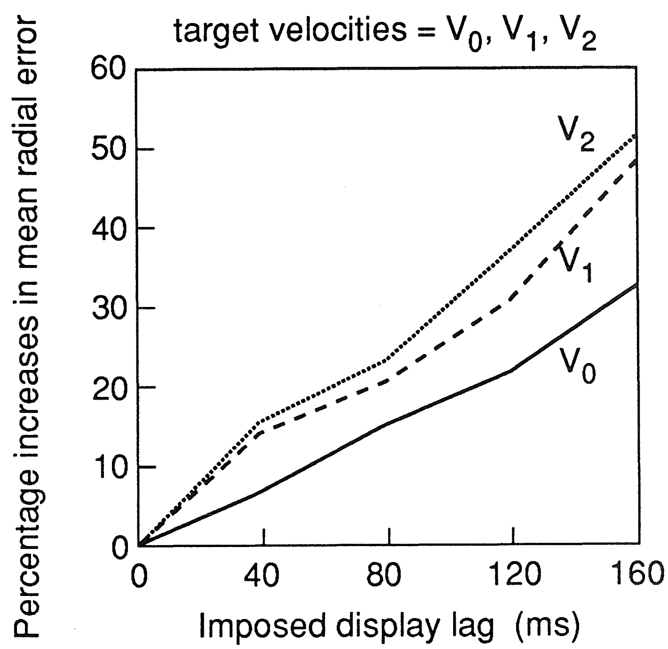

Fig. 9. Percentage increase in mean radial tracking error as a function of lag for three target velocity conditions (medians of eight subjects).

Further investigation is required to isolate the influence of target velocity separately from the influence of target displacement.

Effects of target velocity on tracking degradations caused by lags: To determine the effect of target velocity on the degradation of tracking performance caused by lags, the percentage increases in mean radial errors across the five lags were calculated for the three target velocities (Fig. 9). The percentage increases are shown relative to the zero lag condition. Inspection of Fig. 9 reveals a trend towards a greater increase in error due to lag with greater target velocities and displacements. Friedman two-way analysis of variance indicated that target velocities and displacements had a significant effect on the percentage increase in error across the five lags ($p < 0.001$).

CONCLUSIONS

Head tracking performance was significantly degraded by an imposed display lag of 40 ms or more (in addition to a system display lag of 40 ms). This agrees with previous findings by the present authors.

No significant improvement in head tracking performance was found through practice with 80-ms display lag.

At frequencies above approximately 0.5 Hz, human operator gain and human operator phase lag increased with increasing display lag. At about 0.1 Hz, human operator phase lag decreased with increasing display lag. However, at these frequencies the decrease in phase lag was not sufficient to fully compensate for the increased display lag. Both input-correlated tracking errors and uncorrelated tracking errors (i.e., remnant) increased with increasing display lag. To reduce these undesirable changes in head tracking strategy caused by display lags, a lag compensation technique is required.

For a random target forcing function having a velocity of $2° \cdot s^{-1}$ r.m.s. in both axes, scaling the target displacement so that the velocity was increased to 3.5 and $5° \cdot s^{-1}$ r.m.s. increased mean radial head tracking error. The increases in tracking error were found to be approximately proportional to the increases in target displacement. Further investigation is required to isolate the influence of target velocity separately from the influence of target displacement.

ACKNOWLEDGMENTS

This work was sponsored by Armstrong Aerospace Medical Research Laboratory through the European Office of Aerospace Research and Development.

REFERENCES

1. Allen JH, Hebb RC. Helmet-mounted display feasibility model. Naval Training Equipment Center, Orlando, FL: Advanced Simulation Concepts Laboratory, 1983; Report TR-NAVTRAEQUIPCEN 1H-388.
2. Bendat JS, Piersol AG. Random data: analysis and measurement procedures, 2nd ed. New York: Wiley, 1986; ISBN 0-4710-4000-2.
3. Birt JA, Furness TA. Visually-coupled systems. Air Univ. Rev. 1974; 20:28–40.
4. Bryson S, Fisher SS. Defining, modelling and measuring system lag in virtual environments. SPIE Conference on stereoscopic display and applications, Santa Clara, CA: SPIE, 1990; 1256: 98–109.
5. Krendel ES, McRuer DT. A servomechanisms approach to skill development. J. Franklin Institute. 1960; 269:24–42.
6. Lewis CH, Griffin MJ. A review of the effects of vibration on visual acuity and continuous manual control. Part II: continuous manual control. J. Sound Vibration. 1978; 56:415–57.
7. McRuer D. Development of pilot-in-the-loop analysis. J. Aircraft. 1973; 10:515–23.
8. So RHY. Effects of visual time delays and target velocities on subject performance of a head tracking task. Proceeding of the United Kingdom Informal Group Meeting on Human Response to Vibration, A.F.R.C. Wrest Park, Silsoe, Bedforshire, England: Institute of Engineering Research, 1989.
9. So RHY, Griffin MJ. Compensating lags in head-coupled displays using head position prediction and image deflection. J. Aircraft. 1992; 29:1064–8.
10. Woodruff RR, Hubbard DC, Shaw A. Comparison of helmet-mounted visual displays for flight simulation. Displays. 1986; 7:179–85.