Technical Memorandum

Research and Special Programs Administration

John A. Volpe National Transportation Systems Center

Topic: **Recommended minimal cockpit head motion box dimensions**

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Outline

Purpose

For given head-up display (HUD) optics and symbology placement, the Cockpit Head Motion Box (CHMB) can be defined, which is a fixed volume in space in which the pilot's head must remain for all flight critical symbology to be visible in at least one eye.[1] For certification purposes, the volume should be large enough to accommodate the vast majority of natural head motion that the vast majority of pilots exhibit when attempting to look through the HUD.

It is not necessary for the volume to include head motion that results from the pilot deliberately looking away from the HUD to use other displays or objects (e.g., control display unit data entry, approach plate referencing). However, it should not be necessary for the pilot to exercise substantial will to keep his or her head in the CHMB as this would represent additional workload and potentially physiological strain. Example sources of head motion the CHMB should accommodate include head reactions to control inputs, aircraft accelerations resulting from normal maneuvers and turbulence, and minor adjustments to head and body position for the sake of comfort.

This memo provides recommendations for the dimensions of the minimal CHMB based on a study of pilot head motion in actual flight. These recommended dimensions should accommodate the vast majority of the targeted head motion exhibited by the vast majority of pilots.

Recommendation

Minimal CHMB

For HUD usage in any flight phase, the lateral dimension should be at least 3.5 inches centered on the cockpit design eye position (DEP), and the vertical dimension should be at least 1.9 inches centered on the DEP. For the longitudinal dimension, the forward face (as the pilot sits) of the CHMB should be at least 2.1 inches from the DEP and the rear face should be at least 1.8 inches for a total length of 3.9 inches. These measurements are relative to the plane of the floor of the cockpit.

Application

This recommendation is considered valid for general aviation and transport fixed wing aircraft that are manually flown in no turbulence or light turbulence. It is assumed that pilot task characteristics and crew responsibilities are such that there is limited need for the pilot using the HUD to keep its symbology in peripheral view when the pilot looks away from it.

Supporting Study

Approach

The CHMB of a HUD should be large enough to accommodate the natural head motion a pilot exhibits. A study was conducted to determine the range of this head motion by measuring pilot head displacements over the course of actual flight. Measurements were made when a HUD was *not* used in order to determine the range of motion that must be accommodated by a HUD, not the range of motion that results from HUD usage.

Only head motions associated with using the aircraft's primary flight reference (PFR) were included because they best represent the use of HUD. Head motion associated with looking away from the PFR (e.g., out the window or at other displays or artifacts) were removed from analysis because for these motions, the pilot would not be able to effectively monitor the HUD irrespective of the size of the CHMB.

Measurements were taken for multiple pilots flying two aircraft, one representing general aviation and another representing transports. Measurements were taken across the multiple phases of flight in case head motion varies with it. Efforts were made to fly in turbulent conditions in order to capture its effect on head motion.

The CHMB should be large enough to accommodate vast majority of head motion of the vast majority of pilots. For analysis, this is interpreted to mean that the CHMB accommodates about 90% of the head motion of about 90% of the population. These are conventional proportions used in ergonomic design.

Method

Measurement Apparatus

Head motion was measured with an infrared motion tracker mounted on or above the glare shield of the test aircraft's forward instrument panel. It tracked an adhesive reflector about 0.5" in diameter that was affixed to the pilot's forehead. Thirty-six times a second, the tracker sent the reflector's lateral, longitudinal, and vertical coordinates to a laptop computer for recording. Precision of measure is on the order of 0.01 inches or less.

The tracker was unable to track the reflector if the pilot turned his head approximately 60 degrees. Such head turns, which were almost certainly intentional, would not be associated with monitoring the PFR. The tracker was also found to provide erroneous data or no data if sunlight shined directly on its lenses. Brief periods of data were therefore lost for certain headings flown at certain times of the day.

A video camera, positioned above, behind, and to the right of the pilot, recorded all flights.

Pilots

Pilots included contractor and federal employee research pilots from the Volpe National Transportation System Center and the FAA Technical Center. These pilots participated in the study as part of their normal work, and were compensated accordingly. Additional pilots were recruited from a local flight club. They were not compensated beyond being given an opportunity to log time in a light twin airplane.

A total of eight pilots participated. All pilots were male. Reported height ranged from 5'9" to 6'0," mean 5'10" or close to average for males. One flight for each pilot was used in the analysis.

Aircraft and Flights

Two aircraft were used, a Piper Aztec reciprocating light twin, and a Convair CV-580 twin turboprop air transport. Flights were conducted in visual meteorological conditions with the pilots hand-flying simulated instrument flying rules for all phases of flight. All pilots flew from the left seat with another pilot in the right seat responsible for pilot non-flying (PNF) duties and visual lookout for traffic. Each pilot flew between one and four flights for a total of 23 flights. From this set of 23, seven flights each featuring a different pilot were selected for analysis. Flights that encountered the strongest turbulence and the least difficulties with the tracking apparatus were selected. Pilots were strapped in for all flights.

Head motion measurements were taken through takeoff, climb, cruise, approach, and landing/rollout. Statistics on the durations of each phase for the seven selected flights are given Table 1.

Table 1. Statistics on flight phase durations.

Statistic	Takeoff	Climb	Cruise	Approach	Roll-out
Mean	0:28	5:24	18:21	9:12	0:27
Minimum	0:14	1:36	8:55	4:02	0:16
Maximum	0:37	8:24	34:52	22:14	0:53

Cruising altitudes were generally below 4000' above sea level in order to maximize the encounters with turbulence. These low cruising altitudes eliminated the descent as a separate phase from approach. Turbulence was successfully encountered for nearly all phases of each flight. Table 2 shows the pilot's subjective rating of turbulence for each phase.

Table 2. Turbulence encountered for each flight and phase.

Flight	Aircraft	Climb	Cruise	Approach
9	Aztec	Light	None	Light
11	Aztec	Light	Light	Light
12	Aztec	Light	Occasionally Light	Light
14	Aztec	Light	Light, occasionally Moderate	Light, occasionally Moderate
15	Aztec	Light, occasionally Moderate	Light, occasionally Moderate	Light, occasionally Moderate
21	CV-580	Light to Moderate	Light to Moderate	Light to Moderate
22	CV-580	Light, occasionally Moderate	Light, occasionally Moderate	Light, occasionally Moderate

Analysis

Data Exclusion

All collected head motion data were filtered to obtain as purely as possible only head motion associated with use of the PFR for each flight phase. Range of head motion for takeoff and rollout was found to be inevitably smaller than the other phases for each flight. Under the assumption that no HUD will be built to operate in these phases alone, these phases were not analyzed.

As revealed by inspecting the videotapes of the flight, head motion data for the beginning of climb and after reaching the decision height on approach were associated with the pilot flying by visual references and were removed from the analysis. For the Aztec, this constituted approximately the first two minutes of Climb and the last 1.5 minutes of Approach. For the CV-580, this was the last one minute of Approach.

Inspection of the head motion data in conjunction with the video tapes revealed that head motion right (inboard) of the pilot's median lateral head position frequently included cases of the pilot removing attention from the PFR. These cases included checking centrally located engine instruments and multi-function displays, manipulating the throttles, studying approach plates, and conversing with the PNF. Such diversions of attention to the left were much more limited, generally one or two per flight phase. The diversions of attention from the PFR were represented by pronounced head motion to the right and, frequently, forward, sometimes beyond the limit of the tracker's ability to track. An example is illustrated in Figure 1.

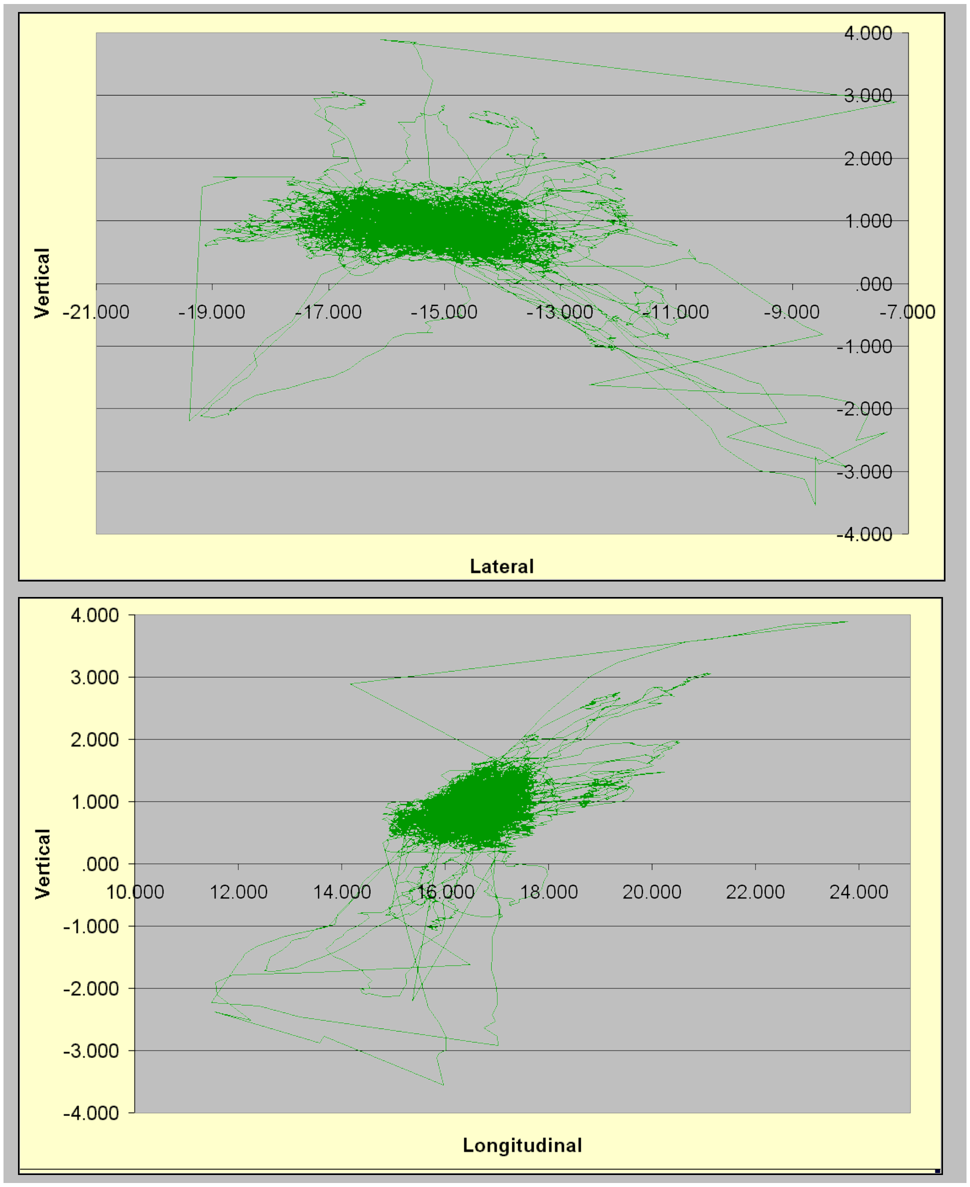

Figure 1. Head motion data for Flight 21, cruise phase. Units are inches from the tracker.

To remove any effects of such diversions of attention from the recommended CHMB, it was assumed that, in the absence of such diversions, pilot head motion would be symmetrical around the median lateral head position. That is, it was assumed that when the pilot is attending to the PFR, average motion on all dimensions on the right mirrors the average motion on the left. This assumption is supported by inspections of head motion data for arbitrarily selected periods when the pilot was clearly attending only to the PFR as indicated by the videotapes. For these data, symmetry was found.

Under this assumption of symmetry, analysis was confined to data on all dimensions collected to the left of the lateral median for each pilot and phase of flight. This effectively filtered out nearly all cases of inattention to the PFR. Note that by conducting the analysis assuming lateral symmetry in this manner, it is guaranteed that the results shall be laterally symmetrical. However, longitudinal and vertical asymmetries are still mathematically possible and may even be expected. The back of the pilot's seat restricts rearward longitudinal while forward motion is relatively free. A pilot can always slouch down or lean forward, producing considerable downward motion, but she or he can only raise the head to a certain height and remain seated.

Range of Motion Determination

For each dimension and each pilot and flight phase, an upper and lower bound of head motion was determined by taking the 98th and 2nd percentile respectively of the collected head motion data, resulting in six data points for each phase and pilot. For this particular distribution of data, the bounds on all three dimensions combined comprised approximately 90% of the head motion exhibited by each pilot. To determine the relative head motion, the median head position for each pilot and phase was subtracted from each of these bounds. As an example, the resulting bounds are shown in Figure 2 for one of the phases.

To test if range of head motion varies with phase of flight (Climb, Cruise, and Approach), the means of the bounds (both 2nd percentile and 98th percentile) were compared for each pair of phases. There were no significant differences in the mean bounds between any two phases at 0.10 level. To test if there is significant asymmetry in the longitudinal or vertical dimensions, the means of the absolute values of the 2nd percentile bounds were compared to the corresponding means of the 98th percentile bounds for each phase. Significance was approached for the longitudinal dimension in the Cruise phase (M of the differences = -0.169, $t(6)$= -2.085, $p < .10$), with an apparent tendency for skewness towards the front of the aircraft. There were also trends in this direction for the longitudinal dimension for Climb and Approach phases. A nonsignificant trend was also observed for the vertical dimension for the Climb phase, with the data showing a slight skewness downward. However the difference between the means was not operationally significant, being less than 0.1 inches.

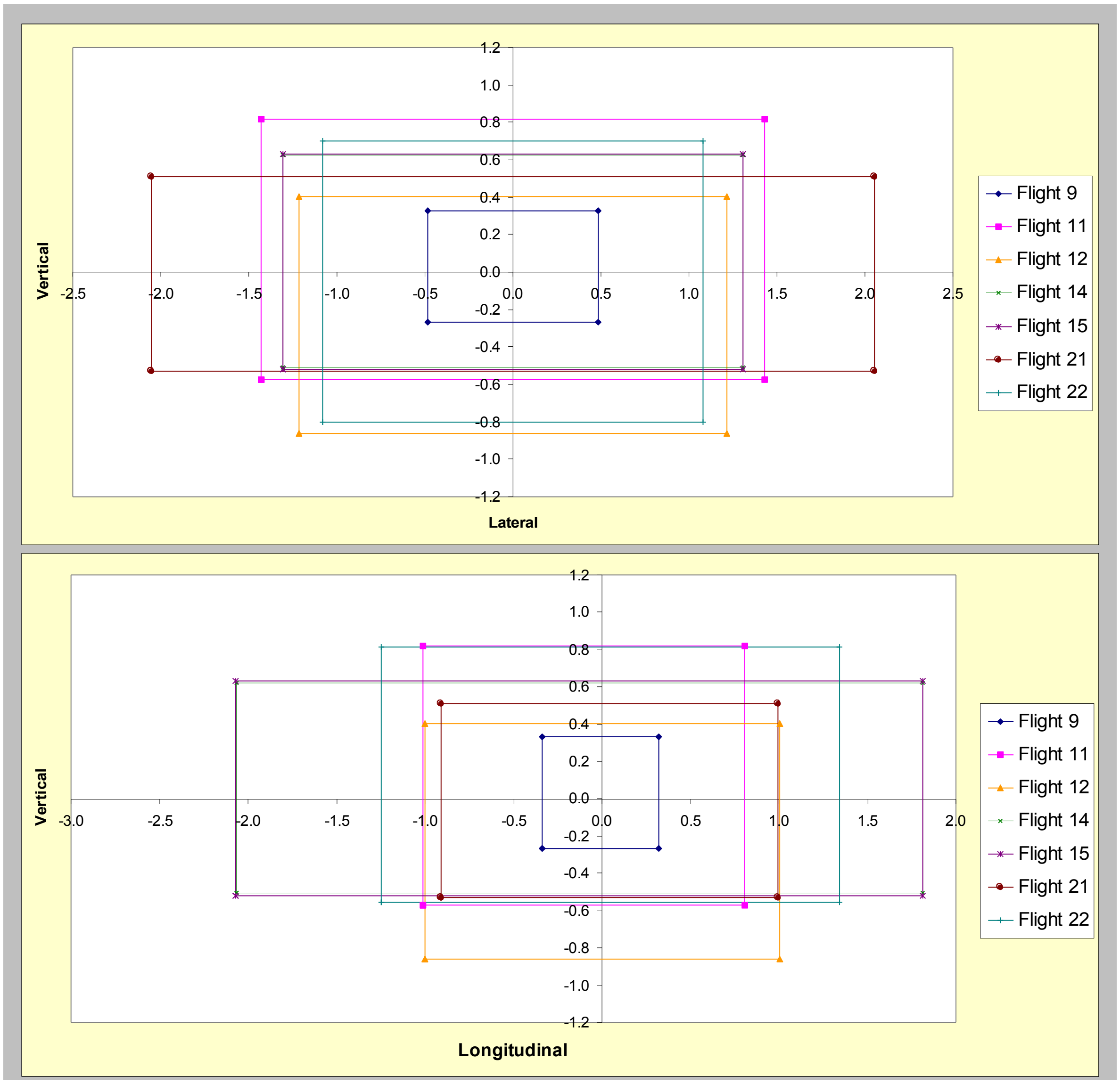

Figure 2. Second and 98th percentile bounds on head motion for Cruise phase.

The generally high symmetry within dimensions and low difference across phases suggests that range head motion on each dimension is a characteristic of the pilot that is generalizable across conditions. Consistent with this, the absolute values of all bounds were highly intercorrelated, with an average Pearson correlation coefficient of 0.452. This implies that the bounds across phases can be averaged to obtain a single more reliable bound applicable to all phases. As an indication of the reliability that can be achieved in this manner, Cronbach's alpha for combining all bounds for each dimension, both upper and lower for all phases, are given in Table 3.

Table 3. Cronbach's alpha for combined bounds along dimensions.

Dimension	Average *r*	# of Items	Cronbach's α
Lateral	0.783	3	0.915
Longitudinal	0.653	6	0.919
Vertical	0.383	6	0.789

Head motion upper and lower bounds were each average across phases to obtain general upper and lower bounds. The tests for symmetry for longitudinal and vertical dimensions were repeated on the resulting data to see if the increase in reliability is sufficient to reveal a significant skewness. There was no significant difference in the absolute values of the vertical upper and lower bounds ($t(6)= 1.480$, $p > .10$), and the difference was not operationally significant in any case (M of the differences = 0.036). This implies that the absolute values of the vertical bounds can be combined to yield a single more reliable vertical bound that can be applied symmetrically.

The difference for the longitudinal, on the other hand, was now significant (M of the differences = -0.212, $t(6)= -3.124$, $p < .05$). On average, the forward bound of the range of head motion is about 0.2 inches further from the median head position than the rearward bound.

Minimal CHMB Determination

The means and standard deviations across all pilots of the 2nd percentile and 98th percentile bounds, combined across phases, are given in Table 4. The vertical bound is the average of the absolute values of the upper and lower bounds. The upper and lower longitudinal bounds are averaged separately across phases given the significant asymmetry it exhibits. The lateral dimension was assumed to be symmetrical early in the analyses, so only one value is given.

Table 4. Statistics for combined bounds.

Statistic	Lateral	Longitudinal		Vertical
		Forward	Rearward	
Means	1.247	1.240	1.027	0.589
Standard Deviations	0.401	0.467	0.367	0.117
Standard Errors	0.151	0.176	0.139	0.044

The means in Table 4 represent the average bounds that comprise about 90% of pilot head motion. That is, one would expect half the pilots to exhibit head motion beyond these means. To derive the values that comprise about 90% of the pilot head motion for about 90% of the pilots, each bound is increased by the standard deviation times the value of the t distribution that corresponds to the 95th percentile (1.943 for $df = 6$). With the bounds extended out by this amount at both ends, the resulting value is statistically expected to comprise at least 90% of the population. A normal distribution of the bounds across subjects can be assumed because the bounds are the average of a random variable from the same distribution (the bounds observed for each phase), for which the central limit theorem proves will approach a normal distribution.[2] There was no apparent skewness in the bounds across pilots, with the mean and median within .05 inches of each other for all dimensions. The resulting values are presented in Table 5.

Table 5. Values comprising the head motion of at least 90% of the pilots.

Statistic	Lateral	Longitudinal		Vertical
		Forward	Rearward	
Distance from DEP	2.165	2.061	1.833	0.929
Total Distance	4.330	3.894		1.858

The longitudinal and vertical values may be used directly to design and evaluate HUDs. For example, the CHMB top face should be at least 0.929 inches above the DEP, while the bottom face should be at least 0.929 inches below, for a total size of 1.858 inches. Given the standard errors observed for the underlying mean bounds (see Table 4), it is just as well to round to the nearest 0.10 inches.

The pilot's laterally separated eyes complicate the lateral values for the recommended CHMB. Given that the CHMB is defined to be the space where flight critical symbology is visible in at least one eye, the lateral values can be reduced by the interpupillary breadth. As pilot's head slides laterally and the first eye moves out of the CHMB, a distance equal to the interpupillary breadth must be transverse before the second eye leaves the CHMB. The interpupillary breadth for the 5th percentile female is 2.0 inches[3]. Thus, the lateral dimension of CHMB may be as low as 2.3 inches total distance and still allow the vast majority of pilots to see flight critical symbology the vast majority of the time.

However, the interpupillary distance for the median person is 2.4 inches. Thus adopting 2.3 for the lateral CHMB size would mean that most pilots would *never* look through the HUD with both eyes. It would seem more reasonable to design HUDs such that the vast majority of pilots look through the HUD with both eyes at least half of the time. Under the assumption of lateral symmetry, the first and third quartile of our head motion data, averaged across phases and pilots, is 0.433 inches from the median. The 95th percentile male has an interpupillary breadth of 2.7 inches[4]. Thus for the vast majority of pilots to be looking at flight critical symbology with both eyes for at least half of the time, the lateral dimension of CHMB must be 2.7 + 0.4 + 0.4 or 3.5 inches. This becomes the recommended minimal lateral dimension.

Methodological Considerations

The validity of the recommendations that resulted from this research is subject to the underlying assumptions. One of these assumptions is built into the definition of CHMB itself: that it is adequate if pilots see flight critical information with only one eye. Operational experience from monocular head mounted displays used in military aviation suggests that this is an acceptable assumption. However it is also assumed to be unacceptable for most pilots *always* view flight critical symbology with one eye, and this assumption ultimately determined the size of the lateral dimension of the CHMB.

Flights were limited to normal maneuvers in generally light continuous turbulence. This was necessary for practical and safety reasons. The implied assumption is that in order to see symbology the pilot should not have to exercise will to hold the head still during *common* maneuvers and turbulence. During extreme maneuvers and more intense turbulence it is assumed to be acceptable for the pilot deliberately hold his or her head still for HUD usage for the relatively short durations this is likely to be necessary. The pilot's *ability* to hold the head inside the minimal CHMB recommended here under such conditions remains untested.

In order to filter out cases of the pilot diverting attention from the PFR, symmetrical lateral motion was assumed. The data appear consistent with this assumption, but a true test of it is not possible without a measure of pilot attention separate from head motion itself. The videotapes have proven inadequate for this.

The use of upper and lower bounds relative to each pilot's median implies the assumption that the pilot is responsible for positioning him/herself properly with respect to the DEP. This is a working assumption in the design of any flight display, but given the relative small size of practical CHMBs, it is a particularly important one for HUDs. It is not known if all pilots are willing or able to position themselves at the DEP, or whether forcing all to do so compromises their skills (e.g., disrupting judgments of when to flair).

As an indication of how actual seating position varies among pilots, median head positions for the Cruise phase are given in Table 6. Variations up to an inch are common. The seat adjustments on the Aztec are limited and there are no rudder pedal adjustments, so these data are not generalizable to air transports. On the other hand, the build of the pilots in this study was relatively homogenous compared to the population, with a standard deviation of pilot stature being 1.2 inches, when the standard deviation for males in the general population is more like 2.6 inches[5]. Thus actual variation in median head position is possibly greater than observed here.

Table 6. Median head positions for Cruise phase. Units are inches from the tracker. The tracker position in the Aztec was substantially different than the CV-580 so data are not comparable across aircraft.

Flight	Aircraft	Lateral	Longitudinal	Vertical
9	Aztec	-1.70	20.84	3.91
11	Aztec	0.19	22.19	4.07
12	Aztec	-1.09	21.86	4.98
14	Aztec	0.08	23.20	5.78
15	Aztec	0.41	23.20	5.79
21	CV-580	-15.31	16.51	0.99
22	CV-580	-14.85	16.49	0.49

The recommendations were derived from a study of only seven pilots. As indicated by Figure 1, however, this study found that there is substantial variation across pilots in head motion. This results in a fairly large standard error for the mean bounds, as shown in Table 4. The actual bounds for the population may easily be over a tenth of an inch greater or less than the bounds used for the recommendations here. About 15 more pilots would have to be flown to reduce all standard errors below 0.1 inches, which was impractical for this study. These recommendations use the sample mean bounds, as opposed to an upper or lower confidence interval. In using the means, the recommendations represent a "best guess" of the proper minimal CHMB, being neither conservative nor liberal.

Concern may be raised regarding the use of multiple individual tests for the effects of phase and asymmetry rather than a combined test such as a repeated measures analysis of variance. Use of multiple tests elevates family-wise error rates, effectively increasing Type I errors. However, unlike more theoretical research, the costs a Type I error in this application are comparable to the costs of a Type II error. Given the small sample size, it was judged acceptable to maximize power and accept the higher family-wise error rate.

Acknowledgments

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Abbreviations and Acronyms

CHMB.........Cockpit Head Motion Box

DEP.............Design Eye Position

FAA............Federal Aviation Administration

HUD............Head-up Display

PFR..............Primary Flight Reference

PNF..............Pilot Not Flying

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[4] ibid.

[5] ibid.