WORKLOAD MEASUREMENTS FOR OPERATIONS UNDER SIMULATED SINGLE PILOT INSTRUMENT FLIGHT RULES

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Abstract

Operations under a single pilot instrument flight rule for general aviation aircraft are known to be one of the most demanding pilot tasks. Pilot workload measurements using a PC-based flight simulator have been done to investigate the pilot's skills and the pilot workload. A pilot workload evaluation method has been established which is partly based on the time and motion studies and which mainly concentrates on the pilot's information processing. The time-record of a pilot's eye movement has been used for the evaluation. Pilots who have different flight experiences attended the tests. Comparisons between the results by experienced pilots and those by novice pilots were made. It was shown that a relatively correct pilot workload has been evaluated by the present method. Results for the VOR tracking flight showed that the workload of the experienced pilots increases only when the airplane attitude has been changed, while the results of the novice pilots show a high workload continuously during the whole flight.

Nomenclature

ail	aileron
alt	altitude
a/s	air speed
bnk	bank angle (attitude indicator)
elev	elevator
hdg	heading angle
pch	pitch angle (attitude indicator)
rud	rudder
t/c	turn coordinator
thr	throttle
trim	elevator trim
vsi	vertical speed
wlail	workload by aileron movement
wlalt	workload by altitude perception
wlbnk	workload by bank angle perception
wlev	workload by elevator movement
wlhdg	workload by heading perception
wlpch	workload by pitch angle perception
W_{all}	total workload = $W_{bnk} + W_{pch}$
W_{bnk}	workload by bank angle operation = *wlbnk* + *wlhdg* + *wlail*
W_{pch}	workload by pitch angle operation = *wlpch* + *wlalt* + *wlev*

1 Introduction

Instrument flight rules enable pilots to fly airplanes safely even under low visibility and low ceiling flight conditions. Operations under a single pilot instrument flight rule (SPIFR) for general aviation (GA) aircraft is known to be one of the most demanding tasks for a pilot [1]. The pilot under SPIFR without an autopilot feature has to fly the airplane manually by selecting the necessary information from numerous flight avionics. He also has to handle all communications including frequency changes, to navigate by the use of many necessary charts, and to comply with ATC procedures [2]. These demands of flying an aircraft sometimes exceed the capabilities of the pilot. Therefore, to maintain the safety of the instrument flight, it is necessary to reduce these demands to the pilot. There have been efforts to improve the safety of GA aircraft by introducing multifunction displays [3]. However, it has been quite difficult to popularize these systems because of their cost [2]. The concepts of physical and mental workload [4-6] have also been used to evaluate the demands to the pilot quantitatively.

Pilots who have a lot of flight experience fly airplanes under SPIFR safely and efficiently. They have gained the capability to maintain the safety of the flight and to reduce their workload through their long-time flight experiences. Therefore, it is believed that an efficient way of flying can be found by investigating the flight characteristics of experienced pilots through workload evaluation studies. Reference 4 investigated whether the pilot workload can be reduced by means of an efficient eye-scanning pattern among avionics and by improving the pilot's task scheduling. Reference 7 tried to gain the characteristics of the pilot's behavior by applying a timeline analysis (TLA) method [8] for the pilots under SPIFR. The TLA method is based on the time and motion study that estimates the workload of an airliner pilot. However, since differences exist between the nature of a pilot's behavior for the airliner and that for the light airplane, an appropriate workload distribution could not be found. The reason is explained as follows. The main task for the light airplane is to control the airplane by obtaining information such as airplane position and attitude from the instrument panel. However, the TLA method is mainly based on the pilot's movement to operate the switches and levers of the flight instruments rather than to keep the airplane stable.

In this paper, a pilot workload evaluation method that is partly based on time and motion studies and which mainly concentrates on the pilot's information processing has been established and is discussed. Pilots who have different flight experiences attended the tests that use a PC-based flight simulator to investigate what kind of flight skills and experiences have reduced the pilot workload. The purpose of this paper is to improve the safety of SPIFR by GA pilots.

2 Pilot Workload Evaluation Methods

To discuss airplane safety, the relationships between the limit of human capability and the tasks required to fly an airplane should be revealed. Thus, pilot workload analysis tests have been conducted and reported [6-12]. Workload is a measure, which indicates the difficulties when performing a task. It is classified into physical workload and mental workload. Since the physical work for an airplane pilot is very light, most research concentrates on the mental workload that is related to information processing [13].

Pilot workload assessment techniques are mainly classified into four different methods: the subjective rating method [9], the secondary-task paradigm [6], the biocybernetic measuring method [10,11] and the time and motion study [8,12]. The last one, the time and motion study, is the method to evaluate a pilot's behavior by recording his actual piloting behavior (task) along a time axis. The workload assessment of this method is based on the two processes, the recording of the tasks and the workload evaluations for each task.

The workload evaluation method used in this paper mainly concentrates on information processing and on piloting tasks that control an airplane's attitude. Here, workload has been classified into two phases: workload based on perception and workload based on piloting behavior.

2.1 Workload based on Perception

It is assumed that the examinee recognizes the value indicated on the instrument panel, which he is looking at, as information. Then the time history of the perceived information can be obtained by analyzing the time history of the indicated values of each instrument and that of the examinee's eye movement. A decision is made based on this perceived information. If a correction should be made, the examinee operates the switches or the levers such as a control yoke, or he records it into his short term memory and the correction is made later. After the correction is made, the perceived information that is based on the piloting behavior is now past information, and it will be deleted from his short term memory. Since there is a limit to the number of items that can be maintained in short term memory [14], the amount of information in his short term memory can be used as one of the elements for workload assessment. If the difference between the perceived information and the value that the pilot expects as appropriate is large, a correction should be made immediately. Therefore, the amount of corrections can be used as another element for the assessment of mental workload originated in decision-making.

If the pilot obtains information that he is flying higher than the altitude that he deems appropriate, he stores this information into his short term memory. After he operates the control yoke to decrease the pitch angle of the airplane, it is believed that he deletes this information from his memory. This means that some aspect of the workload that is related to the adjustment should be recorded during the course between the time he perceived the higher altitude and the time he begins to operate the control yoke.

This idea is applied to four parameters: pitch angle (includes vertical speed), bank angle (includes turn rate), altitude and heading. Each parameter is assumed to have workload scores between 0 and 5. Hereafter, we refer to them as the workload by pitch angle perception *wlpch*, workload by bank angle perception *wlbnk*, workload by altitude perception *wlalt* and workload by heading perception *wlhdg*. The value that the examinee considers to be appropriate for each parameter is assumed from the flight path record and from talking to the examinee after the test.

2.2 Workload based on Piloting

The pilot conducts the control surfaces such as an elevator, according to his perception and judgment. The changing rate of an airplane's attitude is based on how large the pilot controls the control surfaces. The attitude change is accompanied with a parameter change, such as the altitude and the vertical speed, which decides the flight path. If the pilot conducts the control surface larger than usual, the changing rate increases and the airplane accomplishes its expected attitude in a shorter time than usual. However, it often occurs that the pilot controls too much, the airplane tends to be over-controlled and as a consequence the pilot mental workload increases. Theoretically, a pilot's movement should be based on his judgment. Therefore, the time history of the pilot's movement should be obtained by correspondence to the above mentioned time history of judgment. However, since the judgment is done inside the human brain and since it is difficult to comprehend it, the time history of piloting was obtained, for this paper, from the movement of the control surfaces.

This idea is applied to two parameters: elevator movement and aileron movement. Each parameter is assumed to have workload scores between 0 and 5. Hereafter, we refer to them as the workload by elevator movement *wlev* and workload by aileron movement *wlail*. The flight simulator used here can accomplish the coordinate turn without applying a rudder pedal. Therefore, the workload by rudder movement was not considered here.

Hereafter, two kinds of workload will be used for the analysis by combining and rearranging workloads based on perception and piloting. The first one is the workload by pitch angle operation W_{pch}. This is defined as the sum of the workload by pitch angle perception *wlpch*, workload by altitude perception *wlalt* and the workload by elevator movement *wlev*. The second one is the workload by bank angle operation W_{bnk}. This is defined as the sum of the workload by bank angle perception *wlbnk*, the workload by heading perception *whdg* and the workload by aileron movement *wlail*.

The pilot usually decides by himself the flight path that attains the best performance, such as the correction angle to intercept the target radial when he tracks the VOR radial. This decision often affects the workload during the VOR tracking. However, since there is no direct way to evaluate this judgment, this was not included in the present workload assessment.

A detailed description to obtain the time history of the workload from the examinee's results is shown in the Appendix. The appropriateness and the correctness of the present workload evaluation method are difficult to discuss. The present method is applied to the results of the simulated flight as will be shown in Section 4.1. The results will be used to discuss and to evaluate the present method.

3 Experimental Apparatus and Methods

The experimental apparatus (Figure 1) mainly consists of a flight simulator and some data recorders. A PC-based flight simulator for the instrument flight training was used (CirrusII flight console made by Precision Flight Controls Inc. and software Elite Ver. 5.1). This software simulates the instrument flight of a single engine propeller driven aircraft, Cessna 172. The instruments for VFR and IFR are shown on the PC screen. The flight console has a control yoke, throttle lever, rudder pedal, elevator trim and control panel for its navigation equipment. Another PC was used to record the pilot's operation of the control surfaces and other flight equipment. This PC is directly connected to the flight console to monitor his operations. An eye-mark recorder (NAC, EMR-7) was used to record the examinee's eye movement. The example of the picture recorded by the eye-mark recorder is shown in Figure 2. The instruments shown on the PC screen was video-recorded by another CCD camera to record the altitude, heading and attitude of the aircraft.

By using these apparatuses, time histories of the flight parameters were obtained. Movements of the elevator, aileron, rudder, throttle lever and elevator trim wheel were recorded. The eye-mark recorder was used to record the instruments that the examinee was looking at and the duration of time that he spent looking at one particular instrument in 30Hz. The instruments recorded by the eye-mark recorder were the attitude indicator, altimeter, heading indicator, airspeed indicator, turn coordinator, vertical speed indicator, VOR and engine tachometer. The bank angle, pitch angle, altitude, heading, airspeed, turn rate and vertical speed were obtained from the video-recorded data by the CCD camera in 3Hz.

Four pilots who have different flight experiences attended the tests. The examinee's data is shown in Table 1. The examinees are called A, B, C and D, in order of the amount of flight time each examinee has (A has the longest flight time). Three of the pilots have commercial licenses and one has a private pilot license. They each have different flight experiences for the Cessna 172, but none of the examinees had any experience flying the simulator used here.

The flight scenario used for the experiments is shown in Figure 3. The scenario is based on the VOR approach. Measurement started after the straight level flight and the standard rate turn from the starting point, as shown in Figure 3. Workload analysis was made for the straight level flight (maintain heading 160°, altitude 3000feet and airspeed 110kts, refer to Figure 3, I), VOR interception (intercept to VOR radial 020, maintain airspeed and altitude, Figure 3, II) and VOR inbound tracking (descend to 2600feet at 700feet/min descent rate, Figure 3, III). Wind and turbulence were not added into the scenario. The reason why the VOR approach was used for the scenario is that it contains the basic instrument reference flight such as the straight-level flight and the standard rate turn, but also the VOR navigation flight to intercept and to track the VOR radial.

Decreasing the flight accuracy to maintain altitude and heading can easily reduce the pilot mental workload. Therefore, the standard for the present experiment was made based on Ref. 15. The standard is to maintain the target heading within 10° for a straight flight. As for the turning flight, it was required to maintain the bank angle (18°) that accomplishes the standard rate turn (turning rate: 3°/sec) within 5°. When performing the VOR tracking, the bank angle (10°) that accomplishes the half standard rate turn (turning rate: 1.5°/sec) is also possible if the examinee wishes. These bank angles of 18° and 10° were determined from the flight analysis of the flight simulator. Other standards were to maintain the target altitude within

100feet at the airspeed of 110kts within 10kts for the level flight; to maintain a constant descent rate at 700feet/min within 100feet/min at the airspeed of 110kts within 10kts. The experiments were conducted after the examinees were given an explanation concerning the above standards and after they practiced the flight simulator for 30min. to 1 hour.

The flight dynamics model of the ELITE software used for the tests is unknown. All examinees agreed that the model is suitable for IFR training. But there were some comments, pertaining to difficulty, such as the elevator trim point is difficult to find out because the control yoke is very sensitive to the change of pitch angle, and that there is little play in the control yoke.

4 Results and Discussion

4.1 Example of Workload Evaluation

Figure 4 shows the time history of the measured parameters (upper and middle part in Figure 4) and the workload (lower part) of examinee A when the airplane is making a horizontal turn to intercept the VOR (Figure 3, phase II). There are some bold-lines in the upper and middle parts of this figure. This denotes that the examinee is looking at a specific instrument at this time. The attitude indicator indicates both the bank angle and the pitch angle. It was assumed that the examinee is looking at both the pitch angle and the bank angle at the same time, when he is looking at the attitude indicator. The broken lines of the turn rate (*t/c*), bank angle (*bnk*) and heading (*hdg*) indicate the time history of each parameter that the pilot thinks as appropriate or that he should keep, as discussed in Section 2.1. The lowest part of this figure shows the time histories of the workload by pitch angle operation W_{pch}, the workload by bank angle operation W_{bnk} and the total workload W_{all} ($=W_{pch} + W_{bnk}$).

Figure 4 shows that the optimum values of the total workload W_{all} are observed after 110sec. and after 125sec. which coincide with the times that the examinee started and finished turning (see *hdg* in Figure 4). During this turn between 110sec. and 125sec., the workload is relatively low. After he finished turning (after 130sec.), the workload is also quite low. As for the instruments that the examinee is looking at (bold-line), this figure shows that he is mainly looking at the attitude indicator (*pch* and *bnk*) for most of the time. At 120sec. W_{pch} indicates a relatively high value. This is because the examinee operated the elevator when he noticed that the nose of the airplane was going down (see *pch* and *elev*).

As noted in Section 2, each parameter has workload scores between 0 and 5. As mentioned before, the appropriateness of the quantitative value of these scores is not clear. The workload by perception and that by piloting have been simply added. This also has little quantitative basis. Furthermore, the definition of the time history of each parameter which the pilot deems appropriate, as shown in the broken lines in Figure 4, are quite subjective as well. However, Figure 4 shows that the workload distributions appropriately correspond to the piloting behavior. This indicates that the present workload evaluation method could be used to assess the workload originated with piloting.

4.2 Pilot Behavior when Tracking the VOR

In this section, discussion of the piloting behavior of the four examinees is made by analyzing the data from the VOR tracking flight (Figure 3, phase II and III). Figures 5-8 show the altitude-time history (a), flight path history in the horizontal plane (b) and the workload distributions (c) of pilots A-D. The horizontal axis of Figure (b) corresponds to the VOR radial 020. The flight path in Figure (b) has been estimated from the data of the airplane's heading and airspeed. The vertical axis in Figure (b) has been enlarged five times larger than the horizontal axis. The symbols "+" and "•" in the flight path denote the airplane position. These symbols were changed every 5 seconds. The symbol "o" in the flight path denotes when the pilot is looking at the VOR instrument. The vertical arrows in Figures (a) and (b) denote when the workload W_{pch} and W_{bnk} attain their local maximum values.

Figure 5 shows the results by pilot A who has the longest amount of flight time. This shows that the workload distributions attain their local maximum values, such as at 125sec. and at 162sec. These correspond to the time when he alters the heading and the altitude. The workload distributions show a relatively low value during the level flight (e.g. at 140-150secs). As shown in Figure 5b, the time when the workload by bank angle operation W_{bnk} attains its local maximum, such as at 202sec., corresponds to the time when he changes his heading to follow the target VOR radial. This indicates that he tries to keep the path on route, even when the difference between the actual position and the target route is small. He recognizes the airplane position correctly by observing the VOR and he properly changes his course according to the indication of the VOR.

Figure 6 shows the results by examinee B who has the second longest amount of flight time but has not flown for the past year. This figure shows that the workload is continuously high during the whole flight. The flight path (Figure 6b) indicates that the airplane is greatly out of the course even though he looks at the VOR regularly from 140sec. to 210 sec. (see the symbol "o" in Figure 6b). During this time, the airplane is also descending (Figure 6a) and the high workload by pitch angle operation W_{pch} is observed (Figure 6c). This higher workload might have impeded the proper operation of the bank angle to maintain the course. Although the workload by bank angle operation W_{bnk} also indicates a high value from 160sec. to 190 sec., this bank operation is not enough to return to the correct course. In this experiment, the examinee is asked to descend about 700feet/min. As shown in Figure 5, examinee A descended the airplane close to this desired descent rate. However, Figure 6a shows that examinee B descended the airplane at only about 400feet/min. As for the workload by pitch angle operation W_{pch}, examinee A shows a high workload only at the beginning (160sec.) and at the end (185sec.) of the descent flight (Figure 5). On the other hand, examinee B shows a high W_{pch} continuously from the beginning to the end of the descent flight (Figure 6). This is because his workload by pitch angle perception *wlpch* is higher than that of examinee A.

Figure 7 shows the results of examinee C who has less flight time experience but has been under training to become an airline pilot. This figure shows similar results to those by examinee A. Higher workload is seen only when the airplane changes its altitude and heading.

Figure 8 shows the results by the private pilot D who has an FAA instrument flight rating but has the least flight experience. Results show that the workload is continuously high which is similar to the results by examinee B (Figure 6). He has difficulty when intercepting the target VOR radial (Figure 8b) and he never reaches to the target VOR radial. Before he starts descending (110-150sec.), he could not maintain the constant altitude of 3000feet (Figure 8a). But the workload by pitch angle operation W_{pch} has been kept low at 110-150sec. (Figure 8c). This means that he has not recognized the incorrect altitude during that time. He began to change the heading at 160sec. (Figure 8b). At the same time he noticed the difference of the altitude and began the descent at 160-180sec. Therefore during that time, the workload W_{pch} has increased (Figure 8c).

Examinees A and C showed relatively low workload distributions. They corrected the heading and the pitch angle while the differences in the route and altitude between the present position and the target were small. On the other hand, if the correction is made after these differences become large, there is a possibility that other tasks such as a descent or a turn should be started at the same time. This situation causes the workload to increase as seen in the results by examinee B. This is one of the reasons why the workloads of examinees B and D indicated a much larger value than those of A and C. Other reasons are the differences of recent flight experiences and the piloting technique mastered during their flight training.

This paper discussed the workload evaluation method only by using the data of four examinees. However, to increase the accuracy and to improve the present method, it is necessary to conduct these experiments with more examinees.

5 Conclusions

In this paper, pilot workload measurements using a PC-based flight simulator have been conducted for pilots who have different flight experiences. The purpose of this paper is to discuss the piloting techniques, which achieves the safety of the single pilot instrument flight for the general aviation pilot.

The pilot workload evaluation method has been discussed, which is based on time and motion studies and that concentrates on the pilot's information processing, perception and the operation of flight instruments. The results show that the appropriate workload distributions can be obtained, depending on the change in the altitude, pitch angle, heading and bank angle of the airplane.

This method has been applied to the data of VOR tracking flight. The workload of the experienced pilots increases only when he changes the airplane's attitude. High workload distributions were continuously recorded for the results of the novice pilot and for the pilot who did not have recent flight experience. Due to a continuous high workload, they could not make correct judgments and this led to a further high workload. Appropriate judgment and accurate flight techniques afford the safety of instrument flight.

Acknowledgments

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Appendix A Details of Workload Evaluation Method

A.1 Workload by Bank Angle Operation W_{bnk}

The workload W_{bnk} consists of *wlbnk*, *wlhdg* and *wlail*.

A.1.1 Workload by bank angle perception ***wlbnk***

The time history of the perceived bank angle is made by analyzing both the time record of the bank angle and the time record when the examinee is looking at the bank index in the attitude indicator. When he was looking at the bank index, the value of the bank angle at that time was used as the perceived bank angle for the analysis. When he is not looking at it, the value when he last looked at the index was used. Then the workload was scored between 0 and 5 according to the differences in the angle between the perceived bank angle and the bank angle that the pilot should keep as noted in Section 3. Figure A1 shows the relationship between the bank angle and the workload scores (*wlbnk*) that is applied to both the straight flight and the turning flight. The turn coordinator acts similarly to the bank index. Therefore, similar workload scores are added to *wlbnk* when the examinee is looking at the turn coordinator. It is noted that while the workload from the turn coordinator is added, that from the bank index was not added into *wlbnk*, to avoid the duplication. As shown in Figure A1, the distribution of the workload was assumed to have a relatively simple pattern.

*A.1.2 Workload by heading perception **wlhdg** and workload by aileron movement **wlail***

As for the straight flight, the workload scores were given according to the differences in the heading between the actual heading and the one the examinee deems appropriate. The workload scores are added from the time the examinee recognizes the differences until he begins to correct or until he confirms that the correction has been already made. Figure A2 shows the relationship between this difference in heading and the workload scores (*wlhdg*) for the straight flight. When conducting a turning flight, it was assumed that the remaining time to accomplish the turn is estimated in his mind when he observes the heading indicator. The constant value of 2 was added to the workload *wlhdg*.

As for the aileron movement, if the aileron is moved more than a particular angle from the neutral angle, the workload *wlail* that has a similar distribution as that in Figure A2 was added. This particular angle is 10% of the angle between the neutral angle and the maximum aileron angle.

A.2 Workload by Pitch Angle Operation W_{pch}

The workload W_{pch} consists of *wlpch*, *wlalt* and *wlev*. These were estimated by using the same methods as in Section A.1. Details are shown in Reference 16.

Table 1 Examinee's Data JCAB : Japan Civil Aviation Bureau

Examinee	License & Rating	Flight Time	Note
A	JCAB airline transport pilot (multi-engine, instrument rating)	3500 h	Boeing747 Airline Pilot
B	FAA commercial pilot (multi-engine, instrument rating)	650 h	Fixed Wing 250h No flight experience for the last one year
C	JCAB commercial pilot (multi-engine, instrument rating)	290 h	Under training as an Airline Pilot
D	FAA private pilot (single-engine, instrument rating)	200 h	No flight experience for the last one year

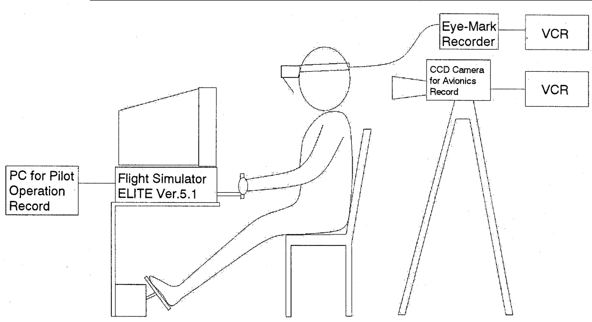

Fig.1 Experiment Block Diagram

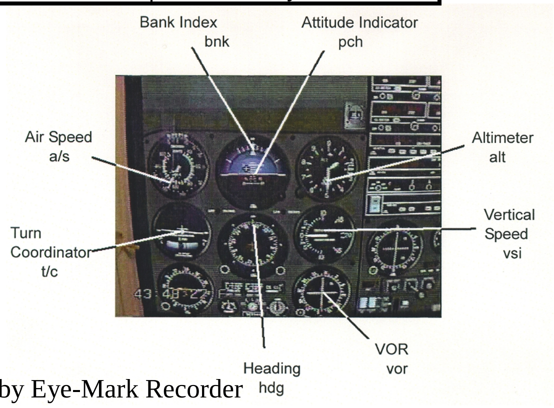

Fig.2 Example of Picture recorded by Eye-Mark Recorder

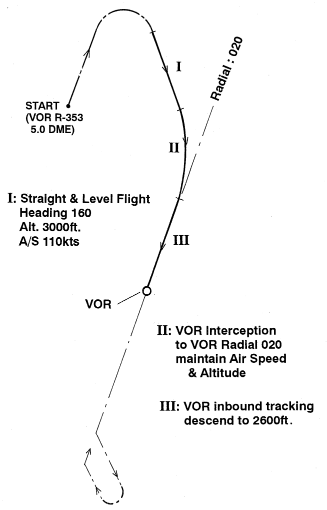

Fig.3 Flight Scenario

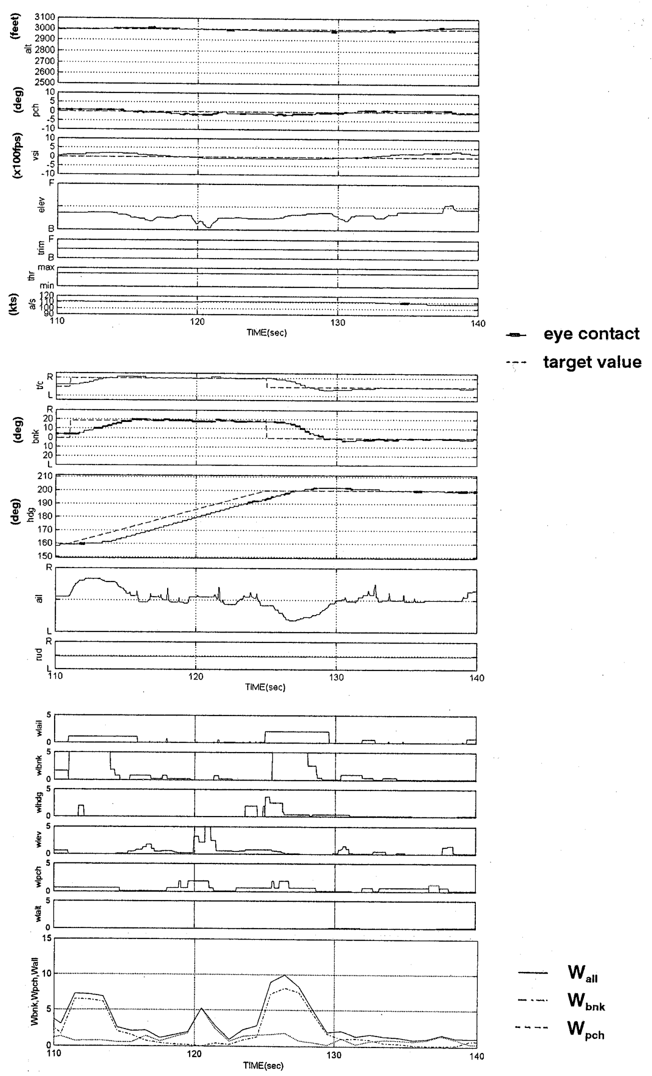

Fig.4 Time Histories of Flight Parameters and Workload (Horizontal Turning Flight, Pilot A)

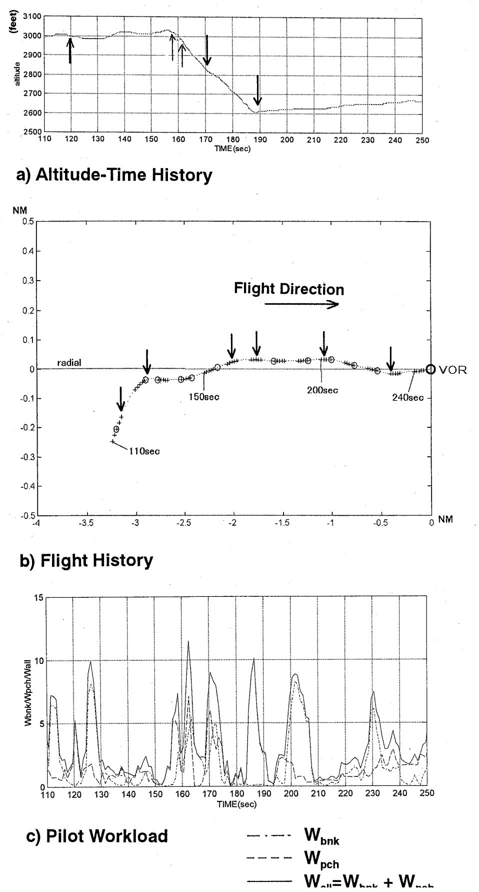

Fig.5 Time Histories of Altitude, Flight Path and Workload (VOR Tracking Flight, Pilot A)

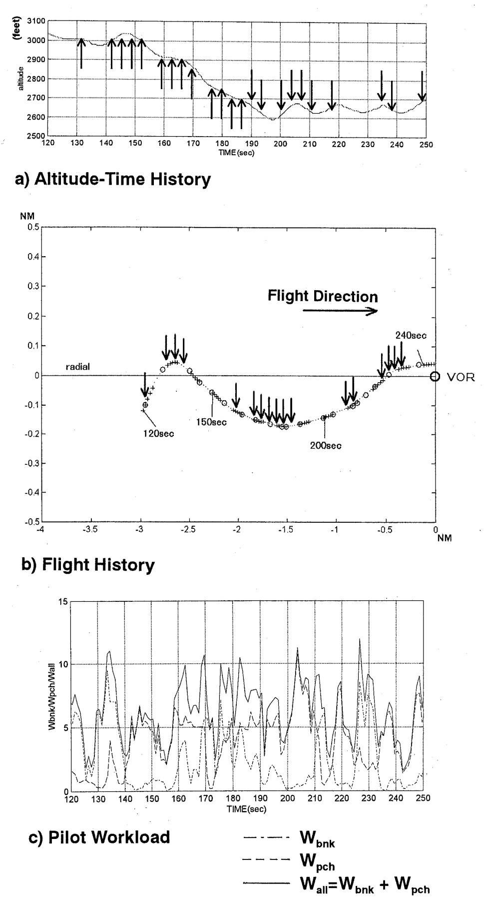

Fig.6 Time Histories of Altitude, Flight Path and Workload (VOR Tracking Flight, Pilot B)

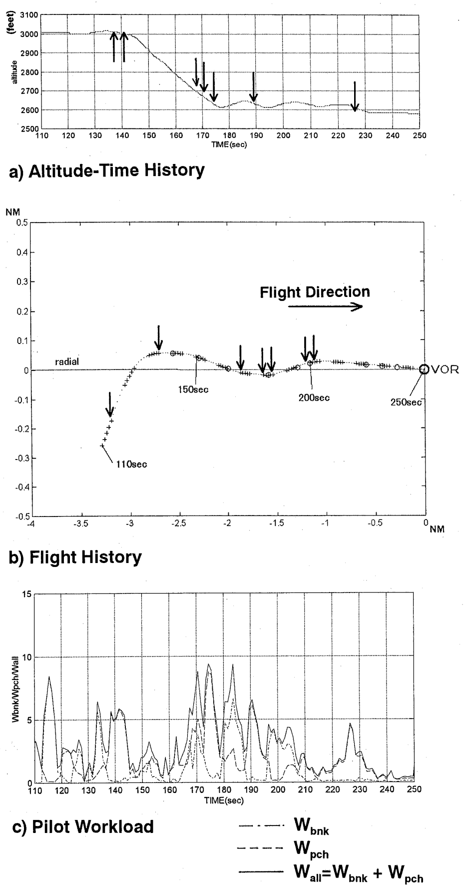

Fig.7 Time Histories of Altitude, Flight Path and Workload (VOR Tracking Flight, Pilot C)

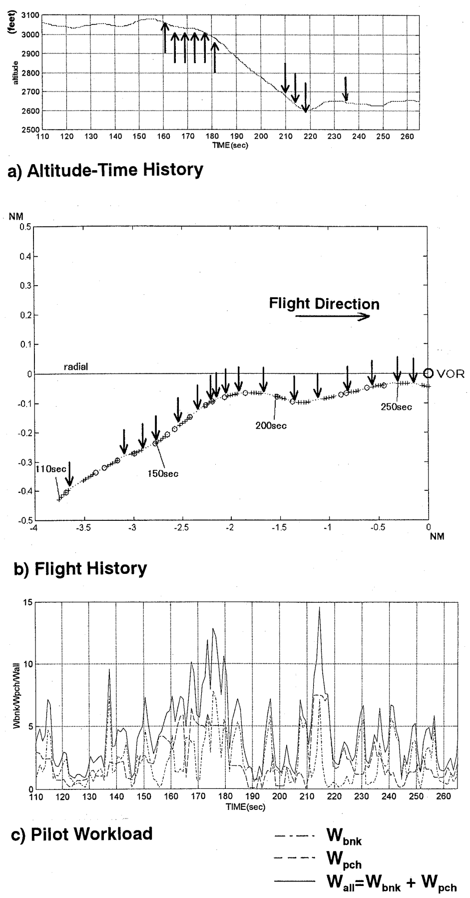

Fig.8 Time Histories of Altitude, Flight Path and Workload (VOR Tracking Flight, Pilot D)

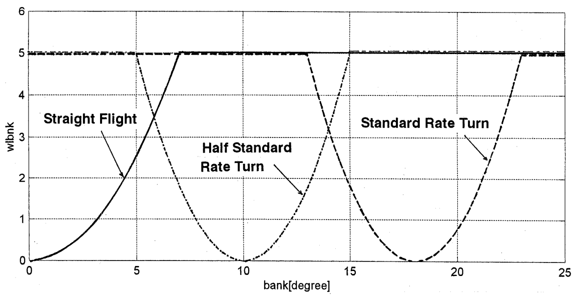

Fig.A1 Workload *wlbnk*

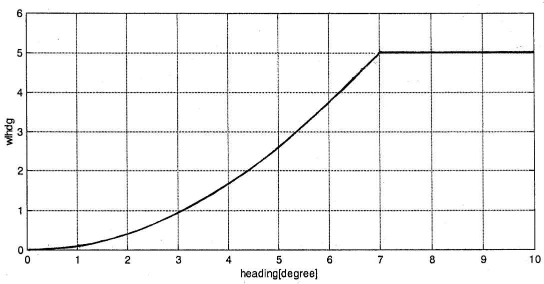

Fig.A2 Workload *wlhdg* for Straight Flight