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Effects of Pilot Workload on EEG Activity Recorded During the Performance of In-Flight Maneuvers in a UH-1 Helicopter

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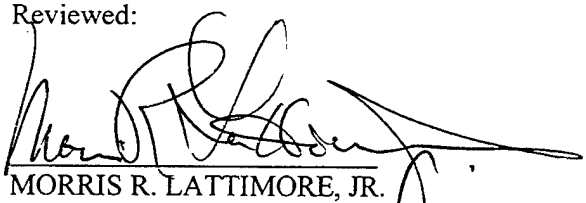

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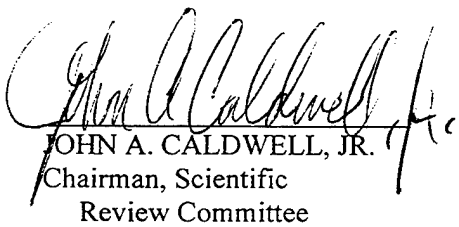

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In the operational environment, measures that can be collected concurrently with an aviator's performance of primary, in-flight duties may offer a way to monitor pilot status in real time so as to predict performance problems prior to their occurrence. Previous research has shown that electroencephalographic (EEG) changes apparently occur as a function of changes in pilot workload; however, these results have not been replicated in the rotary-wing environment. Also, the earlier studies utilized off-line analyses of tape-recorded EEGs rather than real-time telemetry.

The present investigation was designed to: 1) assess the overall quality of EEG recordings collected from helicopter pilots during the actual performance of in-flight maneuvers; 2) determine whether there are workload-induced changes in the EEGs recorded under resting in-flight conditions and "on-the-controls" in-flight conditions; and 3) evaluate whether in-flight EEGs are sufficiently sensitive to detect small changes in the workload levels associated with different types of flight maneuvers. (Continued)

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Twenty subjects (10 aviators and 10 nonaviators) were tested during the performance of standardized flight profiles in a UH-1 helicopter. There was a resting eyes-open EEG condition at the beginning of each flight, and this was followed by 14 maneuver segments during which EEG data were recorded. During the maneuvers, the pilots maintained full control of the aircraft and attempted to maintain ideal flight parameters. The nonaviators sat quietly with their eyes focused on a fixation point.

Results indicated it was feasible to collect valid EEG data on pilots while they were engaged in actually flying a rotary-wing aircraft. In addition, there were indications that occipital EEG theta activity reliably increased from the condition in which pilots were "resting" to those in which the pilots were on the controls. However, it did not appear that the telemetered EEG was sensitive enough to detect the small shifts in cognitive demands induced by standardized flight maneuvers such as climbs, descents, turns, and straight-and-level flight. A follow-on investigation will 1) attempt to replicate the findings that occipital theta is an indicator of large changes in cognitive workload, and 2) establish whether or not the EEG is more sensitive to differences in workload across flight maneuvers in sleep-deprived as opposed to well-rested aviators.

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Background

Military relevance

The development and validation of objective measures of aviator workload during the performance of actual flight duties is important for both the research and operational communities. In the research environment, objective workload assessments that are not influenced by practice or "hypothesis guessing" on the part of subjects will facilitate studies designed to assess the impact of various stressors on aviator status. In the operational environment, measures that can be collected concurrently with the pilot's performance of his/her primary flight duties may offer a way to monitor pilot status in real time so as to predict performance problems prior to their occurrence. Once real-time, in-flight assessments of aviator status are proven to be possible, the development and refinement of computerized safety networks to predict (and thus avoid) pilot degradation and incapacitation will be within the realm of possibility. Such a tool will contribute greatly to the safety and effectiveness of aviation personnel.

Assessment methodologies

As was presented in detail in Caldwell et al. (in press) the status of personnel can be assessed by: 1) examining various mechanisms of human information processing (AGARD, 1989) and assuming that anything affecting these mechanisms will affect the tasks in which they are required; or 2) evaluating job-related performance such as a pilot's ability to control an aircraft (Dellinger, Taylor, and Richardson, 1986; Simmons et al., 1989; Lees and Ellingstad, 1990; and Caldwell et al., 1991) and assuming that "good" and "bad" performance can be quantified to the extent that a computerized algorithm could decide when a pilot has become unsafe.

Unfortunately, for real-world monitoring of individual status, the first approach requires that testing only be performed before or after the task of interest since the administration of tests invariably interrupt primary task performance (i.e., flying the aircraft), and the second approach requires that every potential performance fluctuation be specified to the extent that an automated system could make a valid decision about an aviator's fitness for duty without any knowledge of individual status (other than his/her ability to perform). Thus, the first strategy would be of little use in situations where a pilot's status degrades during lengthy flights because assessments conducted before and after the flights would not provide timely information. The second strategy (which is very timely) would not be feasible in situations where rapid aircraft control changes are part of successful flight performance because, in the absence of information about individual subject status, it would not be possible for an automated scoring routine to know whether or not these unusual control changes were indicative of an impaired pilot. Thus, in order for such assessment schemes to work as intended, there must be a concurrent assessment of the individual aviator's status. Caldwell et al. (1993) has suggested that this possibly can be accomplished using psychophysiological techniques.

It is necessary to identify a method for assessing the operational status of individual aviators which overcomes the problems that exist with standard performance testing algorithms. Specifically, there is need for an approach which: 1) can be conducted during the accomplishment of the operational task (flight); 2) is feasible from an equipment and personnel perspective; and 3) is objective, reliable, and valid. One type of measure which appears to be a reasonable candidate for an assessment technique which would satisfy all three of these basic concerns is one that directly measures aviator status via assessments of psychophysiological variables.

Of the physiological measures available for use, the electroencephalogram (EEG) appears to be the most direct measure of central nervous system functioning. EEGs have been collected during both simulator and actual flights in the fixed wing environment, and attempts have been made to directly relate EEG activity to performance accuracy on operational tasks. Sem-Jacobsen et al. (1959) reported the feasibility of obtaining 8-channel EEG recordings from both pilots and nonpilots in a T-33 jet during operational flight. Later, Sem-Jacobsen (1961) reported success utilizing in-flight EEG analysis in combination with in-flight motion pictures to aid in the selection of pilots for high-performance aircraft. Other authors (LaFontaine and Medvedeff 1966; Maulsby, 1966; Howitt et al., 1978; and Wilson et al., 1987) have offered further evidence for the utility of using EEG as a measure during flights. Sterman et al. (1987) recorded several channels of EEG from pilots flying fixed wing aircraft and simulators, and the data were analyzed offline following flights. The results suggested that EEG activity distribution may be associated with pilot performance. Specifically, these authors found asymmetries between the centrally-recorded alpha EEG activity from the left and right hemispheres of pilots engaged in competent performance (the activity in the left hemisphere was greater than the activity in the right). In addition, Sterman et al. (1987) reported bilateral increases in theta activity (4-7 Hz) and decreases in alpha activity (8-11 Hz) recorded from the sensorimotor and visual cortex in response to increasing cockpit workloads (with some associated G-force effects). Wilson et al. (1994) partially confirmed these workload effects in a study which showed that parietal theta activity increased as a function of cognitive demand when pilots were flying several maneuvers in a fixed wing aircraft. Offline analysis of EEG data showed increases in theta across maneuvers that were subjectively judged to require the most mental effort of the maneuvers flown.

Generally, it appears feasible to evaluate the spontaneous cortical activity from fixed wing pilots and to obtain useful information about workload (and possibly pilot status) from these evaluations. Unfortunately, however, the majority of studies to date have been performed in the fixed wing rather than the rotary-wing environment. In addition, most of these studies have relied upon tape-recorded EEG records that are limited to off-line, after-the-fact analyses rather than real time assessments that can be conducted during the flights of interest.

Recently conducted investigations (Caldwell et al., 1994; and Caldwell et al., in press) suggest it is feasible to collect and telemeter 21 channels of spontaneous EEG from helicopter pilots in flight, despite the significant noise and vibration present in rotary-wing aircraft. However, these studies examined only the in-flight EEG recordings made during resting conditions (with a safety pilot "on the controls"). There was no attempt to assess the feasibility of collecting and

monitoring EEG activity during the conduct of actual in-flight maneuvers in which the subject was flying the helicopter. Thus, it was not possible to determine whether or not telemetered EEGs could provide an indication of pilot workload.

Objectives

The present investigation is designed to: 1) assess the overall quality of EEG recordings collected from helicopter pilots during the actual performance of in-flight maneuvers; 2) determine whether there are workload-induced changes in the EEGs recorded under resting in-flight conditions and "on-the-controls" in-flight conditions; and 3) evaluate whether in-flight EEGs are sufficiently sensitive to detect small changes in the workload levels associated with different types of flight maneuvers.

Methods

Subjects

Twenty subjects were recruited for this study. Ten were UH-1 qualified aviators, and 10 were nonaviators. The average age of the aviators was 31.0 years (ranging from 25-47), and the average age of the nonaviators was 28.5 years (ranging from 23-36). Three of the 20 subjects were females. During testing, the aviators were seated in the front right seat of the aircraft in close proximity to flight instruments. They were tested under resting conditions and during times at which they were actively involved in certain flight tasks. Nonaviators were seated in the back of the aircraft, away from several potential sources of electronic interference, and they remained passive throughout the entire flight.

Apparatus

Airborne and ground-based Spectrum 32

In-flight electroencephalographic evaluations were conducted with a Cadwell Airborne Spectrum 32 in which the high filter was set at 100 Hz and the low filter was set at 0.53 Hz. The 75-pound unit, which is equipped with microprocessors for data acquisition, data transmission, and process supervision, is shock-mounted in an aluminum cage and mounted to the cabin floor in a UH-1 helicopter (see figure 1). The Airborne unit is equipped with the software necessary to acquire EEG data and transmit these data to a ground-based Spectrum 32 equipped with two specialized circuit boards in addition to the typical hardware configuration. One board conditions the incoming and outgoing radio signals and does the serial-to-parallel conversions for both directions. The other board controls the communications processes, buffers outgoing data until ready for transmission, and buffers incoming data until ready for processing. Incoming data are

displayed on the ground-based Spectrum's monitors and stored on an optical storage disk. The ground-based Spectrum 32 is depicted in figure 2.

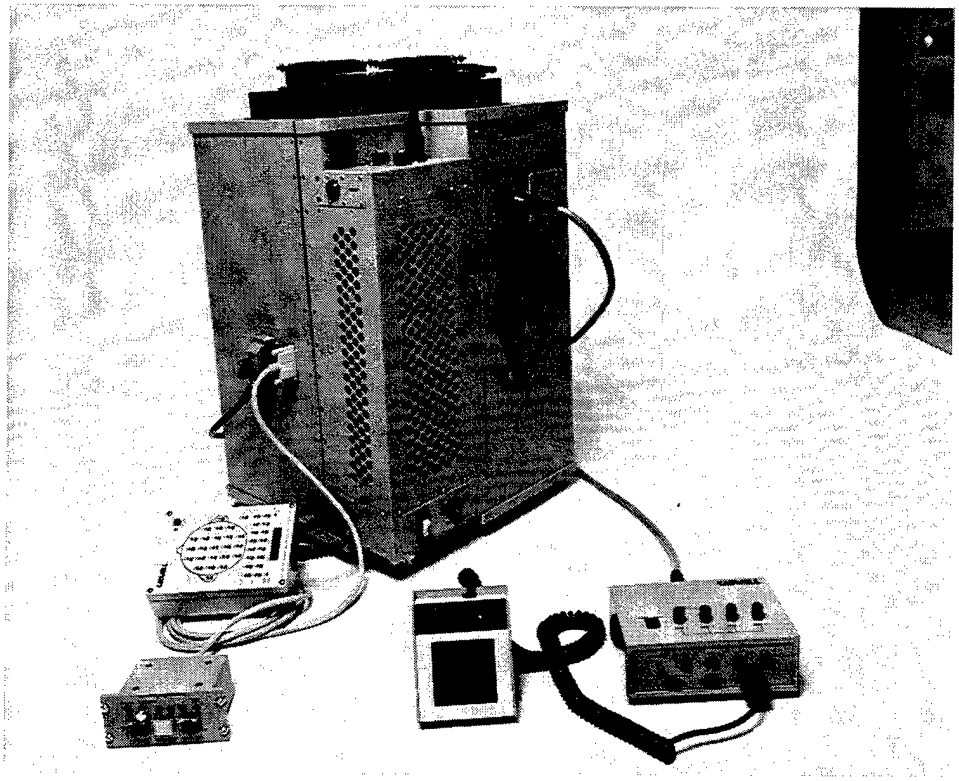

Figure 1. The Airborne Spectrum 32.

The ground-based Spectrum operates similarly to a standard Spectrum 32 although it is equipped with specialized hardware and software to enable radio communications with the Airborne unit. The operator has the same testing features available and can monitor incoming EEG data in near real-time, one "page" at a time, in 8-second blocks. Commands controlling the collection of in-flight data are entered in the usual fashion, and they are transmitted to the Airborne unit via the radio link.

Radio link

The telemetry system uses a two-way microwave radio link to send commands from the ground station up to the aircraft ("uplink") and EEG data signals from the aircraft down to the ground station ("downlink"). Operating at 1740 MHZ, the uplink is composed of a transmitter at the ground station and a matching receiver in the aircraft, and one antenna at each location. The downlink, operating at 1820 MHZ, consists of a transmitter mounted in the aircraft and a matching receiver located at the ground station. It shares the same antennas with the uplink by the use of two diplexers. The ground-based telemetry station is depicted in figure 3.

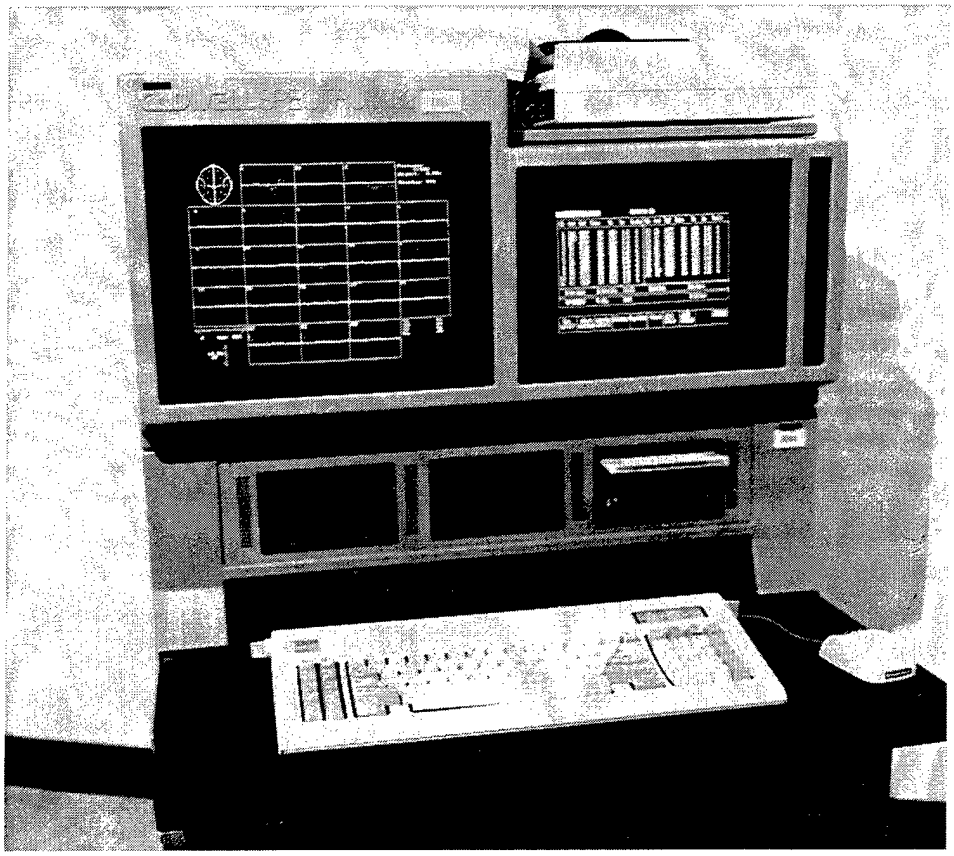

Figure 2. The ground-based Spectrum 32.

Figure 3. The laboratory-based telemetry station with radio transmitter and receiver, antenna tracking controller, oscilloscope, and Cadwell Spectrum 32 equipped with special circuit boards.

The specific components used in the aircraft include a Broadcast Microwave Services (BMS) model TBT-20015SV transmitter mounted in the right aft compartment, and a BMS portable receiver, model TBR-300, located in the left aft compartment. Power for the transmitter and receiver units comes from the aircraft 28-volt DC bus through a 10-amp circuit breaker installed in the overhead control panel. A K&L model 4CZ45-1740/NT1820-N/N diplexer is used to feed the transmitter and receiver cables into a common omnidirectional antenna, a BMS model TBA-2-0, which is mounted to the lower side of the tail boom.

At the ground station, an Anixter Communications Systems model P-1548GN dish antenna is mounted on a Tecom Industries model 203011A Controller and model 203009 rotator system. This azimuth-only system allows the aircraft to be tracked during flight testing. The antenna is connected through a diplexer--as on the aircraft--to the transmitter and receiver. The transmitter and diplexer used at the ground station are identical to those in the aircraft. A Loral Terracom model TCM-601A receiver provides the down-link data signal to the ground-based Spectrum 32.

Recording electrodes

Grass silver cup electrodes, placed on subjects' scalps with collodion, were used to detect EEG signals. These are the standard Grass E5SH electrodes used in typical clinical settings. No modifications to the electrodes or wiring were made (see figure 4).

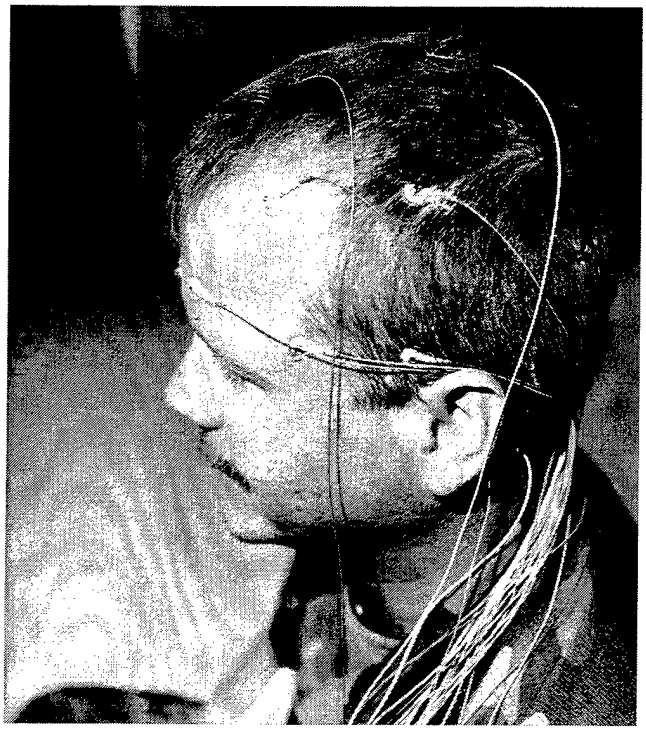

Figure 4. Electrode montage used for the collection of in-flight EEG data.

Procedure

Both pilot and nonpilot subjects were tested during a single, standardized flight in the UH-1 aircraft. Upon arrival at the laboratory, 25 EEG scalp placements were measured, marked, and cleaned with acetone. After each site was thoroughly cleaned, electrodes were attached to the scalp with collodion, and each electrode was filled with electrolyte gel (SignaGel). Impedances were reduced to 5000 ohms or less prior to testing.

In-flight testing for pilots

Pilots were seated in the right front seat of the UH-1 where he/she was connected to the EEG preamplifier. Prior to departing from the helipad, impedances of electrodes and the integrity of the radio link (between ground-based and Airborne Spectrum) were checked, and adjustments were made to maximize the quality of the data.

A USAARL safety pilot conducted each flight in the UH-1, but the test aviator was required to fly the aircraft and complete a profile of upper airwork flight maneuvers lasting approximately 1 hour (see table). The flight profile began at an altitude of 1500 feet mean sea level. The subject flew all of the specified maneuvers under command from the safety pilot. The same sequence of maneuvers was used for every subject.

Table.
Flight profile.

1. Standard rate 360 degree right turn
2. Straight and level number 1 (2 minutes)
3. Standard rate 360 degree left turn
4. Straight and level number 2 (2 minutes)
5. Climb 1000 feet at 500 feet per minute
6. Steep (30 deg. bank) 720 degree left turn
7. Straight and level number 3 (2 minutes)
8. Steep (30 deg. bank) 720 degree right turn
9. Straight and level number 4 (2 minutes)
10. 360 deg. std. rate climbing left turn
11. Straight and level number 5 (2 minutes)
12. 360 deg. std. rate descending right turn
13. Descend 1000 feet at 500 feet per minute
14. Straight and level number 6 (2 minutes)
15. Instrument landing system (ILS) approach

Shortly after takeoff, but prior to the beginning of the standardized flight profile, aviators completed a resting eyes-open EEG (approximately 5 minutes in length) while the safety pilot flew the helicopter. During this phase of the flight, subjects were told to focus on a fixed point in

order to minimize eye movements while data were collected. In the event that the signal was contaminated with artifact, subjects were instructed via radio link from the ground-based receiving station to correct the problem (i.e., minimize eye movements, relax jaw muscles, etc.). Actual data collection continued until approximately 5 minutes of useable data were stored on optical disk for later spectral analysis. Next, the aviator began the series of maneuvers in the standardized flight profile. Once the subject had begun a specific maneuver, the ongoing EEG recording was marked so the data could later be differentiated into different maneuvers. When a subject completed the maneuver, the EEG recording was marked again to indicate the termination of that maneuver. This process was repeated until all maneuvers were performed, with the exception of the last one (the ILS approach). No data were collected during this last maneuver because of the requirement for subjects to actively communicate with air traffic control and the safety pilot at frequent intervals. Upon completing the ILS approach, the subject relinquished control of the aircraft to the safety pilot who then executed a missed approach at Cairns AAF and returned to the helipad at the Laboratory.

In-flight testing for nonpilots

The flight test for nonaviators (conducted separately from the one for the aviators) was similar to the one outlined above. However, the nonaviators were seated in the rear of the aircraft where they completed the resting EEG. In addition, their EEGs were monitored during the execution of the flight maneuvers presented in the flight profile table. Subjects were instructed to keep their eyes open and focused on a fixation point throughout the completion of all flight maneuvers. The USAARL safety pilot and another rated aviator were at the controls during these flights, but no data were collected from either pilot.

Data analysis

Each subject tested in this investigation had his/her EEG recorded during a resting in-flight segment and during the performance of in-flight maneuvers so that potential differences in EEG activity as a function of workload could be explored. Data from both pilots and nonpilots were recorded to provide a control for factors other than pilot workload accounting for differences between pilots' working and resting EEGs. There were a total of 15 segments of EEG data collected from each subject. The first segment was a resting eyes-open EEG, and the remaining 14 segments were eyes-open working EEGs (at least for the pilots). One EEG segment was collected during each maneuver.

Each subject's EEG record was first examined to extract and analyze a minimum of 4 relatively artifact free 2.5-second epochs in the eyes-open resting condition and a minimum of 2 relatively artifact-free epochs in each of the maneuvers (1-14). The EEG epochs from the pilots that were selected for analysis are presented in the appendix. Fast Fourier Transforms (FFTs) were conducted on all 21 active EEG channels for each epoch within each condition, and the results (all sets of FFTs--one per epoch) were averaged for each. This approach yielded

information about the power distribution of EEG activity at each electrode during each condition/maneuver. Once the FFTs were complete, the results were transferred to computer for statistical analyses, and the data collected under the various conditions/maneuvers in the aircraft were compared.

To facilitate the interpretation of potential workload differences, two sets of analyses were conducted on delta, theta, alpha, and beta activity from several electrode locations. The first set of analyses was designed to examine whether there were any differences in the EEG under resting conditions versus "on-the-controls" conditions. In this set of analyses, the EEG collected during the resting eyes-open condition was compared to the EEGs collected during the five types of maneuvers. The first maneuver type included the standard-rate right/left turns; the second type included the straight and level (SL) segments (SL1-SL5); the third included the standard rate climb/descent; the fourth included the steep (30-degree-of-bank) left/right turns; and the fifth included the standard-rate climbing-left/descending-right turns. The second set of analyses was designed to determine whether there were differences in the EEG among the various maneuvers, potentially as a function of workload (the resting EEG condition was excluded). In this analysis, four of the SL segments first were discarded--SL 1 because it was one of the first flight maneuvers, SL 6 because it was the only SL conducted under pure instrument conditions, and SLs 2 and 4 because they were randomly selected for removal. This left two iterations of every type of maneuver: 1) standard-rate level turns, 2) straight and level flight, 3) standard-rate climb/descent, 4) steep turns, and 5) standard-rate climbing/descending turns.

Results

Resting EEG versus "on-the-controls" EEG

A series of 2-way, mixed-factorial analyses of variance (ANOVA) was used to determine whether or not there were differences between resting EEG and "on-the-controls" EEG. The factors were group (pilot versus nonpilot) and condition (resting, maneuver 1, maneuver 2). There were only two maneuvers included in each analysis with the exception of the straight and level where there were six maneuver iterations. Absolute power data from the delta, theta, alpha, and beta bands were examined separately for electrodes C3, C4, Cz, P3, P4, Pz, O1, O2, and Oz.

Standard-rate 360-degree turns

The analysis of the left and right standard-rate turns indicated there were no interactions in the delta band, but there were group main effects at C4 ($F(1,18)=9.35$, $p=.0068$), Cz ($F(1,18)=5.31$, $p=.0334$), P3 ($F(1,18)=4.20$, $p=.0553$), P4 ($F(1,18)=8.54$, $p=.0091$), and Pz ($F(1,18)=11.09$, $p=.0037$). In each case, there was more delta recorded from the pilots than the nonpilots. In the theta band, there were group-by-condition interactions at O2 ($F(2,36)=4.87$, $p=.0134$) and Oz ($F(2,36)=3.58$, $p=.0383$). Both of these were due to increases in theta activity from the condition in which subjects were resting to the ones in which subjects were flying the aircraft ($p<.05$),

whereas there were no differences in the theta recorded during the flight maneuvers. These effects are depicted in figure 5. There tended to be a similar effect at O1, but it did not attain statistical significance (p=.11). In addition, there was more overall theta recorded from the pilots than the nonpilots at C4 (F(1,18)=4.99, p=.0385), P3 (F(1,18)=5.20, p=.0350), P4 (F(1,18)=5.82, p=.0267), Pz (F(1,18)=7.72, p=.0124), O1 (F(1,18)=4.64, p=.0450), O2 (F(1,18)=8.29, p=.0100), and Oz (F(1,18)=6.58, p=.0195). There were no interactions or main effects in the alpha band. In the beta band, there were group main effects at C3 (F(1,18)=5.76, p=.0275), C4 (F(1,18)=8.85, p=.0081), Cz (F(1,18)=6.17, p=.0231), P3 (F(1,18)=7.25, p=.0149), P4 (F(1,18)=9.27, p=.0070), Pz (F(1,18)=10.03, p=.0053), O1 (F(1,18)=5.32, p=.0332), O2 (F(1,18)=8.18, p=.0104), and Oz (F(1,18)=6.23, p=.0225). Each of these was due to greater amounts of beta activity in the pilots as compared to the nonpilots.

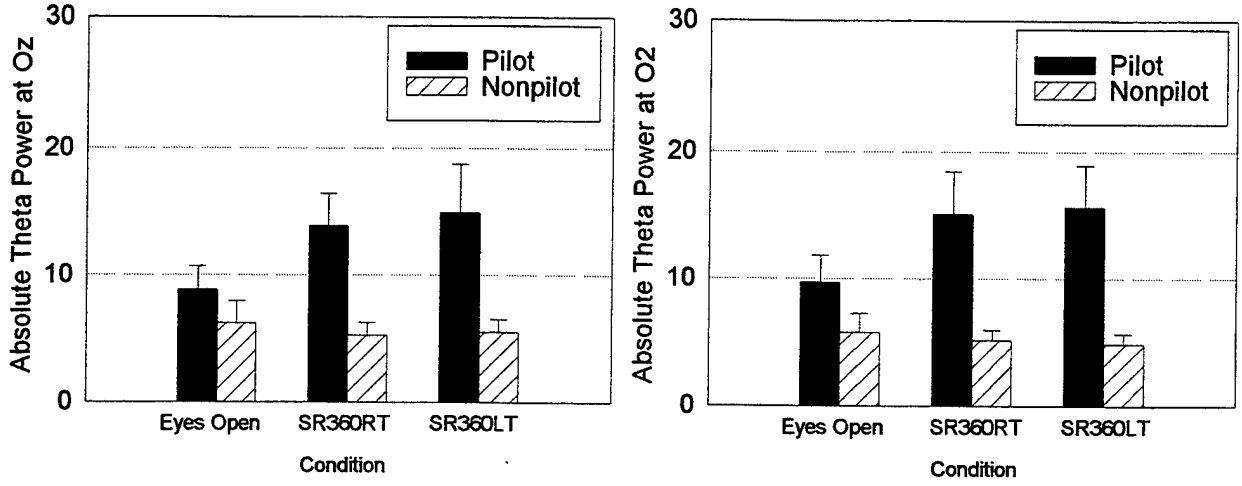

Figure 5. The effects of condition on occipital theta in the pilots versus the nonpilots during the standard-rate turns.

Straight-and-level flight

The 2-way analysis on EEG delta activity during the straight and levels indicated a group-by-condition interaction at P4 (F(6,108)=2.32, p=.0384), and group main effects at C3 (F(1,18)=4.86, p=.0407), C4 (F(1,18)=18.52, p=.0004), Cz (F(1,18)=6.31, p=.0217), P4 (F(1,18)=15.80, p=.0009), Pz (F(1,18)=12.83, p=.0021), and O2 (F(1,18)=4.72, p=.0435). There were no main effects on the condition factor. Analysis of simple effects for the interaction at P4 indicated there were no overall differences among the straight and levels within either the pilot group or the nonpilot group. However, there was a general trend in the nonpilots for delta activity to decrease from the condition in which both groups were resting to the ones in which the pilots were on the controls, whereas in the pilots, delta activity tended to increase (see figure 6). In fact, analysis of simple effects showed that the delta activity of pilots was significantly higher than that of nonpilots at SLs 1, 2, 3, and 6. The overall group main effect was because of higher

levels of delta in the pilots than in the nonpilots. The analysis of theta activity revealed no interactions between group and condition, but there was an overall difference in theta across the conditions at Cz ($F(6,108)=2.74$, $p=.0160$) and O1 ($F(6,108)=2.89$, $p=.0120$). Contrasts for the Cz data indicated that theta activity declined from both the resting condition and SL1 to SL3, and then declined further from SL3 to SL4. Contrasts for O1 showed that theta increased from the resting condition to SL4. Also, theta was greater at SL3 than at either resting, SL4, SL5, or SL6; and theta was greater at SL4 than at SL5 ($p<.05$). There also were overall differences in theta activity between the pilots and nonpilots at C4 ($F(1,18)=4.39$, $p=.0505$), P4 ($F(1,18)=6.05$, $p=.0242$), Pz ($F(1,18)=5.16$, $p=.0356$), O1 ($F(1,18)=5.31$, $p=.0334$), O2 ($F(1,18)=9.50$, $p=.0064$), and Oz ($F(1,18)=6.84$, $p=.0175$). All were due to the fact there was more theta recorded from the pilots than the nonpilots. The analysis of alpha activity revealed no 2-way interaction, but there was more overall alpha in the pilots than in the nonpilots at C4 ($F(1,18)=5.42$, $p=.0318$) and Cz ($F(1,18)=6.16$, $p=.0231$). Also, there was a main effect on the condition factor at O1 ($F(6,108)=2.19$, $p=.0495$) which was due to more alpha at SL3 than at the resting condition, SL4, or SL6; and less alpha at SL6 than at SL4 or SL5 ($p<.05$). In the beta band, there were main effects on the grouping factor at C3 ($F(1,18)=14.67$, $p=.0012$), C4 ($F(1,18)=17.38$, $p=.0006$), Cz ($F(1,18)=19.57$, $p=.0003$), P3 ($F(1,18)=18.43$, $p=.0004$), P4 ($F(1,18)=20.32$, $p=.0003$), Pz ($F(1,18)=21.64$, $p=.0002$), O1 ($F(1,18)=23.73$, $p=.0001$), O2 ($F(1,18)=32.19$, $p<.0001$), and Oz ($F(1,18)=24.32$, $p=.0001$), all of which were due to the presence of more beta in the pilots than in the nonpilots.

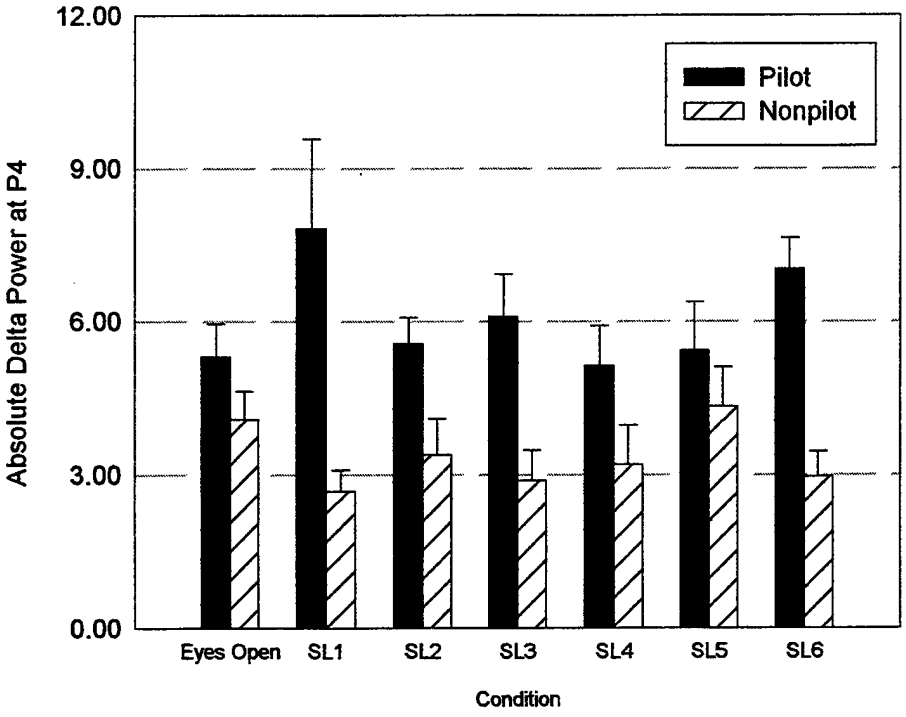

Figure 6. The effects of condition on parietal delta activity in the pilots and nonpilots during the straight and levels.

Straight climbs and descents

The 2-way ANOVA on EEG data recorded during resting conditions and the climb and descent indicated several effects. In the delta band, there were main effects on the condition factor at C3 ($F(2,36)=5.43$, $p=.0087$), C4 ($F(2,36)=5.30$, $p=.0096$), and Cz ($F(2,36)=12.30$, $p=.0001$). In each case, these effects were due to a reduction in delta activity from the condition in which all subjects were resting to the condition in which the pilots were flying the maneuvers ($p<.05$). There also were main effects on the grouping factor at C3 ($F(1,18)=4.62$, $p=.0454$), C4 ($F(1,18)=10.58$, $p=.0044$), P4 ($F(1,18)=11.31$, $p=.0035$), Pz ($F(1,18)=13.17$, $p=.0019$), O2 ($F(1,18)=12.45$, $p=.0024$), and Oz ($F(1,18)=4.67$, $p=.0444$) which were due to greater delta activity in the pilots than in the nonpilots. In the theta band, there was a group-by-condition effect at Oz ($F(2,36)=3.16$, $p=.0545$) attributable to differences across the three conditions in the pilots ($p<.05$), but not in the nonpilots. Contrasts indicated a substantial increase in theta from the resting condition to the condition in which the pilots were on the controls, whereas there was no difference between the theta recorded during the two maneuvers (see figure 7). There were group main effects in the theta recorded from Pz ($F(1,18)=6.04$, $p=.0468$), O1 ($F(1,18)=6.04$, $p=.0244$), O2 ($F(1,18)=9.55$, $p=.0063$), and Oz ($F(1,18)=8.69$, $p=.0086$), all of which were due to the presence of more theta activity in the pilots than in the nonpilots. There also were condition main effects on the theta recorded from Cz ($F(2,36)=3.34$, $p=.0466$), O1 ($F(2,36)=3.72$, $p=.0340$), and Oz ($F(2,36)=3.18$, $p=.0535$). At Cz, the effect was due to the fact that theta activity was greater during the rest condition than during the climb, but only marginally greater than during the descent. At O1 and Oz, theta was less during resting than during the maneuvers ($p<.05$). It is noteworthy that the effect at O1 tended to be similar to the interaction found at Oz, although the differences between pilots and nonpilots were not significant ($p=.15$). However, for the sake of comparison, the data are presented in figure 8. The analysis of alpha activity during the climb and descent revealed a group-by-condition interaction at Pz ($F(2,36)=3.25$, $p=.0504$) which was due to differences among the conditions within the pilots ($p<.05$), but not within the nonpilots. Analyses of the pilots' data showed that alpha activity tended to increase from the resting condition to the climb (the effect was not significant), and then decreased substantially from the climb to the descent (see figure 9). There was also a condition main effect at Pz ($F(2,36)=3.19$, $p=.0530$), as well as one at P3 ($F(2,36)=3.24$, $p=.0507$) and Oz ($F(2,36)=3.73$, $p=.0338$). Contrasts indicated that at Pz and Oz, alpha activity was greater during the climb than during the descent, and alpha activity tended ($p=.07$) to be greater during the climb than during rest. At P3, the same basic relationship was observed, but the differences between the climb and the other two conditions only approached significance ($p=.07$ in both cases). There were main effects on the grouping factor at C3 ($F(1,18)=4.44$, $p=.0494$), C4 ($F(1,18)=4.77$, $p=.0424$), and Cz ($F(1,18)=7.34$, $p=.0144$) which were due to higher levels of alpha activity in the pilots than in the nonpilots. In the beta band, there were no significant interactions, nor was there a significant main effect on the condition factor. However, there was much more beta activity recorded from the pilots than the nonpilots at C3 ($F(1,18)=6.51$, $p=.0200$), C4 ($F(1,18)=10.04$, $p=.0053$), Cz ($F(1,18)=6.66$, $p=.0189$), P3 ($F(1,18)=8.32$, $p=.0099$), P4 ($F(1,18)=10.16$, $p=.0051$), Pz ($F(1,18)=9.95$, $p=.0055$), O1 ($F(1,18)=5.28$, $p=.0337$), O2 ($F(1,18)=4.90$, $p=.0400$), and Oz ($F(1,18)=4.94$, $p=.0393$).

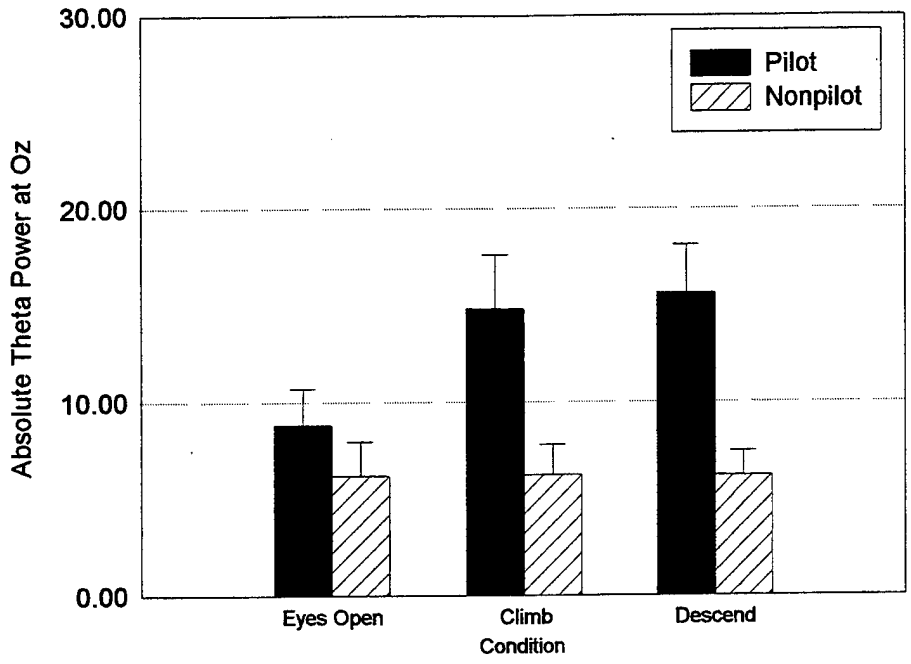

Figure 7. The effects of condition on theta at Oz in the pilots versus the nonpilots during the standard-rate climb and descent.

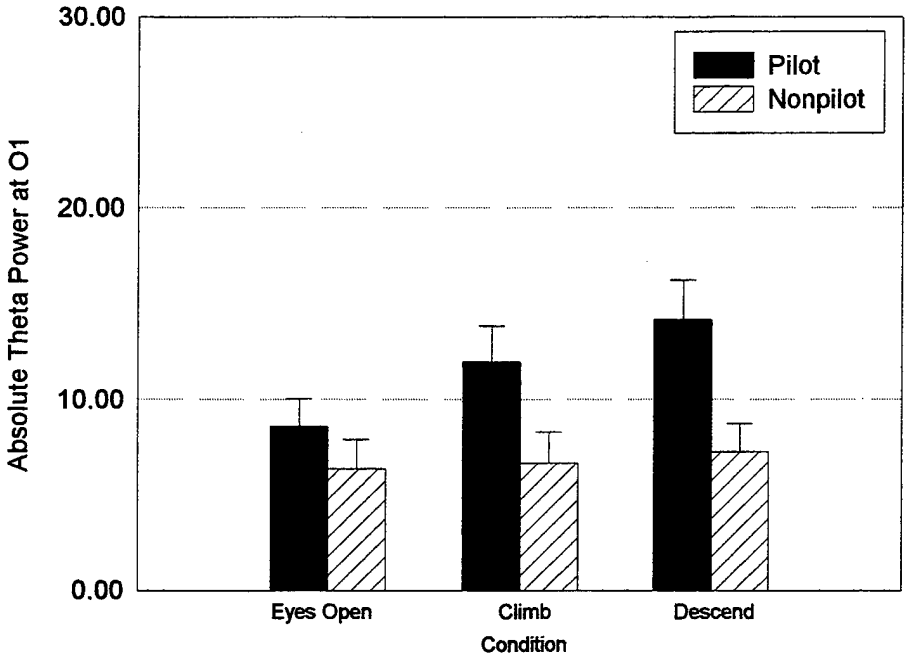

Figure 8. The effects of condition on theta at O1 in the pilots versus the nonpilots during the standard-rate climb and descent.

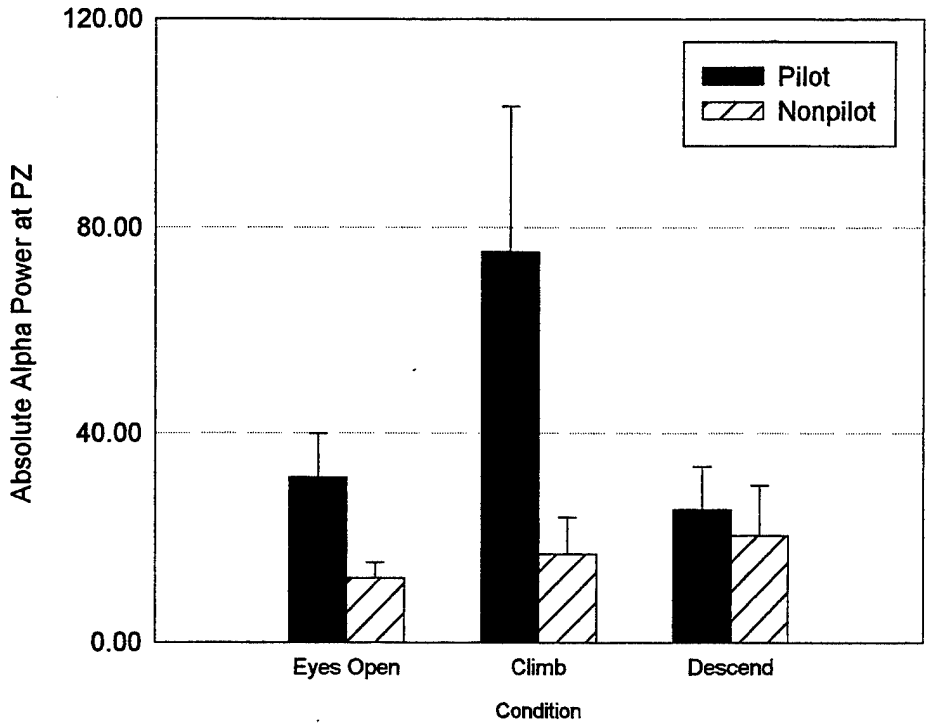

Figure 9. The effects of condition on alpha activity at Pz in the pilots versus the nonpilots during the standard-rate climb and descent.

Steep left and right turns

The analysis of delta activity in the steep turns indicated no significant interactions, but there were main effects on the condition factor at C3 ($F(2,36)=10.68$, $p=.0002$), C4 ($F(2,36)=6.37$, $p=.0043$), and Cz ($F(2,36)=8.21$, $p=.0012$). In every case, there was more overall delta activity during the resting condition than during the maneuvers ($p<.05$) while there were no differences in EEG activity between the two maneuvers. There also were main effects on the grouping factor at C3 ($F(1,18)=6.35$, $p=.0214$), C4 ($F(1,18)=15.91$, $p=.0009$), Cz ($F(1,18)=8.70$, $p=.0086$), P3 ($F(1,18)=4.34$, $p=.0516$), P4 ($F(1,18)=16.44$, $p=.0007$), and Pz ($F(1,18)=11.78$, $p=.0030$). Within the pilots, there was more delta activity than within the nonpilots at every recording location. Theta activity was affected by the combination of group and condition at O2 ($F(2,36)=3.26$, $p=.0502$) and Oz ($F(2,36)=5.48$, $p=.0084$) because, at both sites, there were differences within the pilots but not within the nonpilots. Contrasts on the data recorded from pilots showed there was less theta under the resting condition than during either of the maneuvers (right or left turn). These effects are shown in figure 10. There were overall condition main effects at Cz ($F(2,36)=3.58$, $p=.0383$) and Oz ($F(2,36)=4.52$, $p=.0177$). The effect at Cz was due to tendencies ($p<.08$) toward reductions in theta from the resting condition to the maneuvers, whereas the effect at Oz was due to increases in theta from the resting condition to the maneuvers ($p<.05$). There also were overall group effects at P3 ($F(1,18)=5.40$, $p=.0321$), P4 ($F(1,18)=8.05$,

p=.0109), Pz (F(1,18)=8.67, p=.0087), O1 (F(1,18)=6.02, p=.0245), O2 (F(1,18)=9.39, p=.0067), and Oz (F(1,18)=9.99, p=.0054). Generally, more theta activity was recorded from the pilots than the nonpilots. The analysis of alpha activity revealed a condition main effect at O1 (F(2,36)=3.36, p=.0461) which was due to less alpha under the resting condition than during the steep right turn (p<.05), with a similar tendency in the steep left turn (p<.09). Also, there were group main effects at C4 (F(1,18)=4.97, p=.0387), Cz (F(1,18)=5.19, p=.0352), and O1 (F(1,18)=4.58, p=.0463), all of which were due to higher levels of alpha within the pilots than within the nonpilots. In the beta band, there were significant main effects on the grouping factor at C3 (F(1,18)=4.94, p=.0393), C4 (F(1,18)=6.97, p=.0166), Cz (F(1,18)=5.71, p=.0280), P3 (F(1,18)=4.94, p=.0394), P4 (F(1,18)=5.91, p=.0257), Pz (F(1,18)=7.88, p=.0117), O1 (F(1,18)=4.46, p=.0488), O2 (F(1,18)=5.97, p=.0251), and Oz (F(1,18)=5.39, p=.0322) due to greater amounts of beta activity from the pilots than the nonpilots.

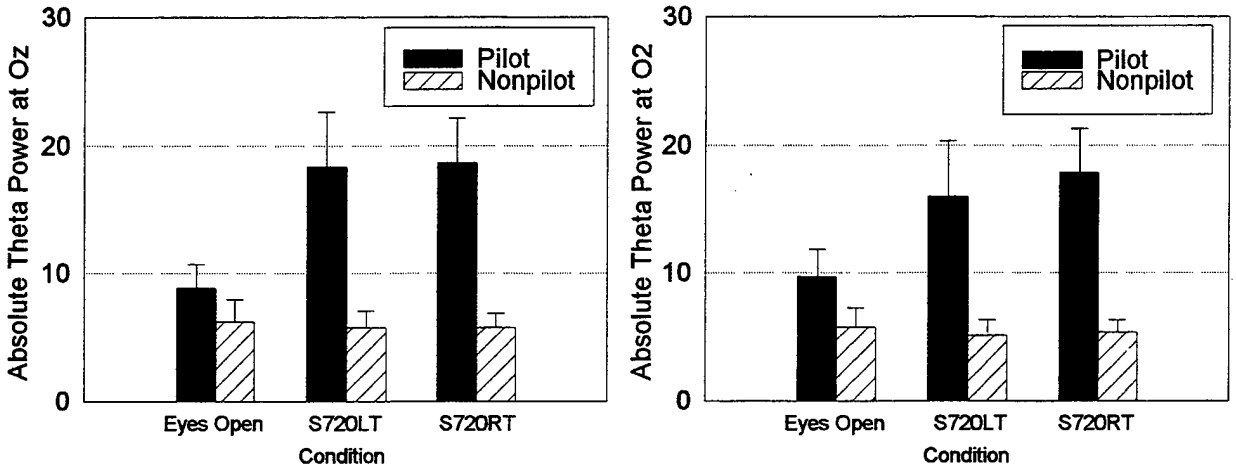

Figure 10. The effects of condition on theta activity at Oz and O2 in the pilots and the nonpilots during the steep turns.

Climbing and descending turns

The analysis of the climbing left turn and the descending right turn indicated a number of effects. In the delta band, there were condition main effects at C3 (F(2,36)=6.86, p=.0030), C4 (F(2,36)=5.85, p=.0063), Cz (F(2,36)=5.57, p=.0078), P3 (F(2,36)=3.60, p=.0377), P4 (F(2,36)=3.97, p=.0276), and Pz (F(2,36)=3.87, p=.0300). In every case, contrasts showed there was more delta activity under the resting condition than during the maneuvers (p<.05; except for the resting-versus-descending turn comparison at P3 and the resting-versus-climbing turn comparison at Pz where p<.07). In addition to these condition main effects, there were group main effects at C3 (F(1,18)=6.30, p=.0219), C4 (F(1,18)=12.82, p=.0021), Cz (F(1,18)=6.85, p=.0174), P3 (F(1,18)=5.06, p=.0372), P4 (F(1,18)=9.99, p=.0054), Pz (F(1,18)=11.97, p=.0028), and O2 (F(1,18)=8.96, p=.0078), all of which were due to more delta within the pilots than within the nonpilots. In the theta band, there were group-by-condition interactions at O2

(F(2,36)=3.15, p=.0551) and Oz (F(2,36)=3.58, p=.0382), both of which were because of differences among conditions within the pilots ($p<.05$), but not the nonpilots. Subsequent contrasts indicated there tended to be less theta under the resting condition than during the maneuvers (the resting-versus-descending turn comparison was significant) (see figure 11). There also were main effects on the grouping factor at P3 (F(1,18)=4.24, p=.0542), P4 (F(1,18)=5.31, p=.0333), Pz (F(1,18)=6.20, p=.0228), O1 (F(1,18)=5.30, p=.0335), O2 (F(1,18)=9.24, p=.0071), and Oz (F(1,18)=7.96, p=.0113). In each case, there was more theta recorded from the pilots than from the nonpilots. In the alpha band, there were group main effects at C3 (F(1,18)=6.15, p=.0233), C4 (F(1,18)=8.31, p=.0099), Cz (F(1,18)=9.93, p=.0055), P4 (F(1,18)=6.65, p=.0189), and Pz (F(1,18)=4.53, p=.0473), due to the fact that more alpha was recorded from the pilots than the nonpilots. In the beta band, pilots produced more beta activity than nonpilots at C3 (F(1,18)=6.29, p=.0219), C4 (F(1,18)=8.33, p=.0098), Cz (F(1,18)=6.22, p=.0226), P3 (F(1,18)=6.57, p=.0196), P4 (F(1,18)=7.36, p=.0143), Pz (F(1,18)=10.40, p=.0047), and O2 (F(1,18)=5.34, p=.0328). There were no other main effects or interactions involving beta activity.

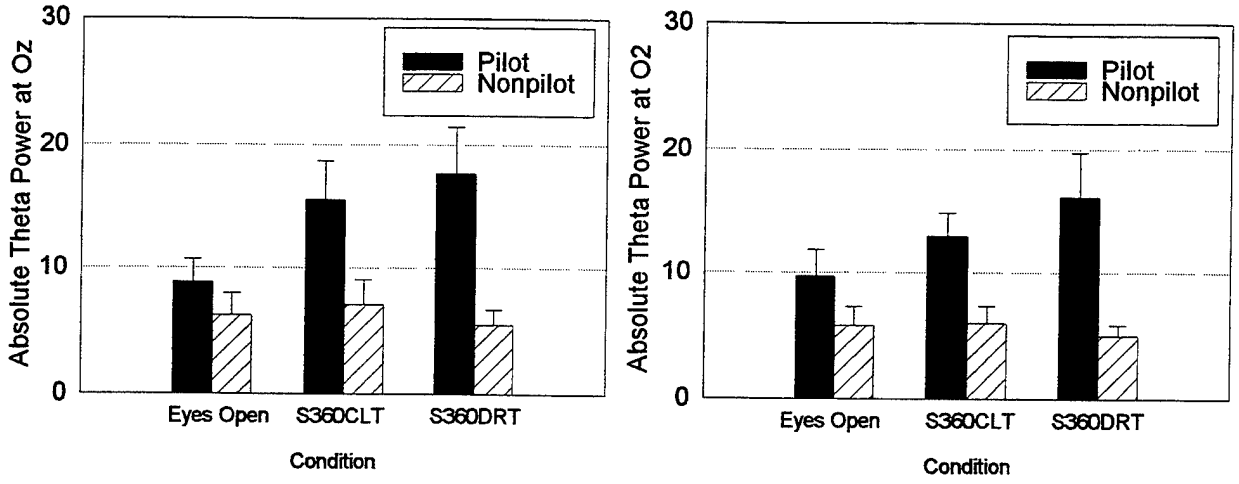

Figure 11. The effects of condition on theta activity at Oz and O2 in the pilots versus the nonpilots during the climbing and descending turns.

EEG effects across the flight maneuvers

The set of ANOVAs conducted to determine whether or not the EEG activity would be sensitive to changes in workload across the flight maneuvers excluded a resting condition. These analyses examined the effects of subject groups (pilots versus nonpilots) across both iterations (one versus two) of the various flight maneuvers (standard-rate turns, straight and levels, straight climb/descent, steep turns, and climbing/descending turn).

Delta activity

Within the delta band, there were interactions between the grouping factor and maneuver iteration (first versus second) at Oz ($F(1,18)=6.87$, $p=.0173$), and marginally at C4 ($F(1,18)=4.15$, $p=.0567$). Simple effects showed that at C4, this was due to an increase in delta activity from the first to the second iteration of maneuvers only within the pilots, and at Oz, this was due to a decrease in delta activity from the first to the second iteration only within the pilots ($p<.05$). In addition to the group-by-iteration interaction, there was a maneuver main effect at Cz ($F(4,72)=2.77$, $p=.0337$) and P4 ($F(4,72)=2.49$, $p=.0510$). Contrasts at Cz showed delta activity was greater during the standard-rate turns than during the straight climb/descent or the steep turn. Contrasts at P4 showed more delta during the standard-rate turns than during straight climb/descent and more delta during the straight and levels than during the steep turns or the climbing/descending turns ($p<.05$). In addition to these effects, there were overall differences between the pilots and nonpilots which were similar to those presented in the previous section. Specifically, there was more delta activity recorded from the pilots at C3 ($F(1,18)=6.34$, $p=.0215$), C4 ($F(1,18)=16.35$, $p=.0008$), Cz ($F(1,18)=6.44$, $p=.0206$), P3 ($F(1,18)=4.26$, $p=.0537$), P4 ($F(1,18)=18.73$, $p=.0004$), Pz ($F(1,18)=16.46$, $p=.0007$), and O2 ($F(1,18)=10.97$, $p=.0039$). There were no interactions between the grouping factor and maneuver which would have indicated differential effects of small changes in workload on delta activity at any electrode. As can be seen in figure 12, the fluctuations in the delta band across the various maneuvers were not systematic.

Theta activity

The 3-way ANOVA on theta activity indicated only a single 2-way interaction which was between maneuver and iteration at O2 ($F(4,72)=2.45$, $p=.0539$). This was attributable to the fact that, for some reason, there was more theta activity during the first than the second iteration of the straight and level ($p<.05$), but no differences in the other maneuvers. Otherwise, there were group main effects at C4 ($F(1,18)=6.36$, $p=.0213$), P3 ($F(1,18)=5.91$, $p=.0257$), P4 ($F(1,18)=11.37$, $p=.0034$), Pz ($F(1,18)=10.30$, $p=.0049$), O1 ($F(1,18)=7.53$, $p=.0134$), O2 ($F(1,18)=11.71$, $p=.0030$), and Oz ($F(1,18)=10.22$, $p=.0050$), all of which were due to the presence of more theta in the pilots than in the nonpilots. As was the case in the delta band, there were no systematic differences in theta activity as a function of whether the pilots were flying one maneuver or another (see figure 13).

Alpha activity

The analysis of alpha activity indicated a group-by-maneuver-iteration interaction at Pz ($F(4,72)=2.86$, $p=.0294$), and a maneuver-by-iteration interaction at C3 ($F(4,72)=2.45$, $p=.0539$) and Pz ($F(4,72)=2.85$, $p=.0300$). The 3-way interaction was because of a maneuver-by-iteration interaction within the pilots ($p<.05$), but not the nonpilots. Further examination of this effect showed that, within the pilots, there was significantly more alpha activity in the first versus the second iteration of the standard-rate turns and the straight climb/descent, but no differences in the

other maneuvers. The 2-way interaction at Pz was because of substantially more alpha at the first versus the second iteration of the straight climb/descent. At C3 there was a similar tendency, but it was not statistically significant. There were no interactions between the grouping factor (pilots versus nonpilots) and maneuver indicative of changes in alpha activity as a function of small changes in workload (see figure 14).

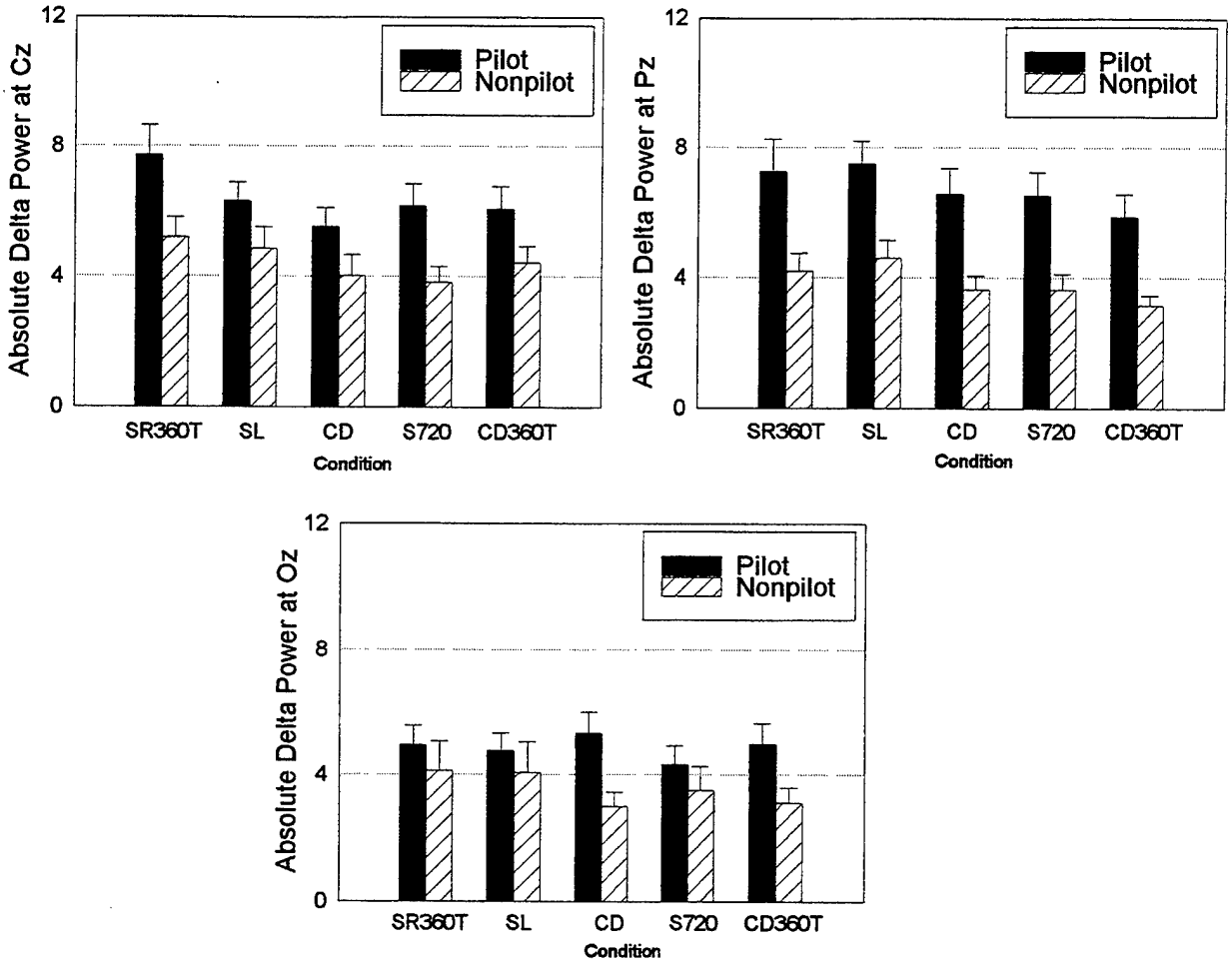

Figure 12. Effects of the different maneuvers on delta activity within the pilots and nonpilots.

Beta activity

The analysis of beta activity revealed an interaction between group and iteration at O2 ($F(1,18)=4.90$, $p=.0400$) which was due to the presence of a decrease in beta activity from the first iteration to the second iteration in the pilots ($p<.05$), but not the nonpilots. Also, there was a consistent overall difference between the first and second iterations at this same electrode ($F(1,18)=5.41$, $p=.0319$). Finally, there were group main effects at C4 ($F(1,18)=4.92$, $p=.0397$), Cz ($F(1,18)=5.20$, $p=.0351$), P3 ($F(1,18)=4.54$, $p=.0472$), P4 ($F(1,18)=5.69$, $p=.0283$), Pz ($F(1,18)=5.20$, $p=.0350$), O2 ($F(1,18)=6.04$, $p=.0244$), and Oz ($F(1,18)=4.80$, $p=.0418$). All

were due to the presence of more beta activity within the pilots than within the nonpilots. There were no group-by-maneuver effects suggestive of differences in beta activity as a function of the different maneuvers flown in the flight profile. As can be seen in figure 15, the differences in the beta band across the maneuvers were essentially random.

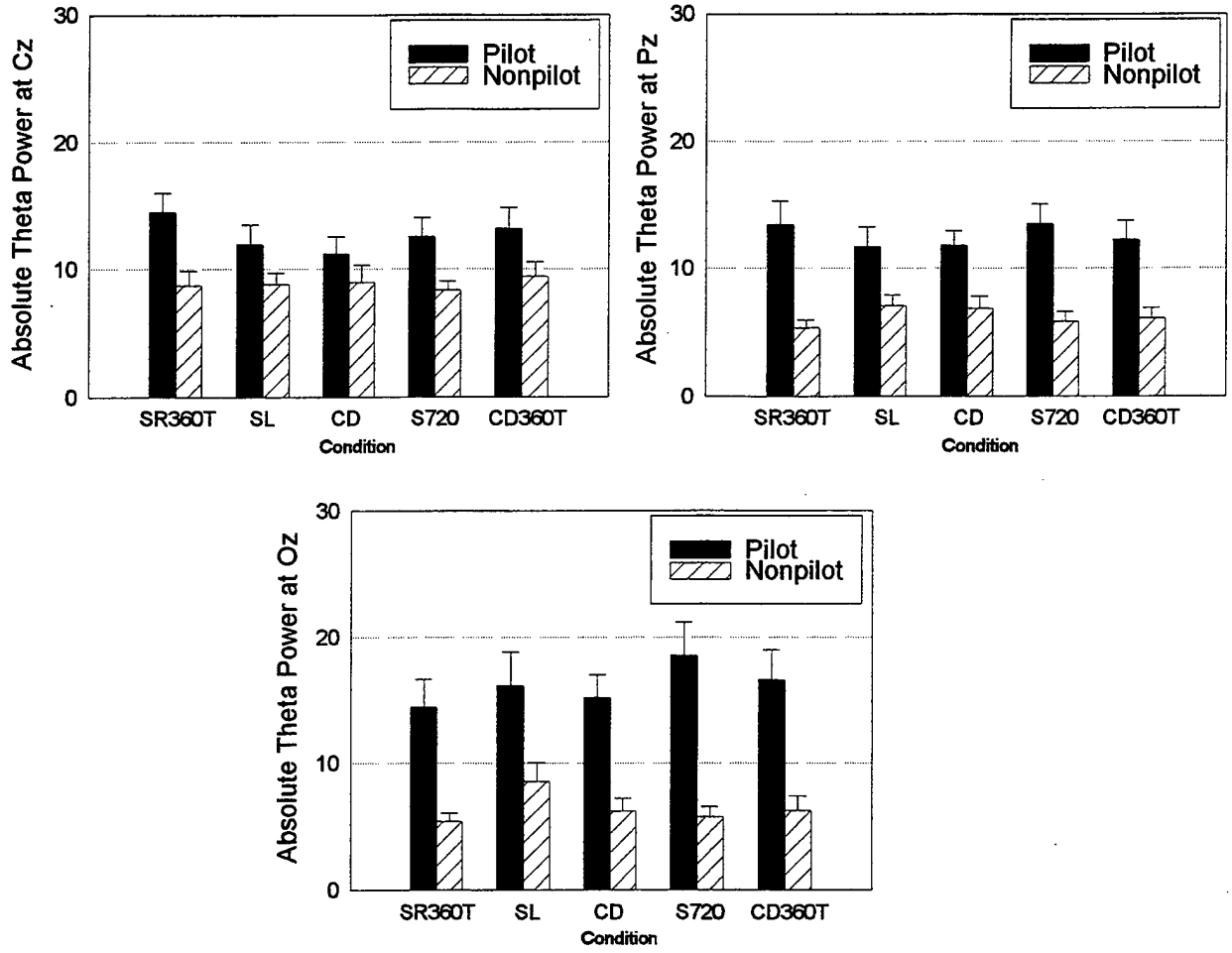

Figure 13. Effects of the different maneuvers on theta activity in the pilots and nonpilots.

Discussion

This study in which 10 pilots and 10 nonpilots telemetered multichannel EEG data from a helicopter during a standard series of flight maneuvers indicated the feasibility of monitoring the brain activity of pilots during the performance of actual flight duties. Furthermore, there were clear indications that telemetered EEG activity was sensitive to work-related changes in cognitive activation (resting versus "on-the-controls" conditions). However, the EEG did not appear sufficiently sensitive to differentiate between the smaller changes in workload (comparing one maneuver to another).

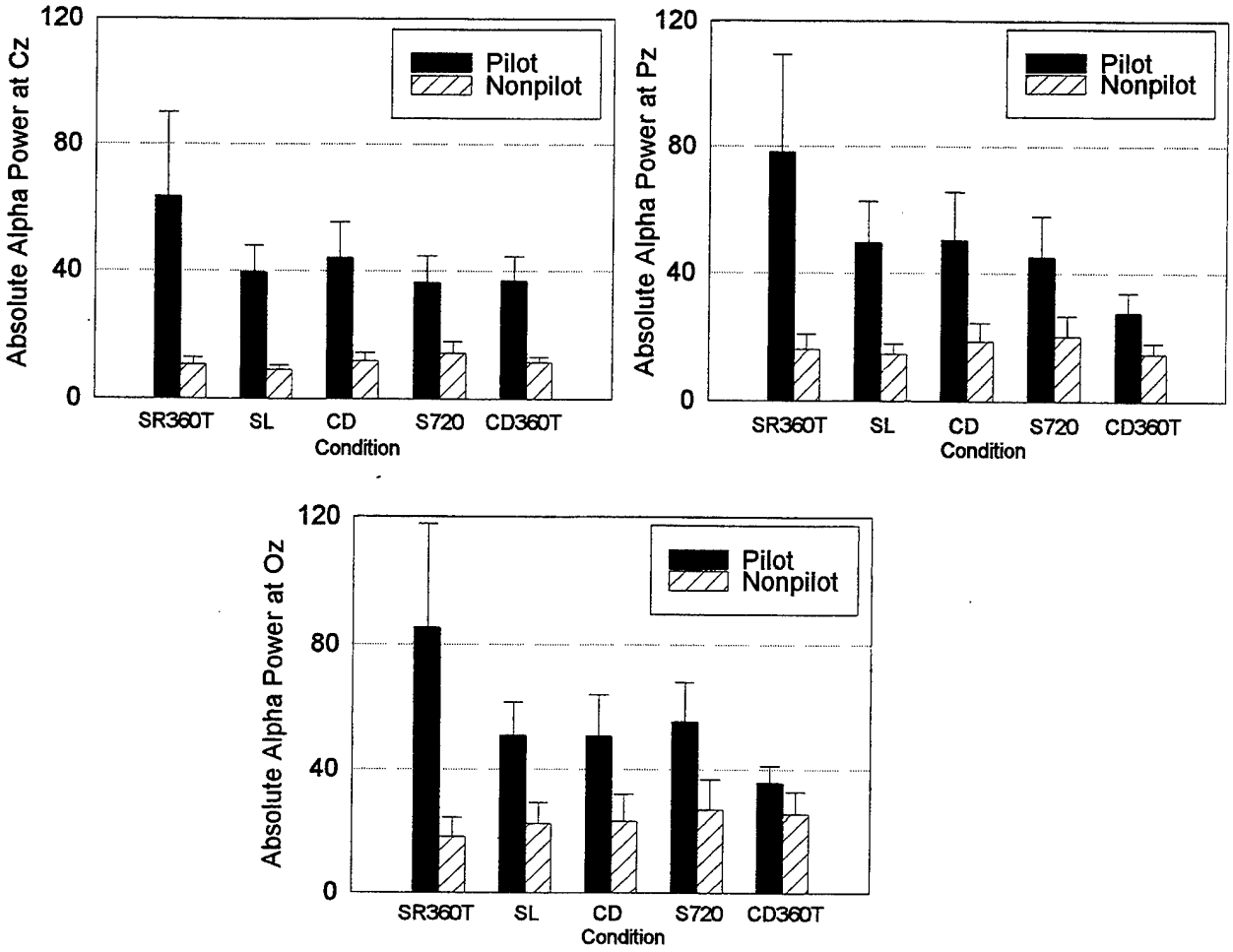

Figure 14. Effects of the different maneuvers on alpha activity within the pilots and nonpilots.

Sensitivity in differentiating resting and "on-the-controls" conditions

Although, as discussed below, occipital theta seemed to be reliably affected by workload-related factors in flight, there were some overall changes apparently unrelated to cognitive demands. There were overall effects across the in-flight conditions (resting versus maneuvering) in both groups of subjects (pilots and nonpilots) with regard to the amount of central and sometimes parietal delta activity, central theta activity, and occipital alpha activity. Central delta was affected in three cases, parietal delta was affected in one case, central theta changed in three cases, and occipital alpha was affected in three cases. These effects, in which delta and central theta decreased and occipital alpha increased from the resting to the maneuvering conditions, apparently resulted from some factor other than workload changes because they were observed in both groups of subjects. Sterman et al. (1987) found that the onset of in-flight G-forces was generally accompanied by increases in slow-wave EEG activity both in pilots and passengers. Thus, perhaps vestibular effects were responsible for the differences in the alpha band; however,

the general impact on delta and theta recorded from the central region of the scalp is opposite of what would have been predicted based on the earlier study. Reasons for such a discrepancy are unclear at this point.

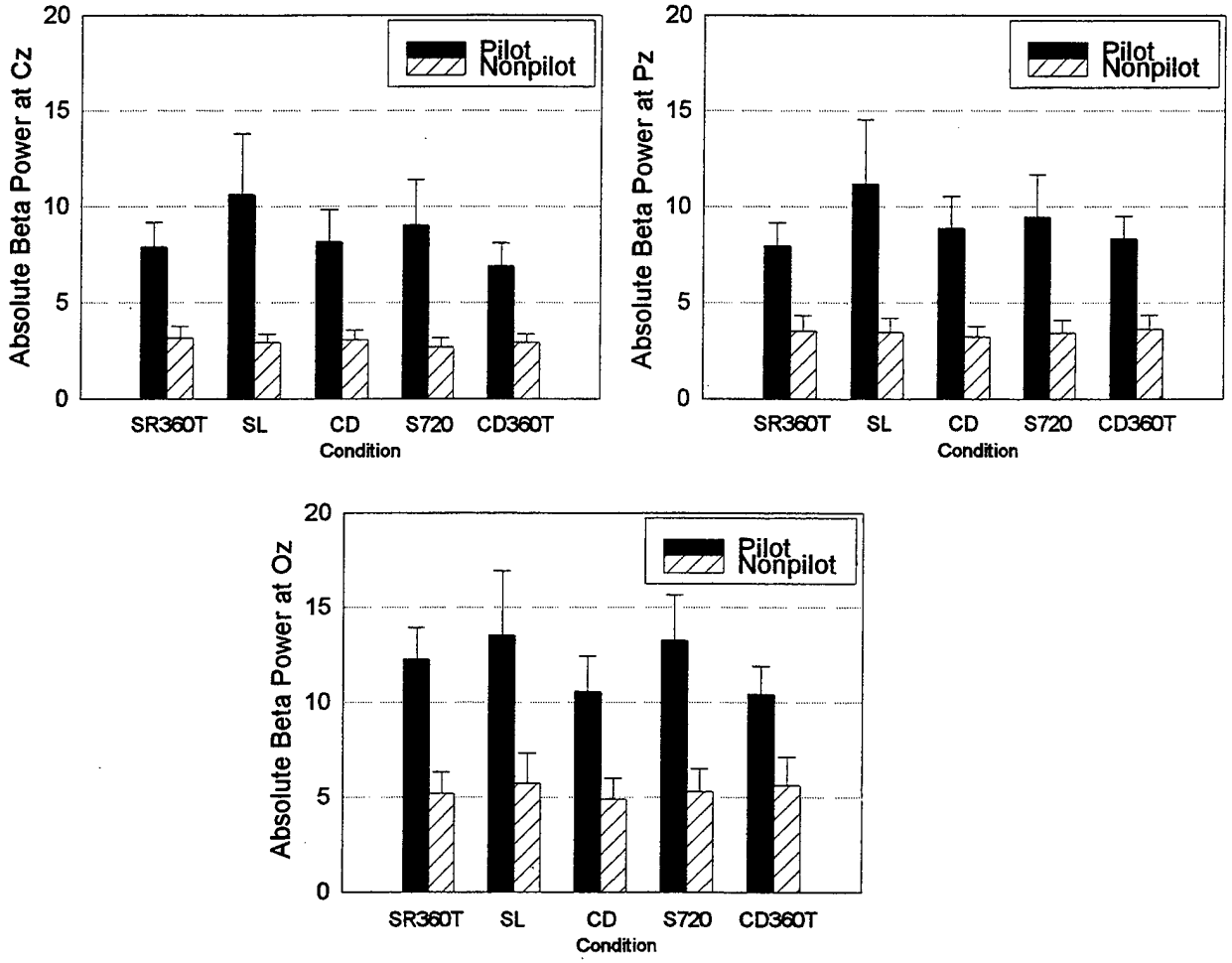

Figure 15. Effects of the different maneuvers on beta activity in the pilots and nonpilots.

In contrast to these overall, non-work-related EEG effects, occipital theta activity in the present investigation did seem to be clearly affected as a function of whether the pilots were resting or "on the controls." This was the case in the standard-rate turns, the straight climb and descent, the steep turns, and the climbing and descending turn, where in each case, one or more of the occipital recording sites (O1, O2, or Oz) evidenced a substantial increase in theta from the condition in which pilots were resting to the ones in which pilots were flying the aircraft. That these changes were not simply a result of vestibular effects, low-level G forces, or other extraneous factors was obvious when the data recorded from the pilots were compared to the data recorded from the nonpilots. In each of the maneuvers mentioned above, there were group-by-condition interactions due to the fact that condition differences were observed only in the

subjects who were actually flying the helicopter. No differences in theta occurred during the transition from resting conditions to maneuvering conditions in the nonpilots.

This finding is partially consistent with the results obtained by Sterman et al. (1987) where theta activity recorded from the visual cortex of fixed wing pilots increased as a function of workload. In addition, these results tend to support those of Wilson (1994) who found that theta activity increased during more demanding in-flight maneuvers (although the observed effects in Wilson's study were seen in the parietal region of the scalp). However, the present research did not confirm the report by Sterman et al. (1987) that similar changes (i.e., increased theta) occurred in the sensorimotor (central) scalp region as well. Instead, the present investigation suggests that the changes in central EEG activity may have simply been a function of some extraneous factor (such as vestibular or G-force effects) since they were observed both in the pilots who were actually flying the aircraft and in the nonpilots who were only passengers.

Sensitivity in differentiating one maneuver from another

Analyses of delta, theta, alpha, and beta activity across the various maneuvers offered no indication that telemetered EEG data were systematically reflective of small changes in workload (as a function of whether the pilots were flying one maneuver versus another). There were several minor effects such as overall differences between the pilots and nonpilots irrespective of task performance, but these were essentially meaningless in the present context. These results were somewhat surprising based on the earlier findings that theta activity was sensitive in discriminating between resting and "on-the-controls" conditions within the pilots. Of course, there is a much larger change in cognitive demand between a resting eyes-open EEG task and flying a helicopter. Perhaps if the differences among the maneuvers had been greater or the subjects had somehow been compromised (by medications, sleep loss, or other factors), significant workload effects may have appeared. However, it is not possible to offer a definitive resolution to this issue based on the data collected in this study.

Conclusions

The present investigation offers clear evidence that it is quite feasible to collect valid EEG data on pilots while they are engaged in actually flying a rotary-wing aircraft. In addition, there are preliminary indications that some types of EEG activity (4-7 Hz occipital waves) can offer information about significant changes in pilot workload. However, it does not appear that telemetered EEG is sensitive to the sorts of small shifts in cognitive demand which are produced by standard higher-altitude flight maneuvers such as routine turns, climbs, descents, and straight-and-level flight (at least in well-rested, fully-functioning subjects).

Unfortunately, despite the fact that 21 channels of EEG data were collected, only those which were over the central, parietal, and occipital regions were useable because the frontal (and some temporal) channels were filled with eye-movement and/or muscle artifact. In fact, the removal of

artifact-contaminated data led to the requirement to estimate approximately 80 percent of absolute power values from the frontal leads (they were excluded from analysis because of this). Due to the fact that flying an aircraft is a visually-dependent task, it is unlikely that these types of artifacts can be avoided by limiting the activities of aviators while they are on the controls. In the future, it may be possible to implement some type of automatic artifact correction system or filtering mechanism to remove enough artifact to make the frontal channels more useable. At present, however, only the EEG channels which are further away from the influence of eye movements should be analyzed.

A follow-on investigation should be conducted in order to: 1) verify the findings that theta recorded from the visual cortex can reliably discriminate between resting and "on-the-controls" conditions in rotary-wing pilots; and 2) establish whether the EEG might be more sensitive to small workload-induced changes in cognitive demand when compromised (i.e., sleep-deprived) pilots serve as subjects.

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Appendix.

Examples of EEG data collected from each subject.

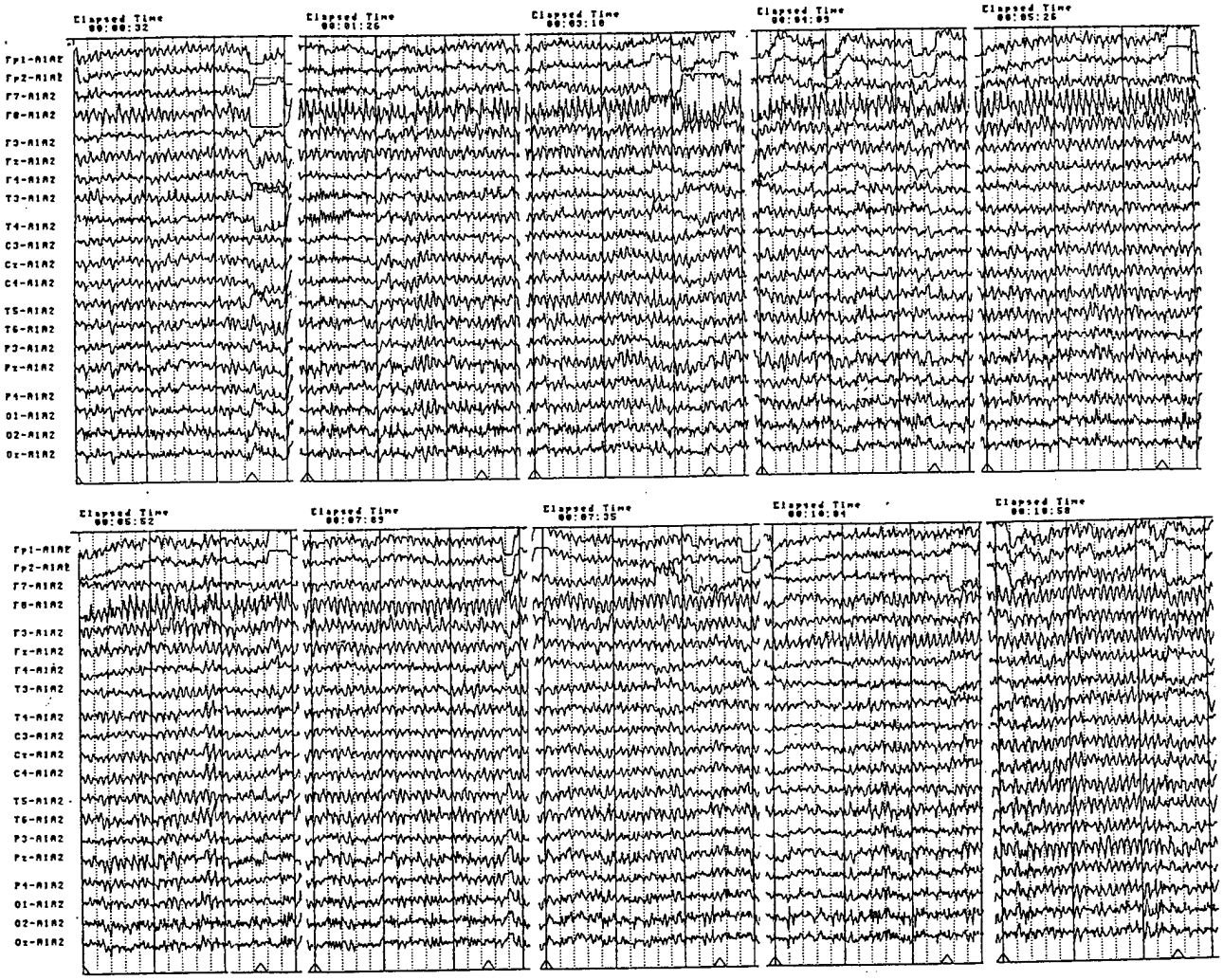

Figure 1. The EEG epochs selected for analysis from flight maneuvers 1-5 for subject 1.

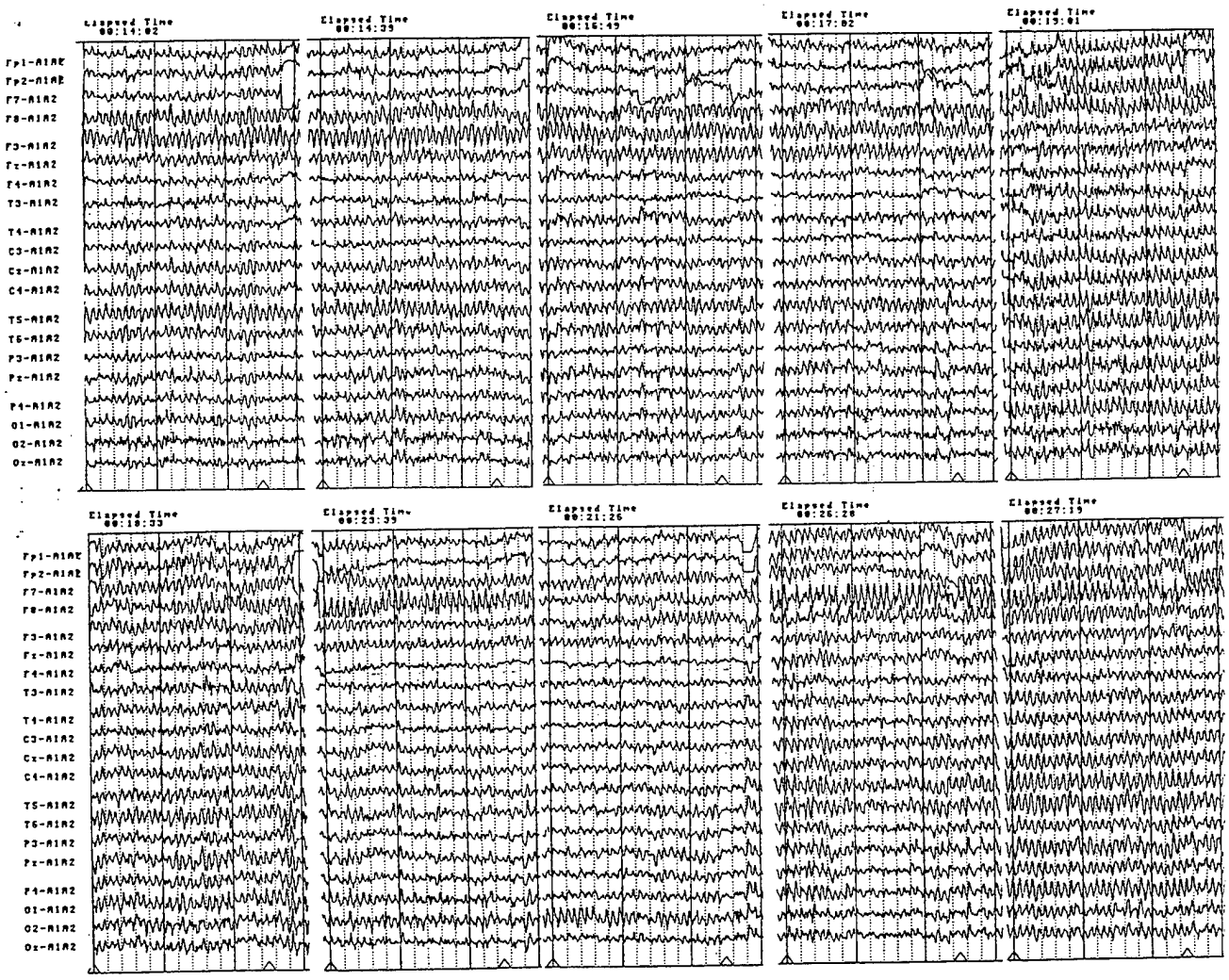

Figure 2. The EEG epochs selected for analysis from flight maneuvers 6-10 for subject 1.

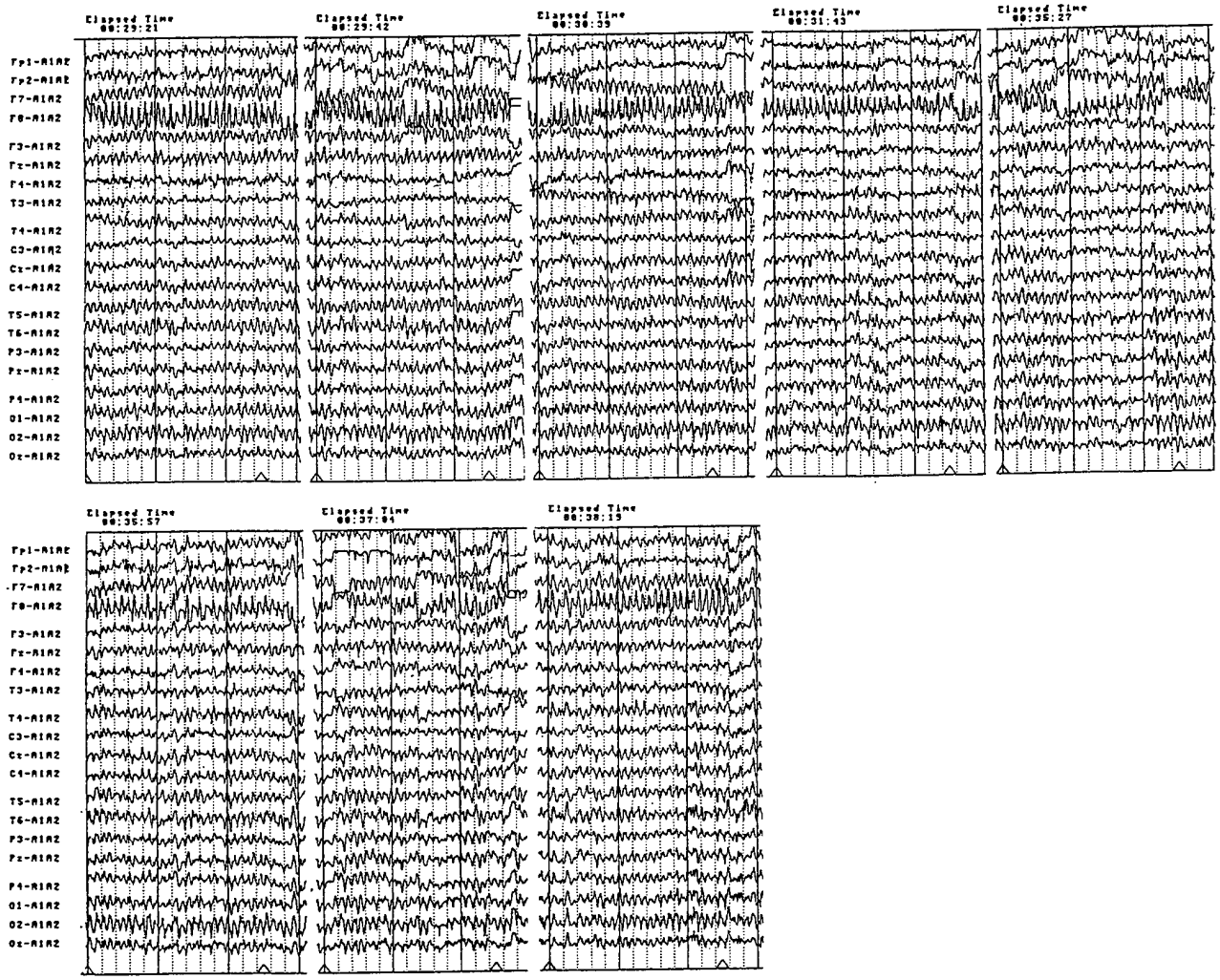

Figure 3. The EEG epochs selected for analysis from flight maneuvers 11-14 for subject 1.

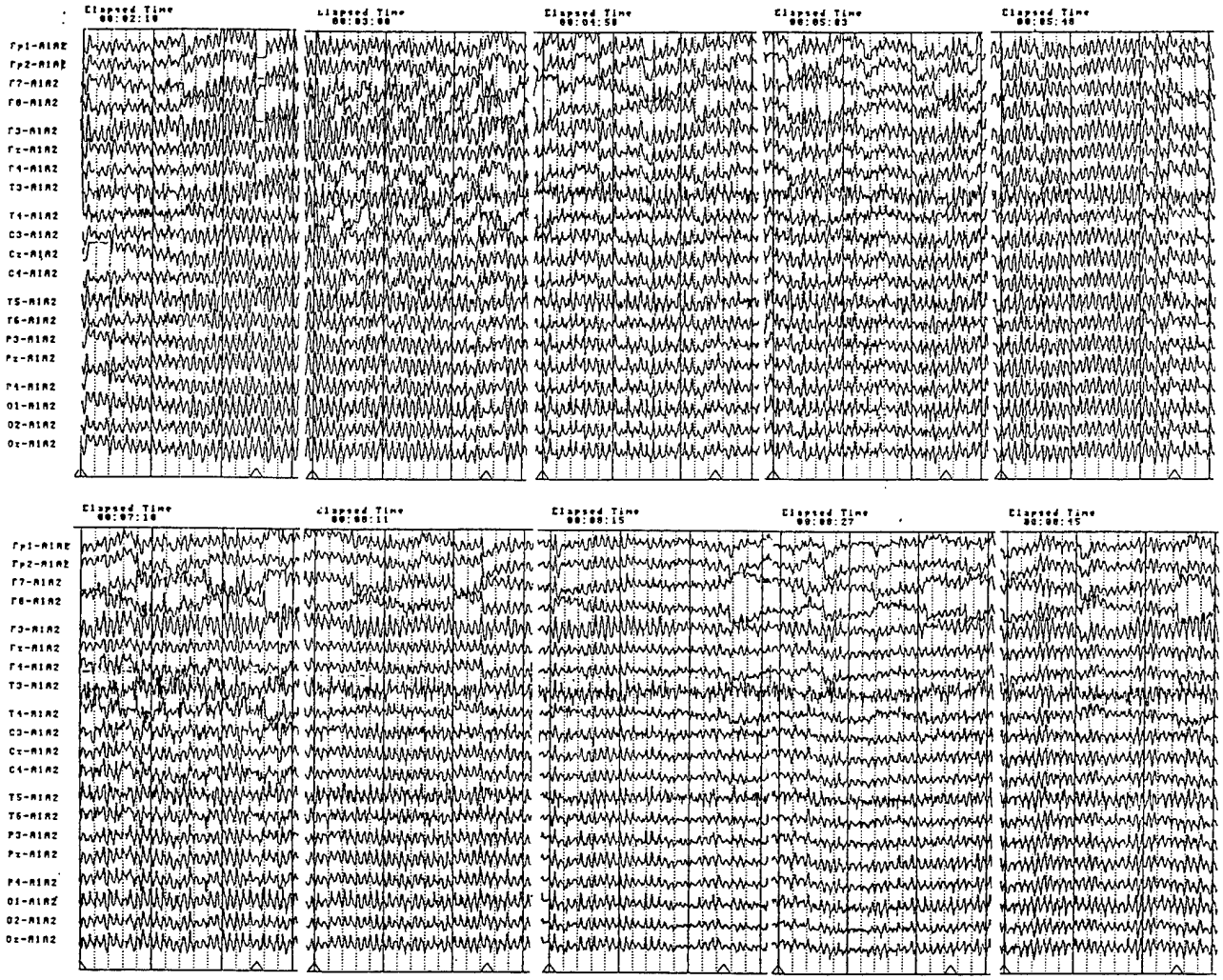

Figure 4. The EEG epochs selected for analysis from flight maneuvers 1-5 for subject 2.

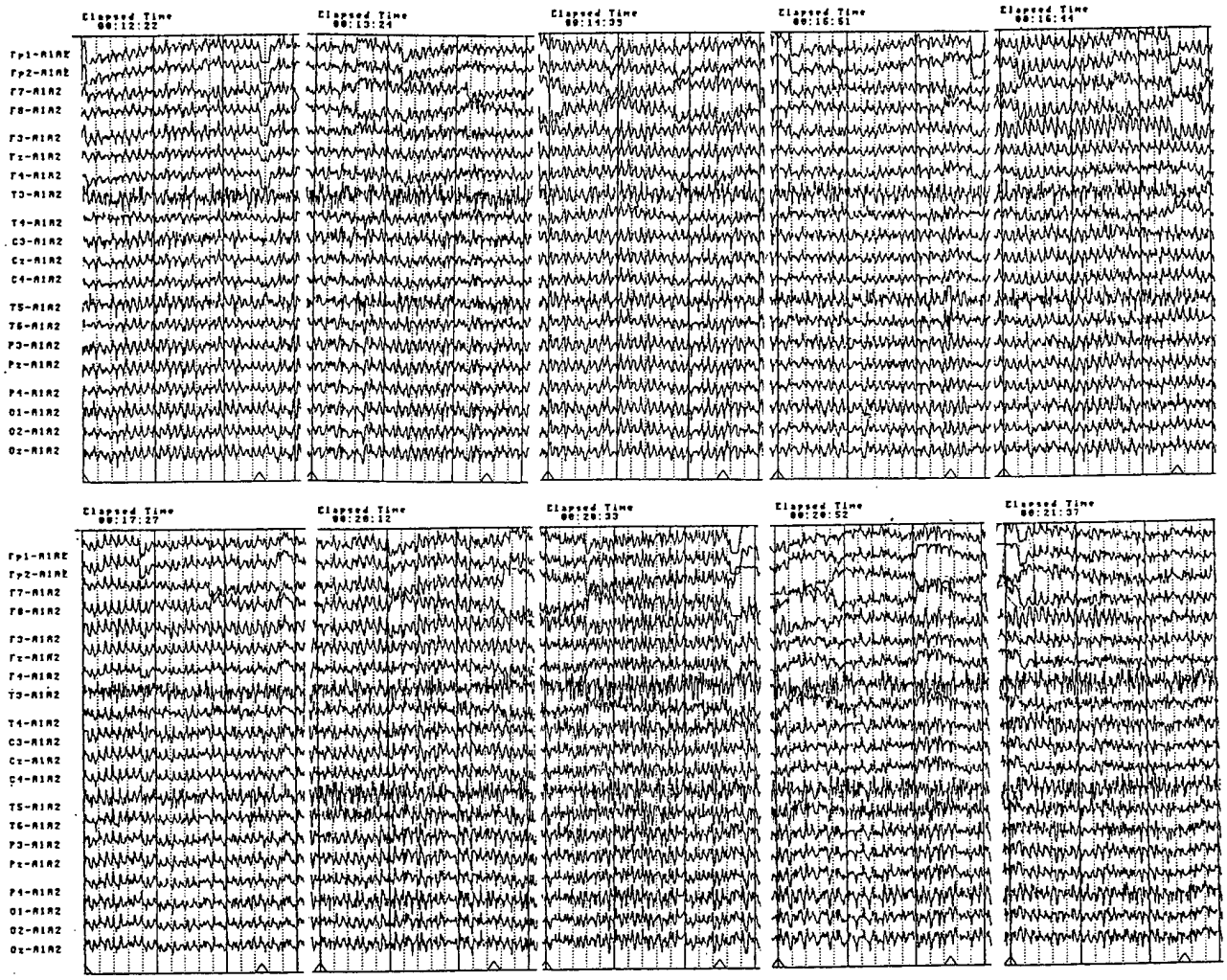

Figure 5. The EEG epochs selected for analysis from flight maneuvers 6-10 for subject 2.

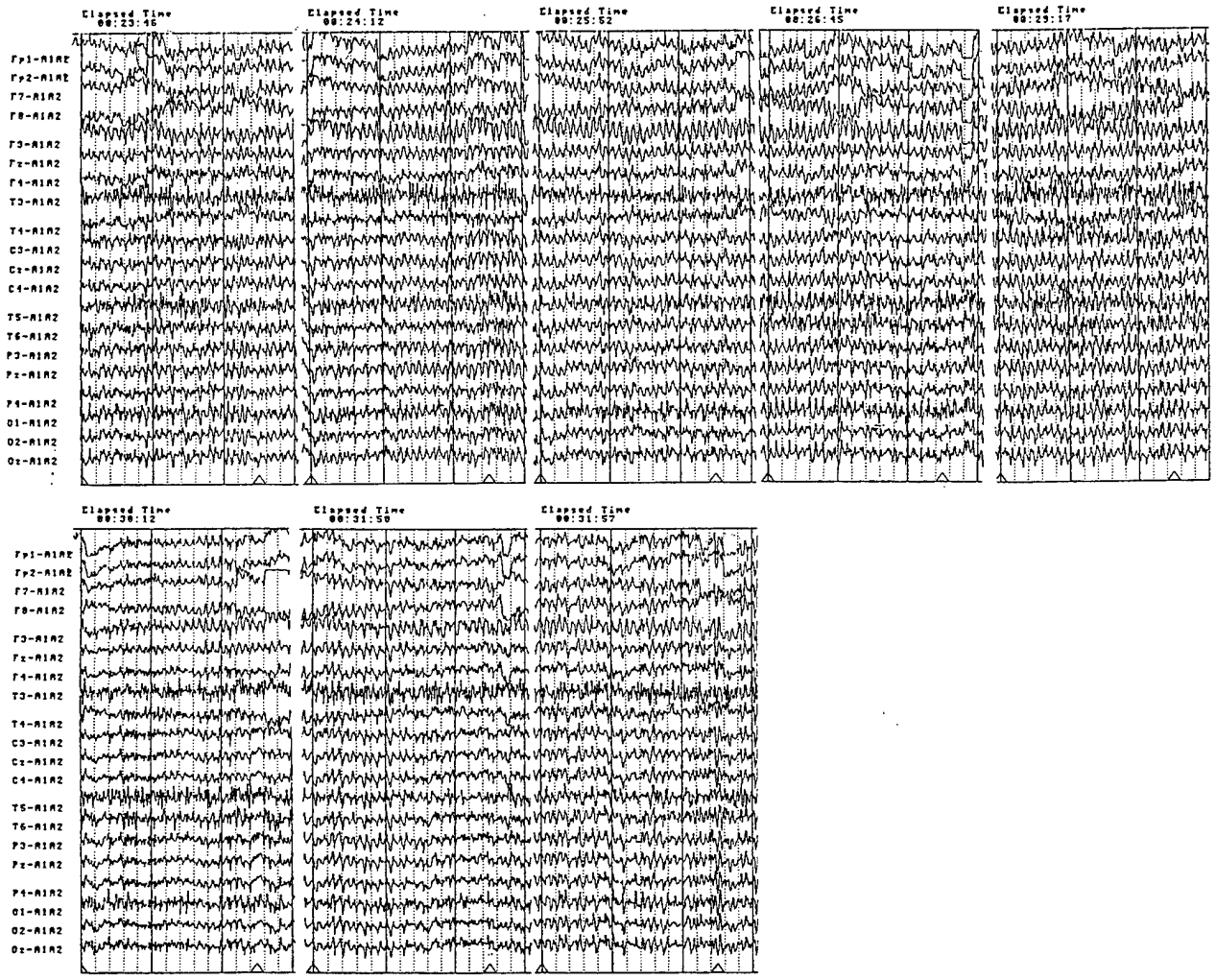

Figure 6. The EEG epochs selected for analysis from flight maneuvers 11-14 for subject 2.

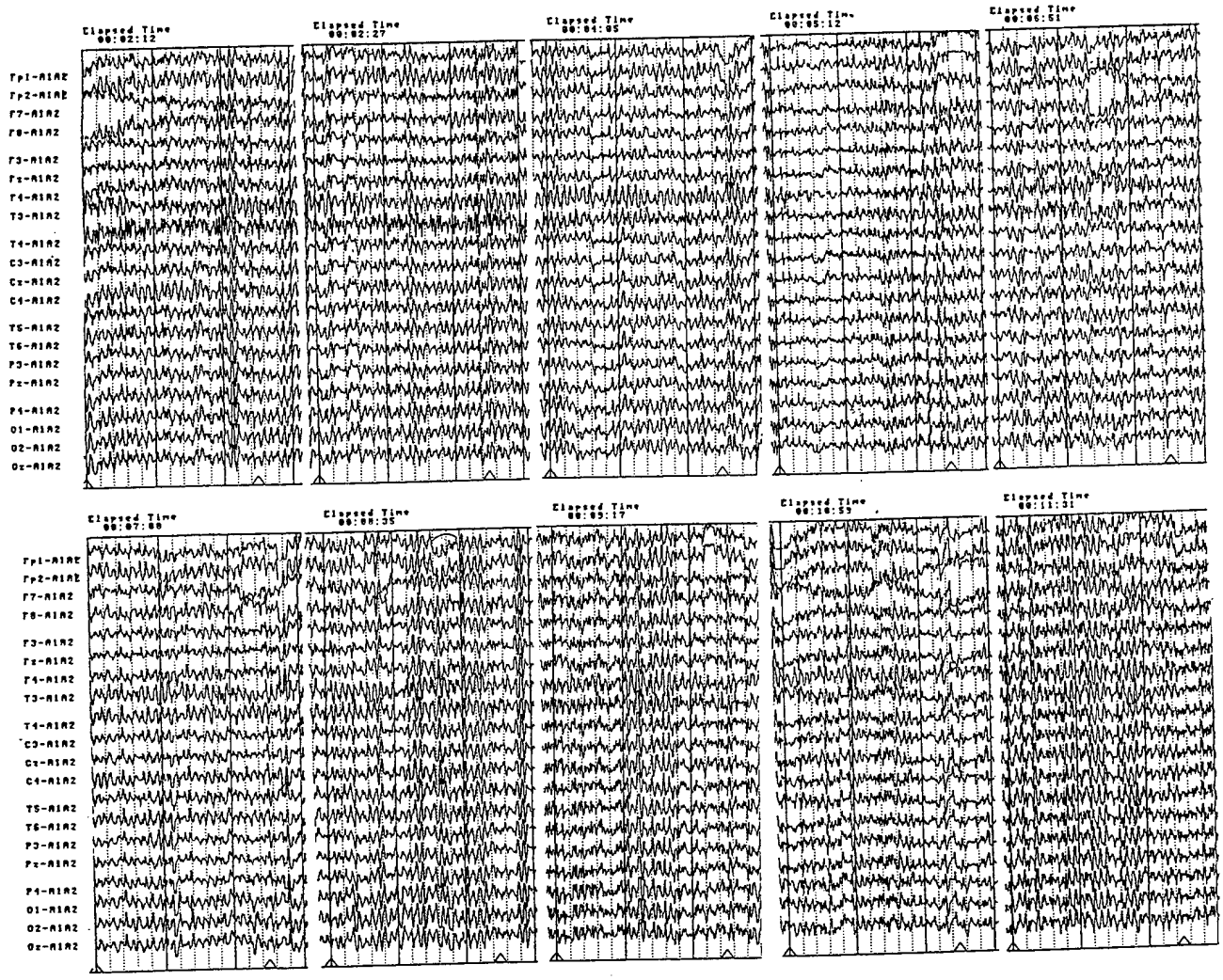

Figure 7. The EEG epochs selected for analysis from flight maneuvers 1-5 for subject 3.

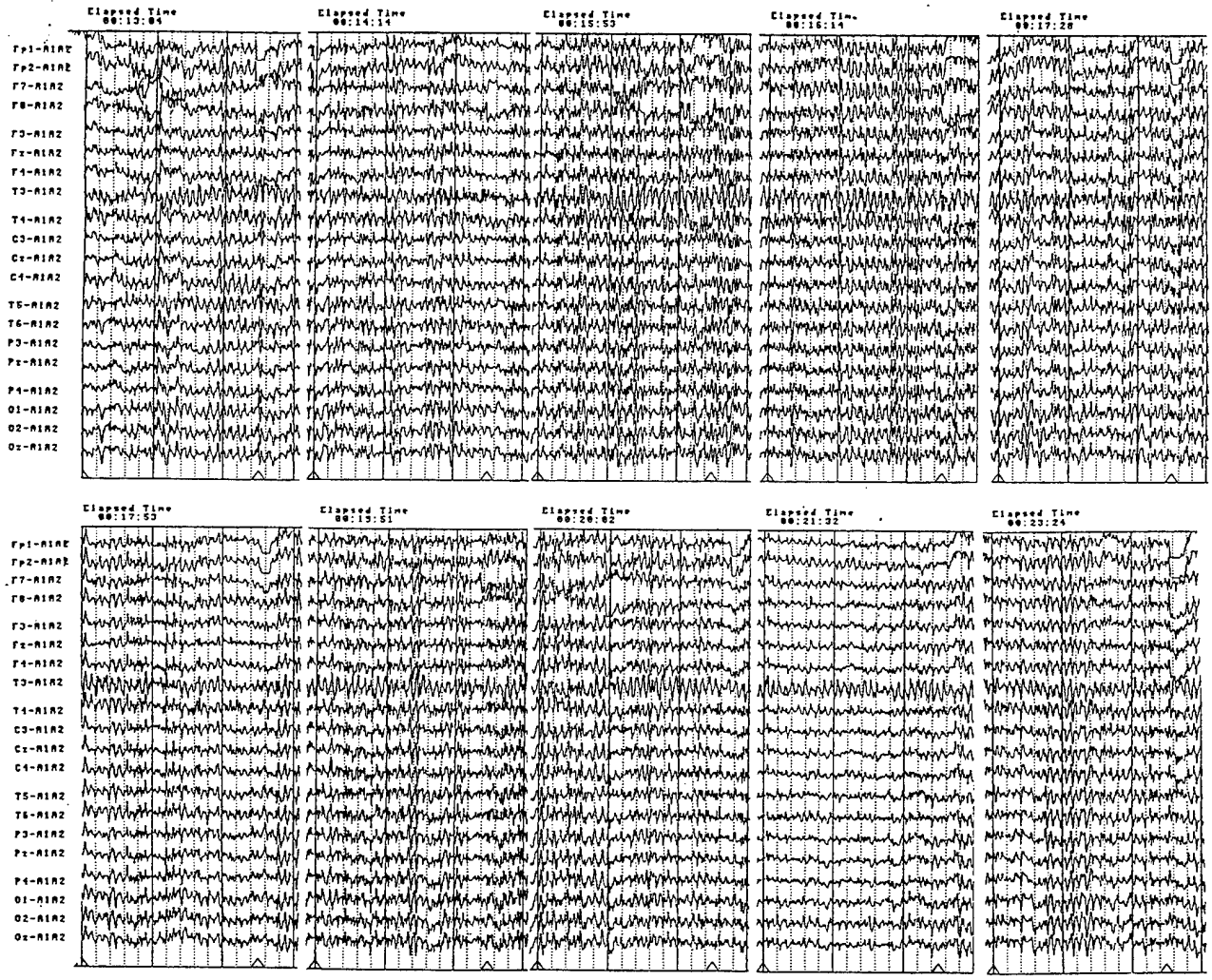

Figure 8. The EEG epochs selected for analysis from flight maneuvers 6-10 for subject 3.

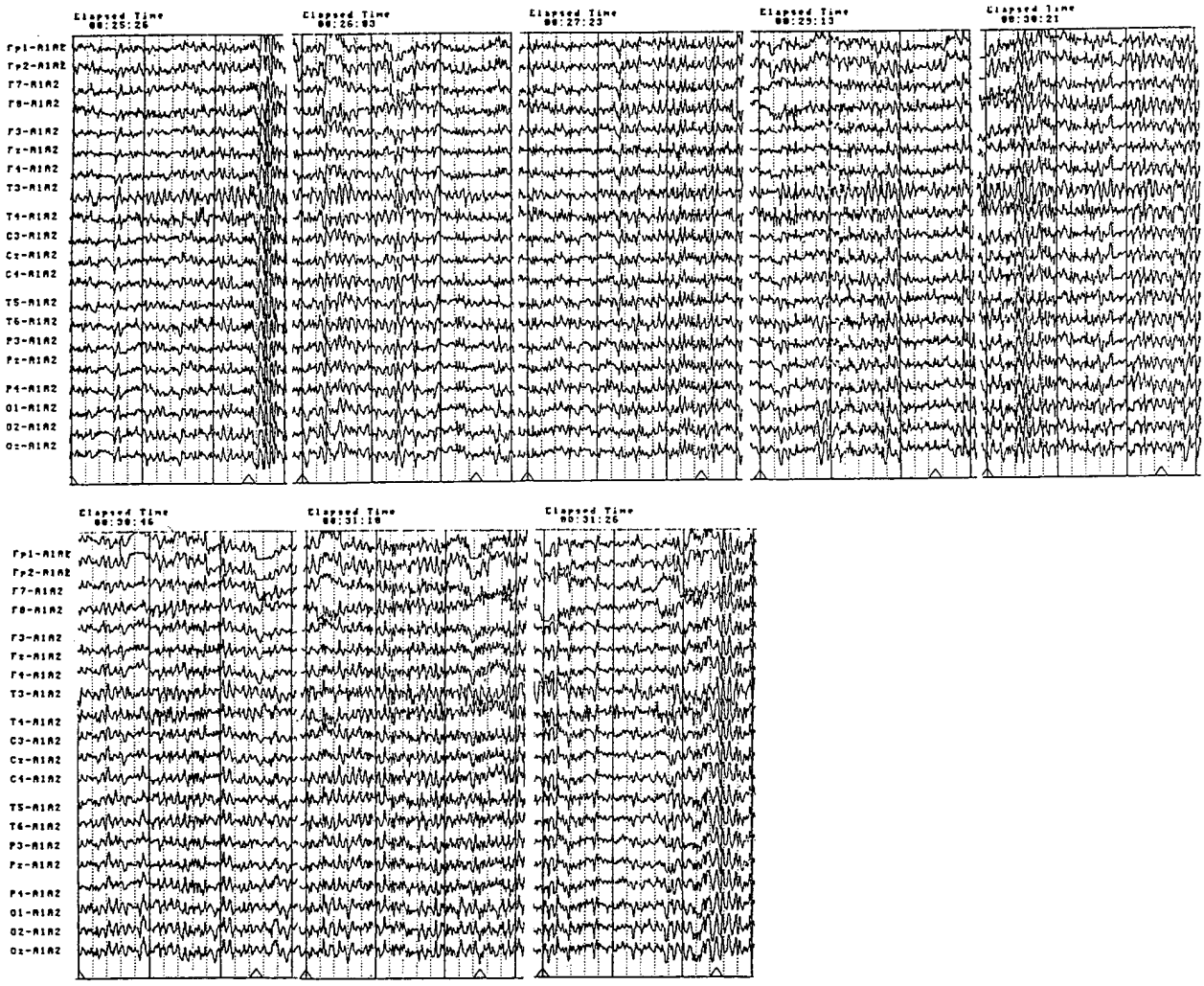

Figure 9. The EEG epochs selected for analysis from flight maneuvers 11-14 for subject 3.

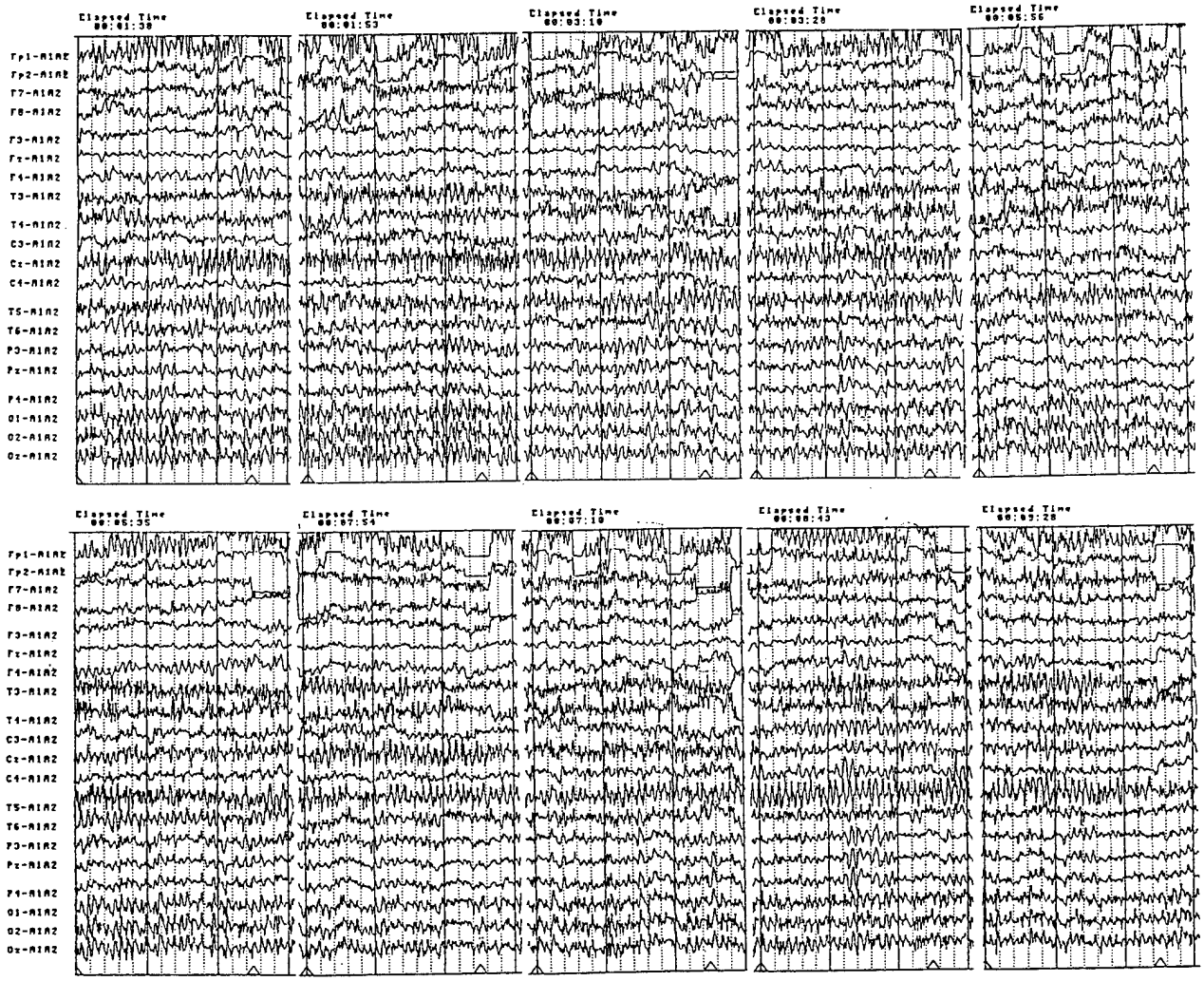

Figure 10. The EEG epochs selected for analysis from flight maneuvers 1-5 for subject 4.

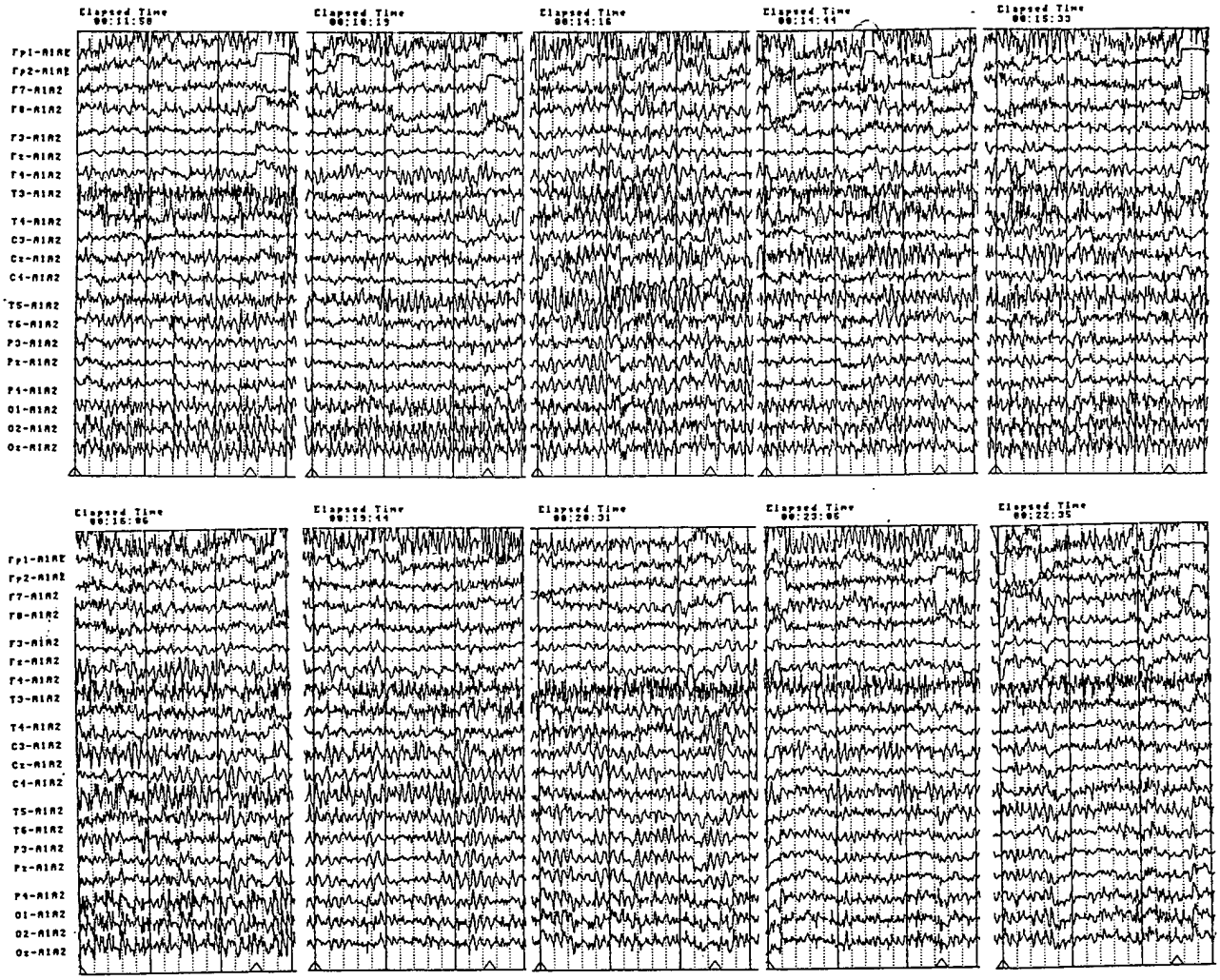

Figure 11. The EEG epochs selected for analysis from flight maneuvers 6-10 for subject 4.

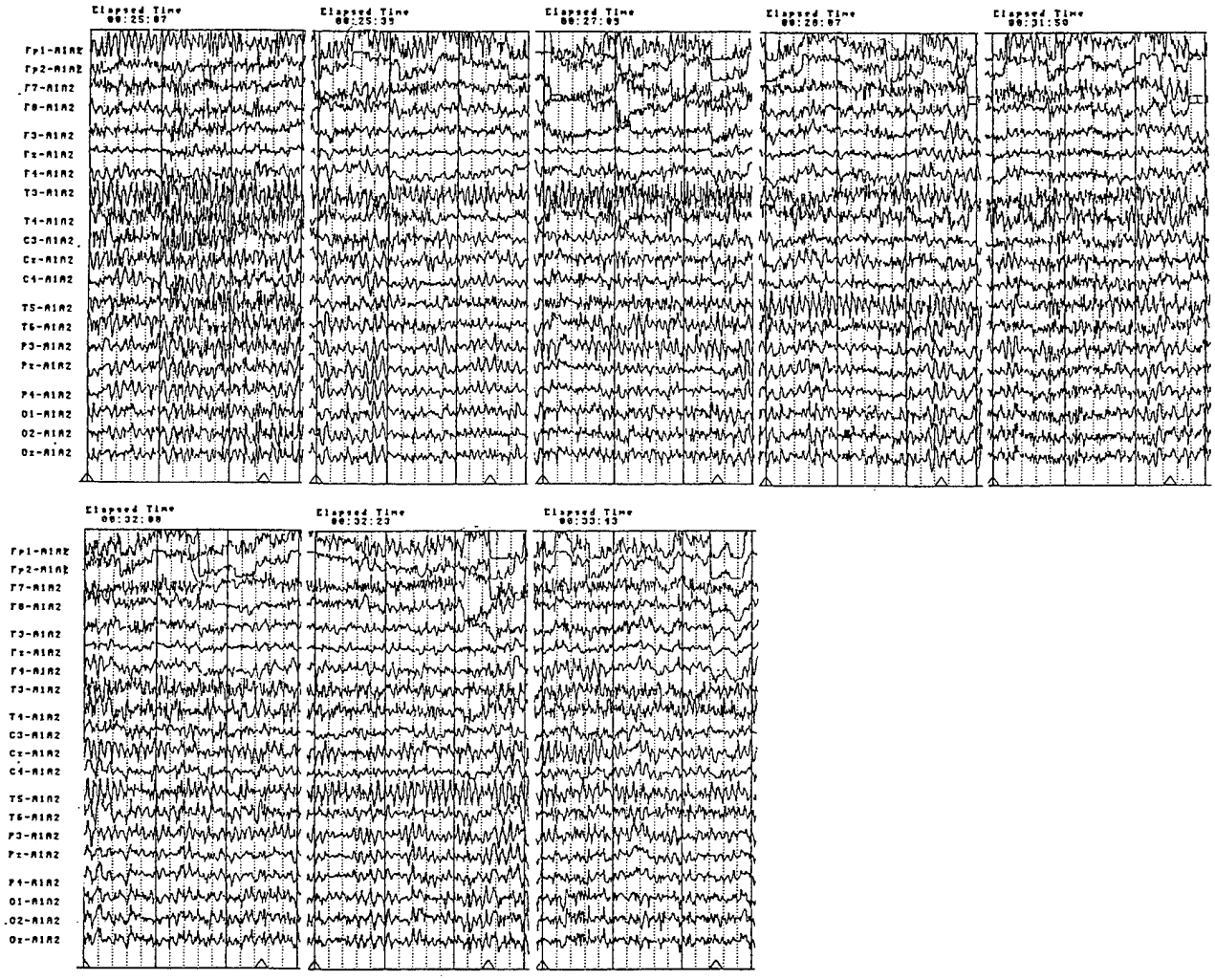

Figure 12. The EEG epochs selected for analysis from flight maneuvers 11-14 for subject 4.

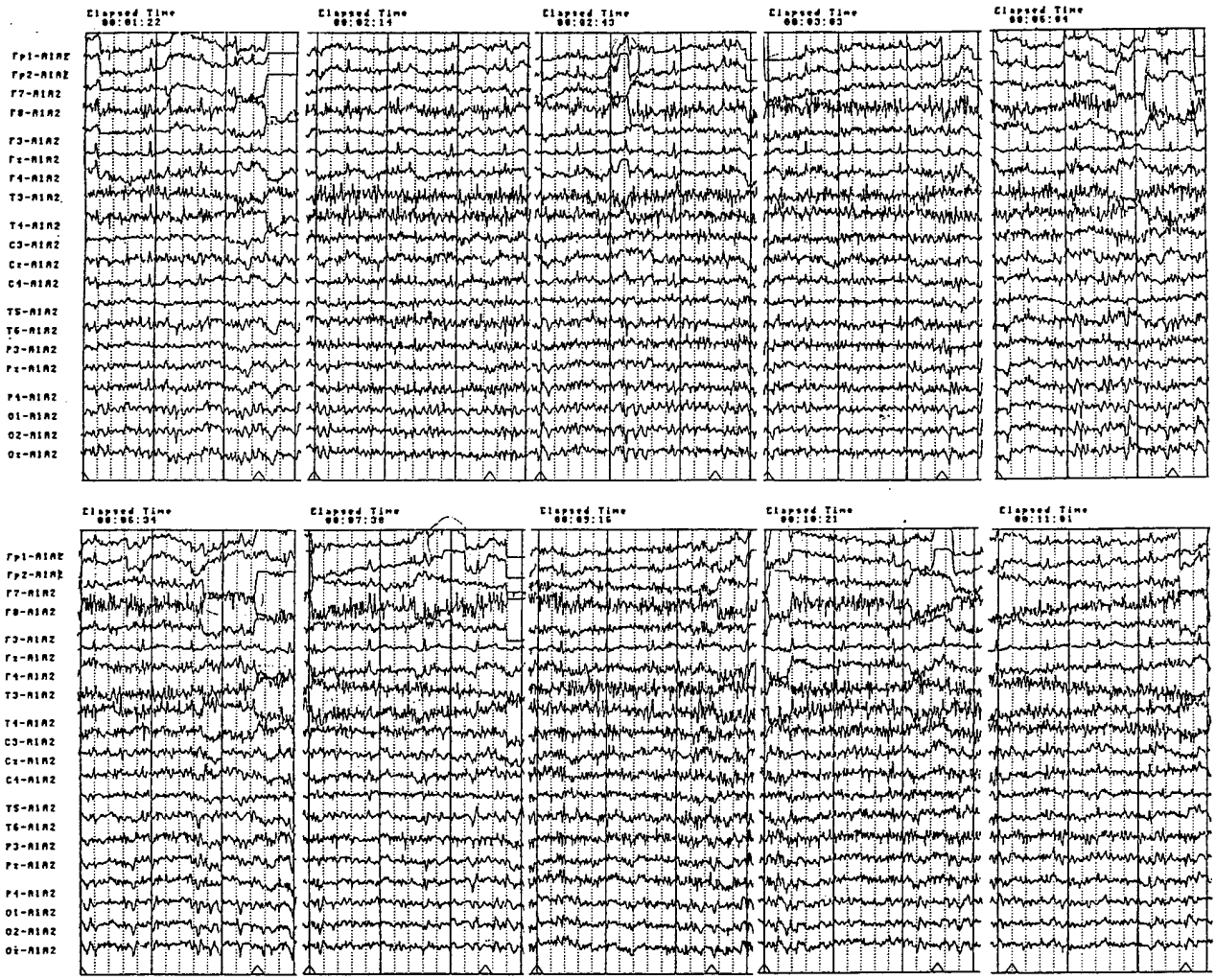

Figure 13. The EEG epochs selected for analysis from flight maneuvers 1-5 for subject 5.

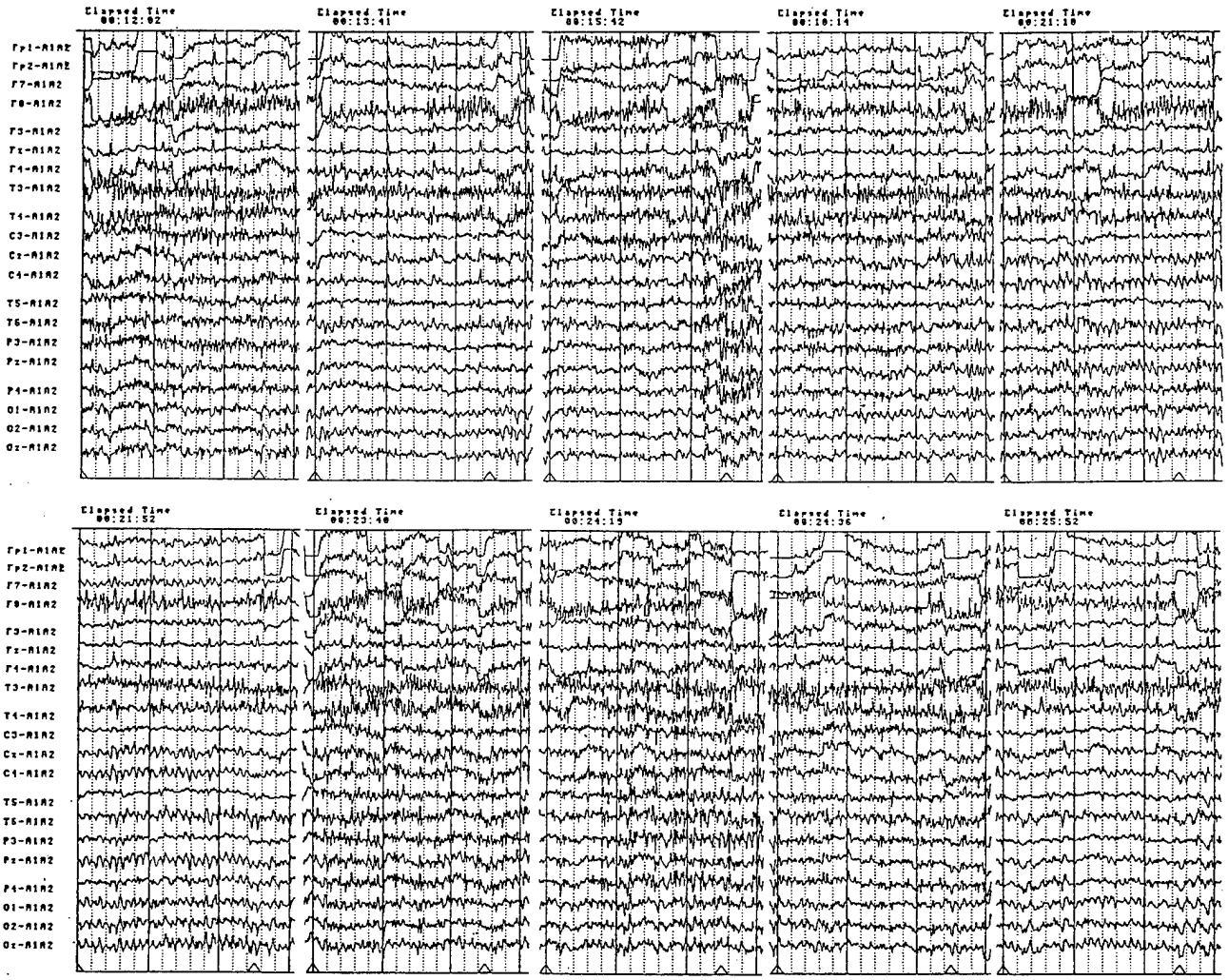

Figure 14. The EEG epochs selected for analysis from flight maneuvers 6-10 for subject 5.

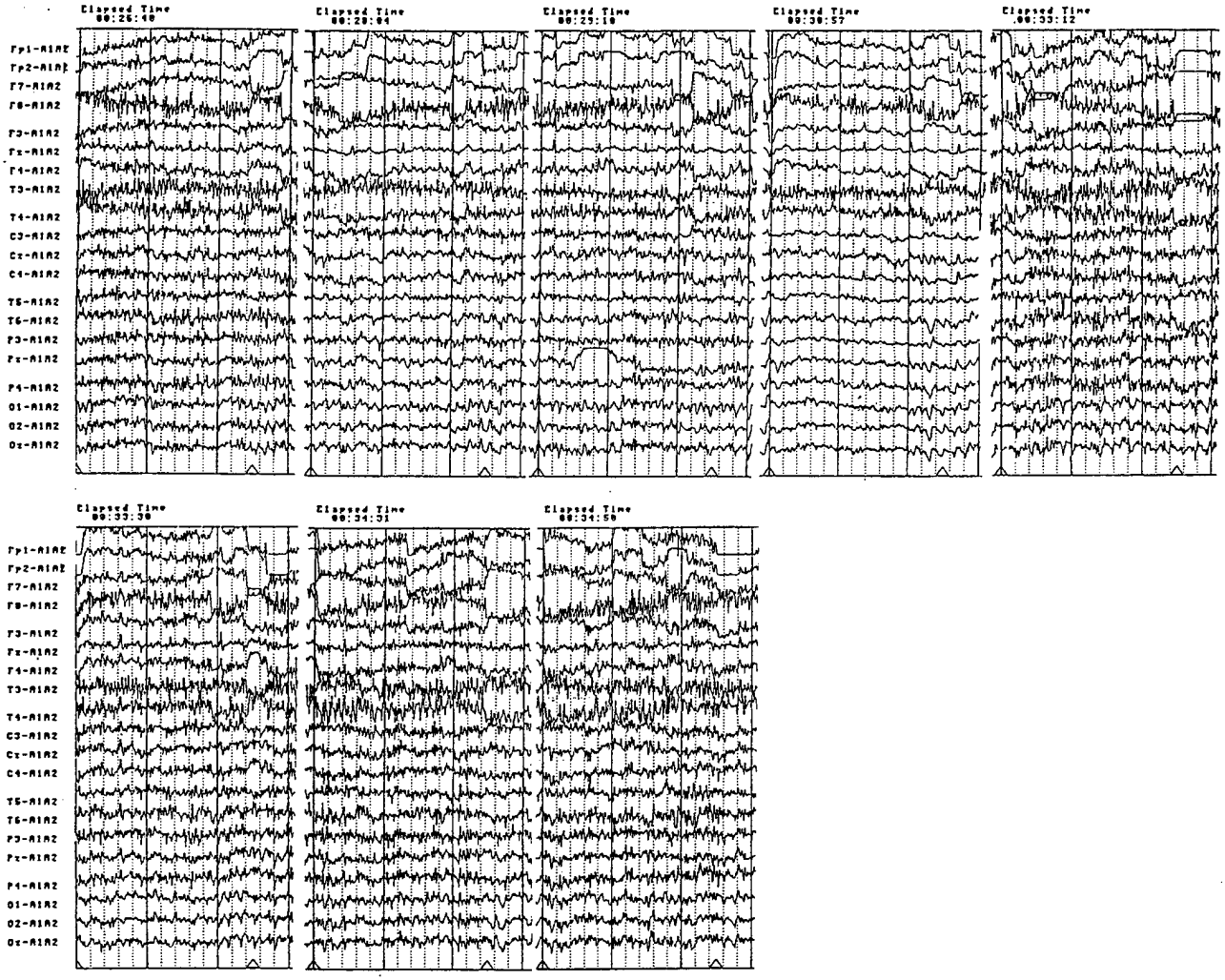

Figure 15. The EEG epochs selected for analysis from flight maneuvers 11-14 for subject 5.

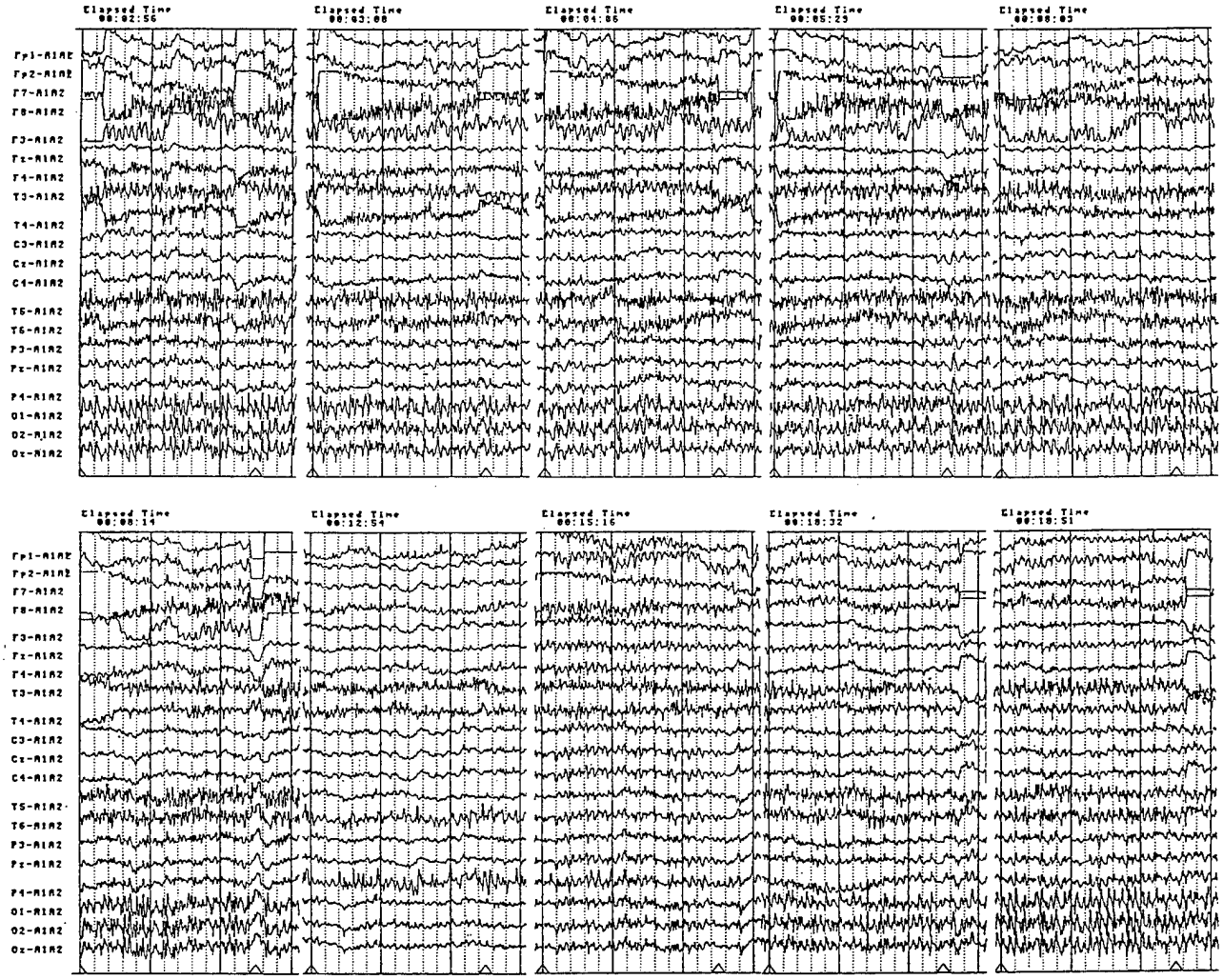

Figure 16. The EEG epochs selected for analysis from flight maneuvers 1-5 for subject 6.

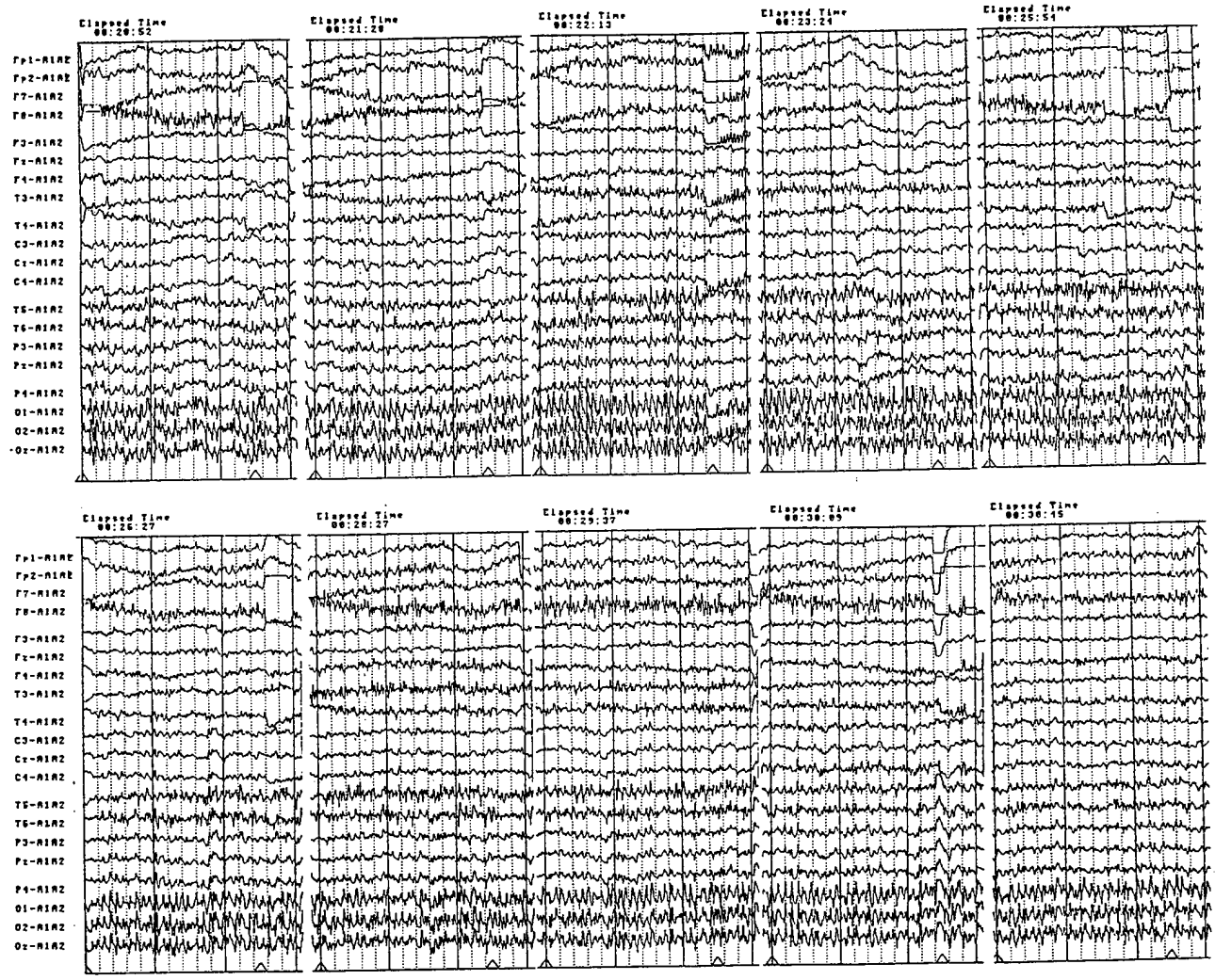

Figure 17. The EEG epochs selected for analysis from flight maneuvers 6-10 for subject 6.

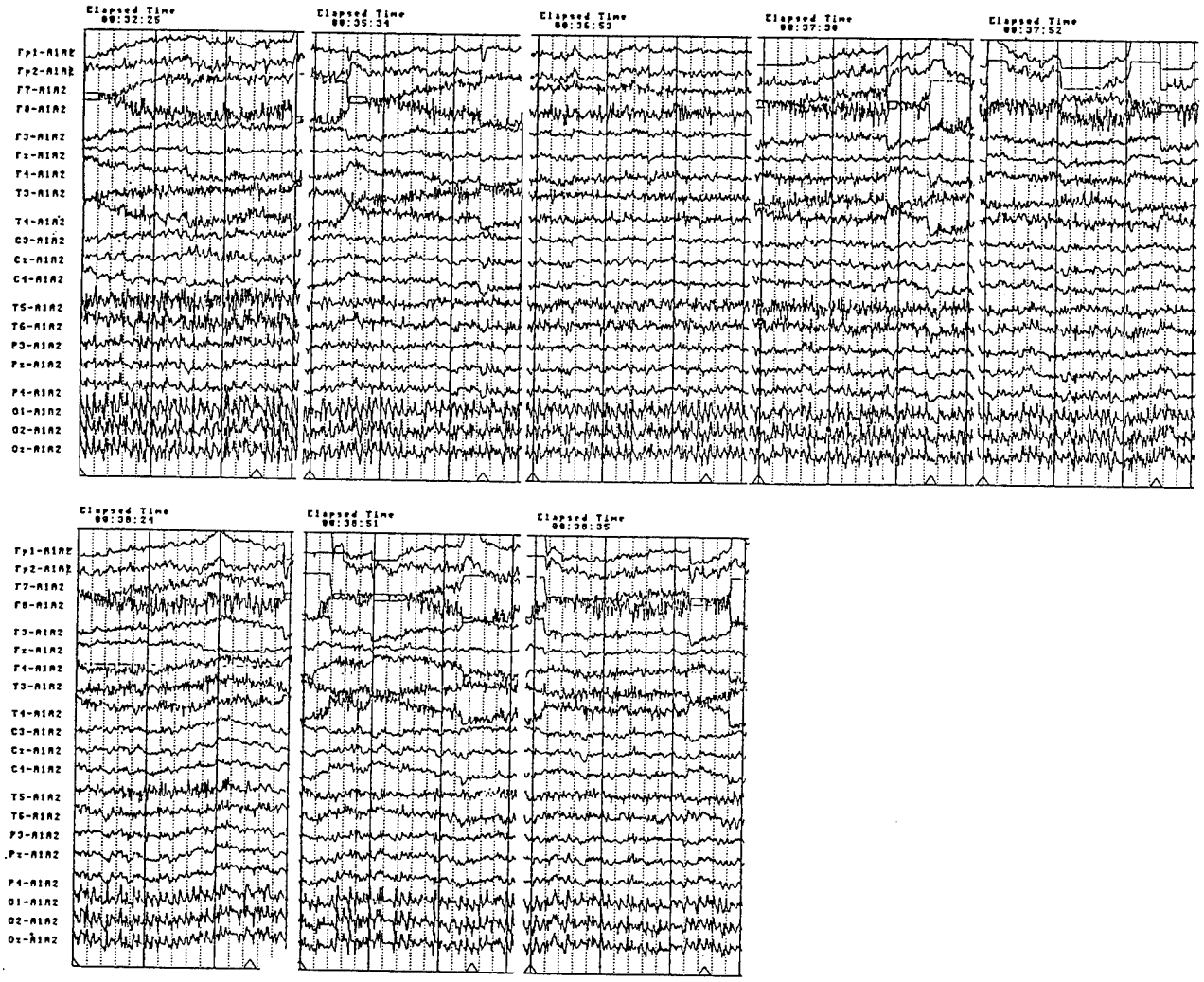

Figure 18. The EEG epochs selected for analysis from flight maneuvers 11-14 for subject 6.

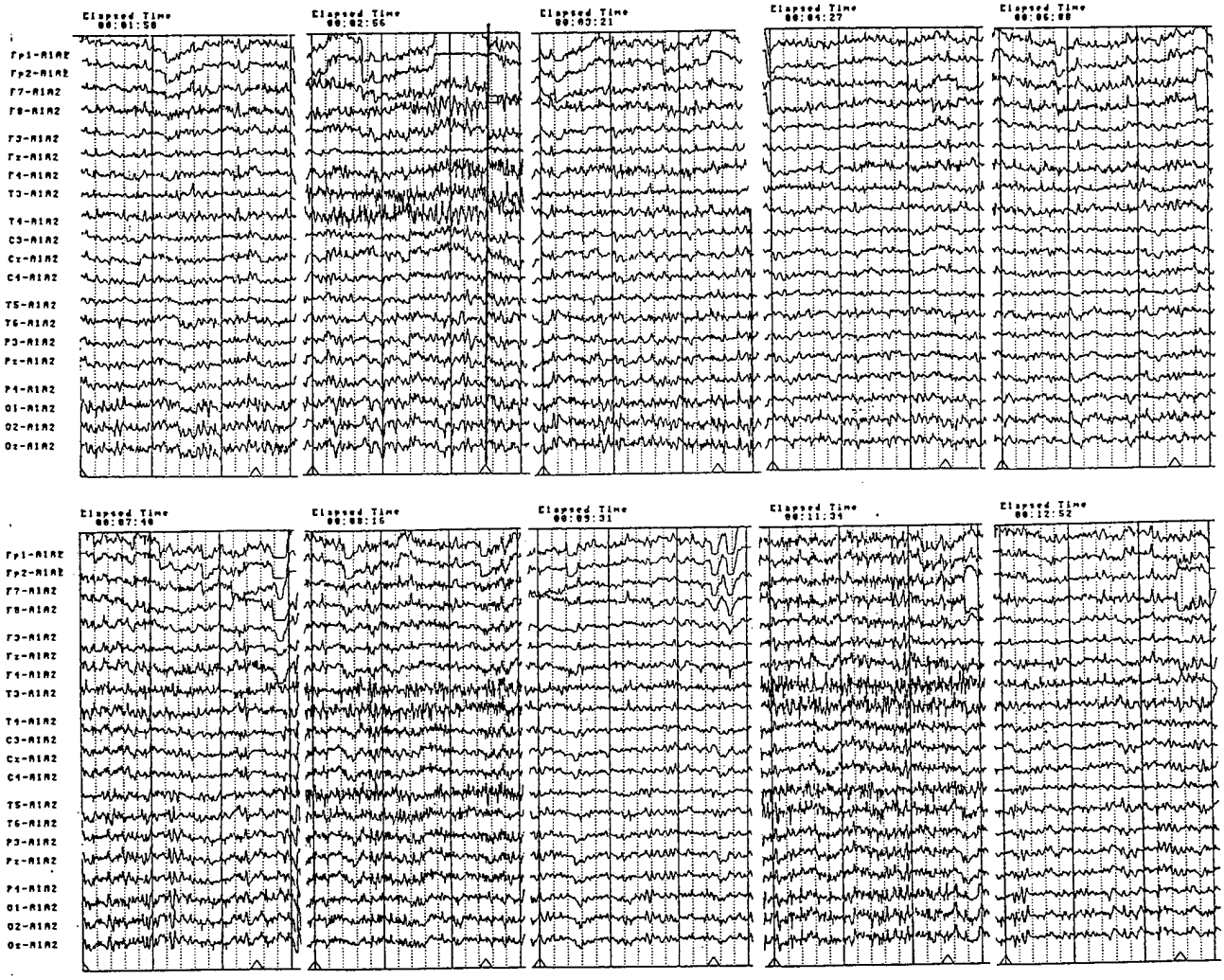

Figure 19. The EEG epochs selected for analysis from flight maneuvers 1-5 for subject 7.

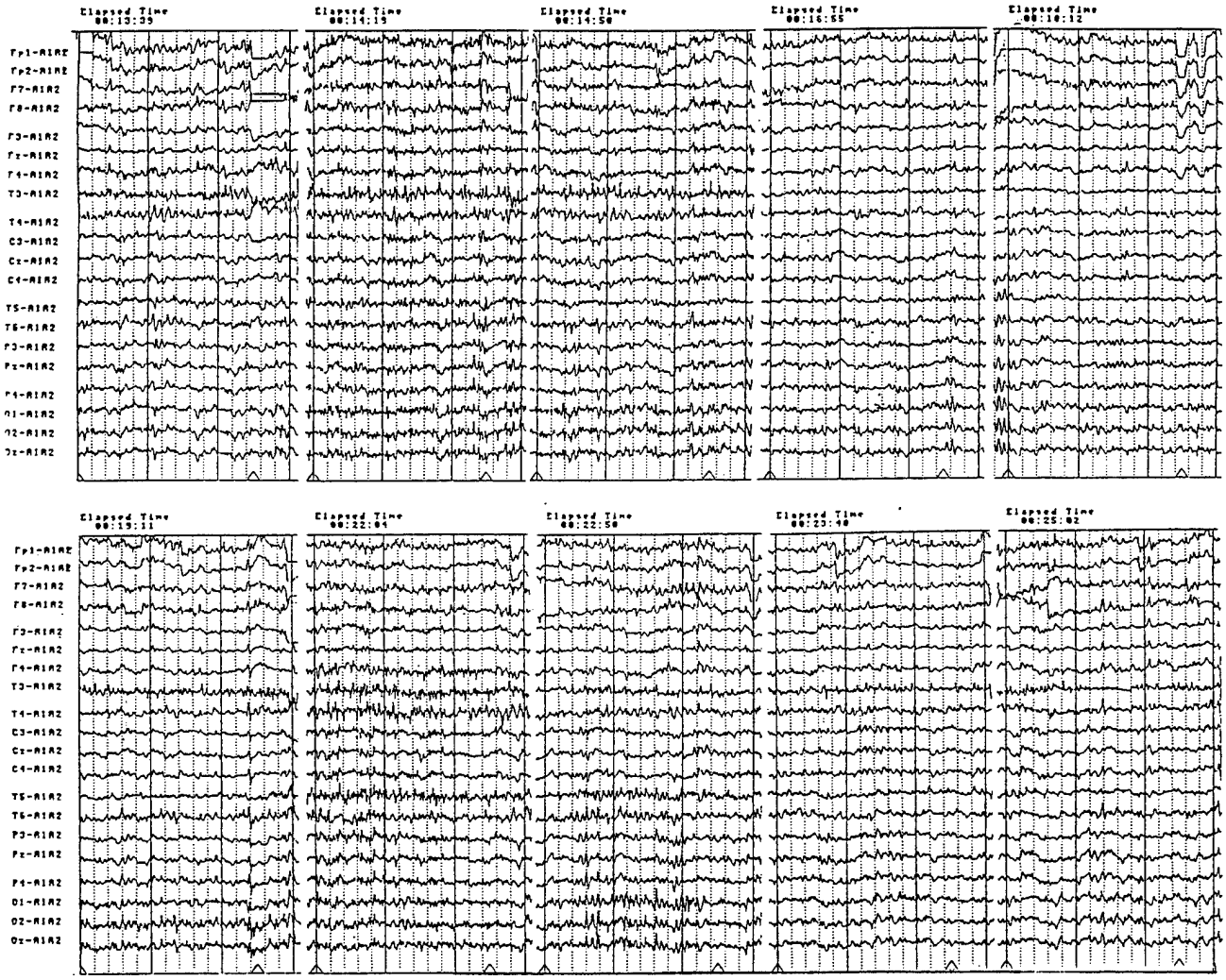

Figure 20. The EEG epochs selected for analysis from flight maneuvers 6-10 for subject 7.

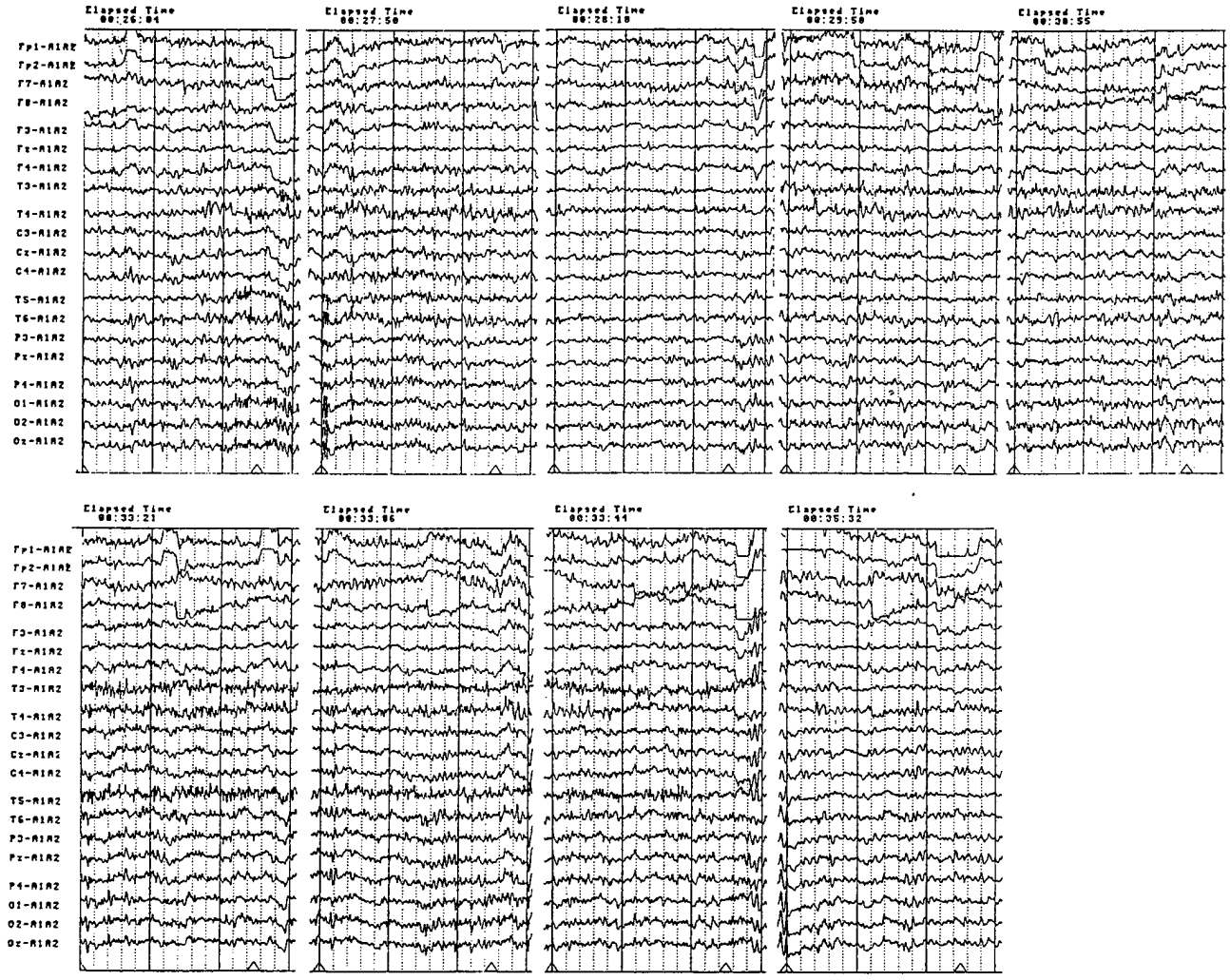

Figure 21. The EEG epochs selected for analysis from flight maneuvers 11-14 for subject 7.

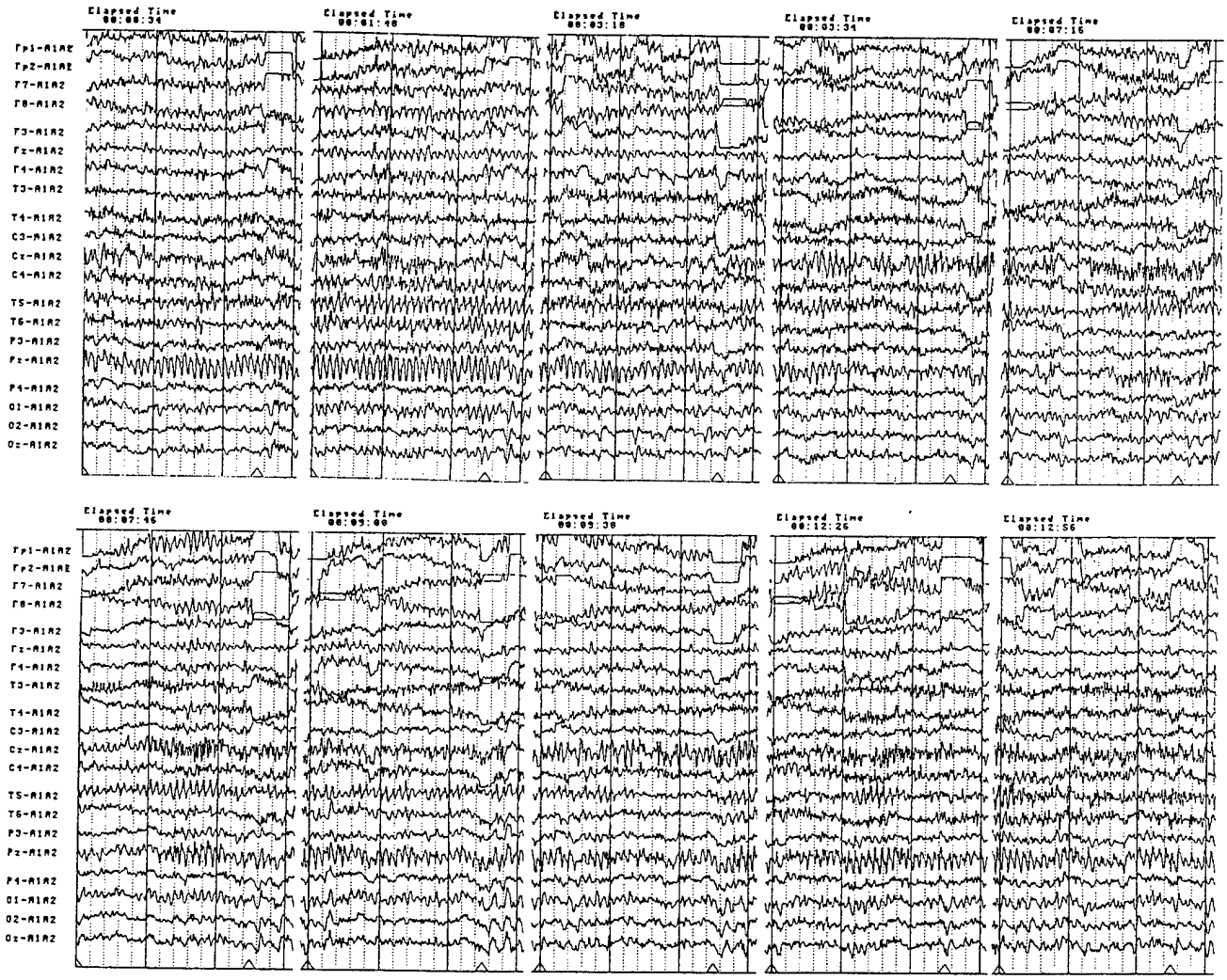

Figure 22. The EEG epochs selected for analysis from flight maneuvers 1-5 for subject 8.

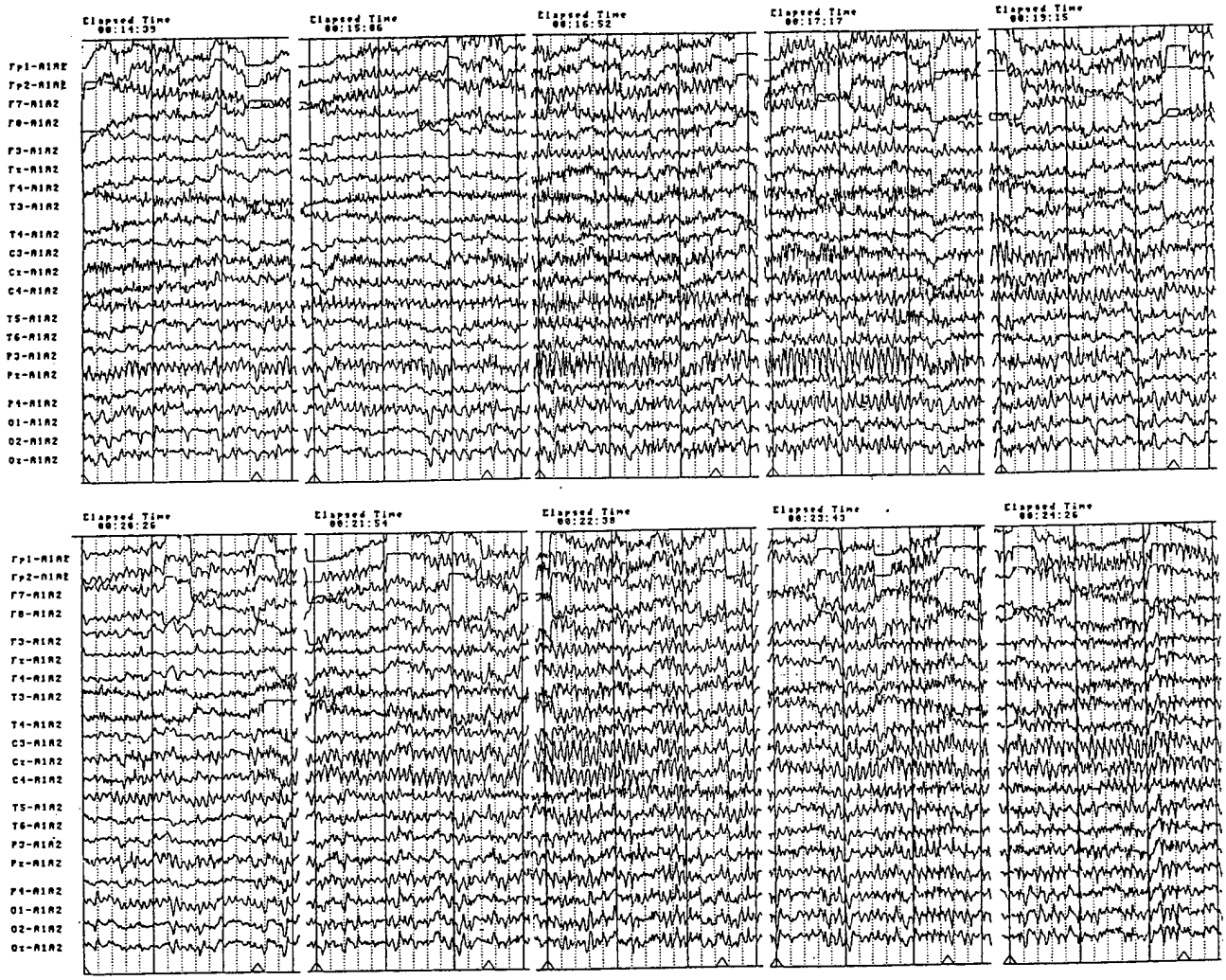

Figure 23. The EEG epochs selected for analysis from flight maneuvers 6-10 for subject 8.

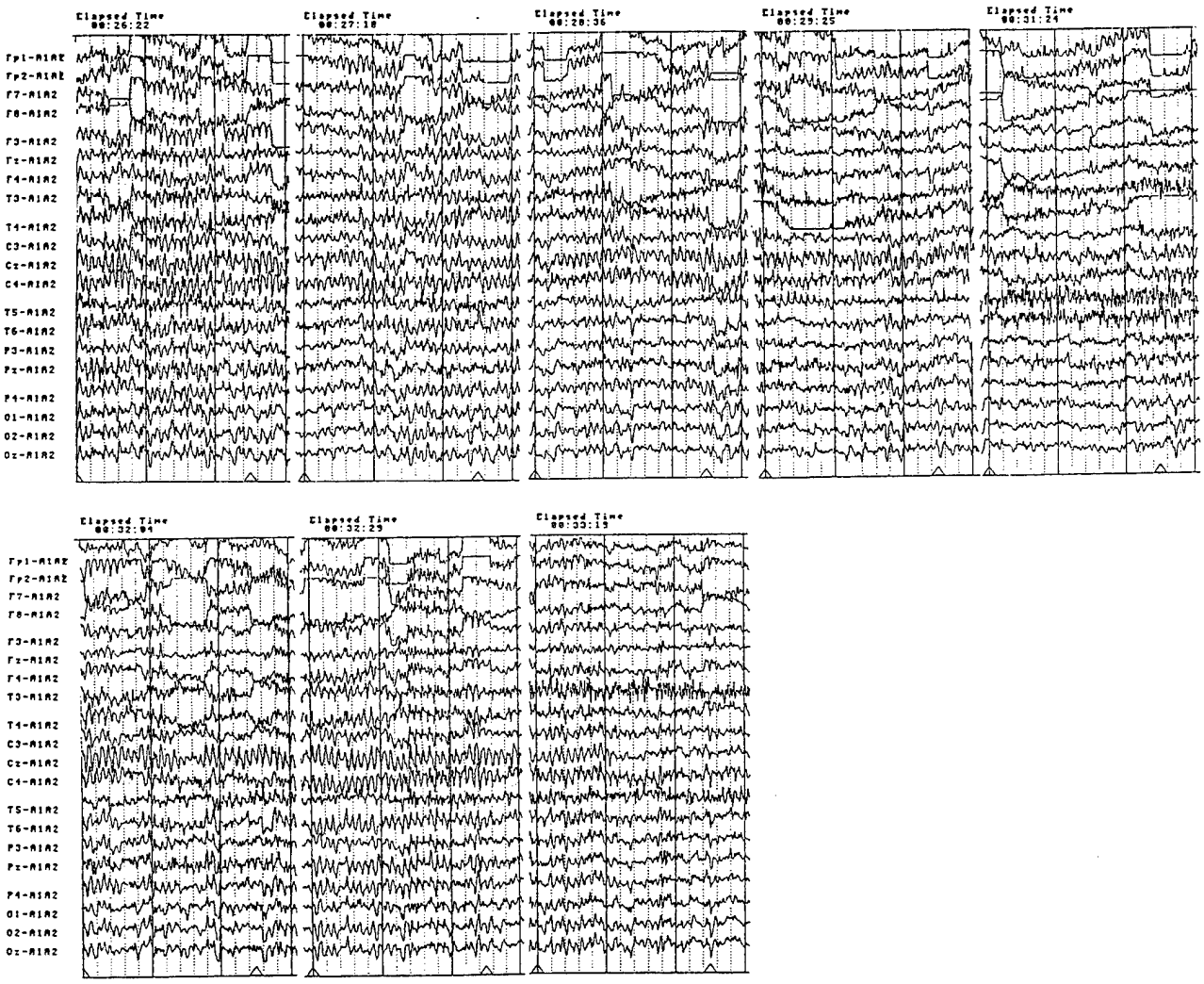

Figure 24. The EEG epochs selected for analysis from flight maneuvers 11-14 for subject 8.

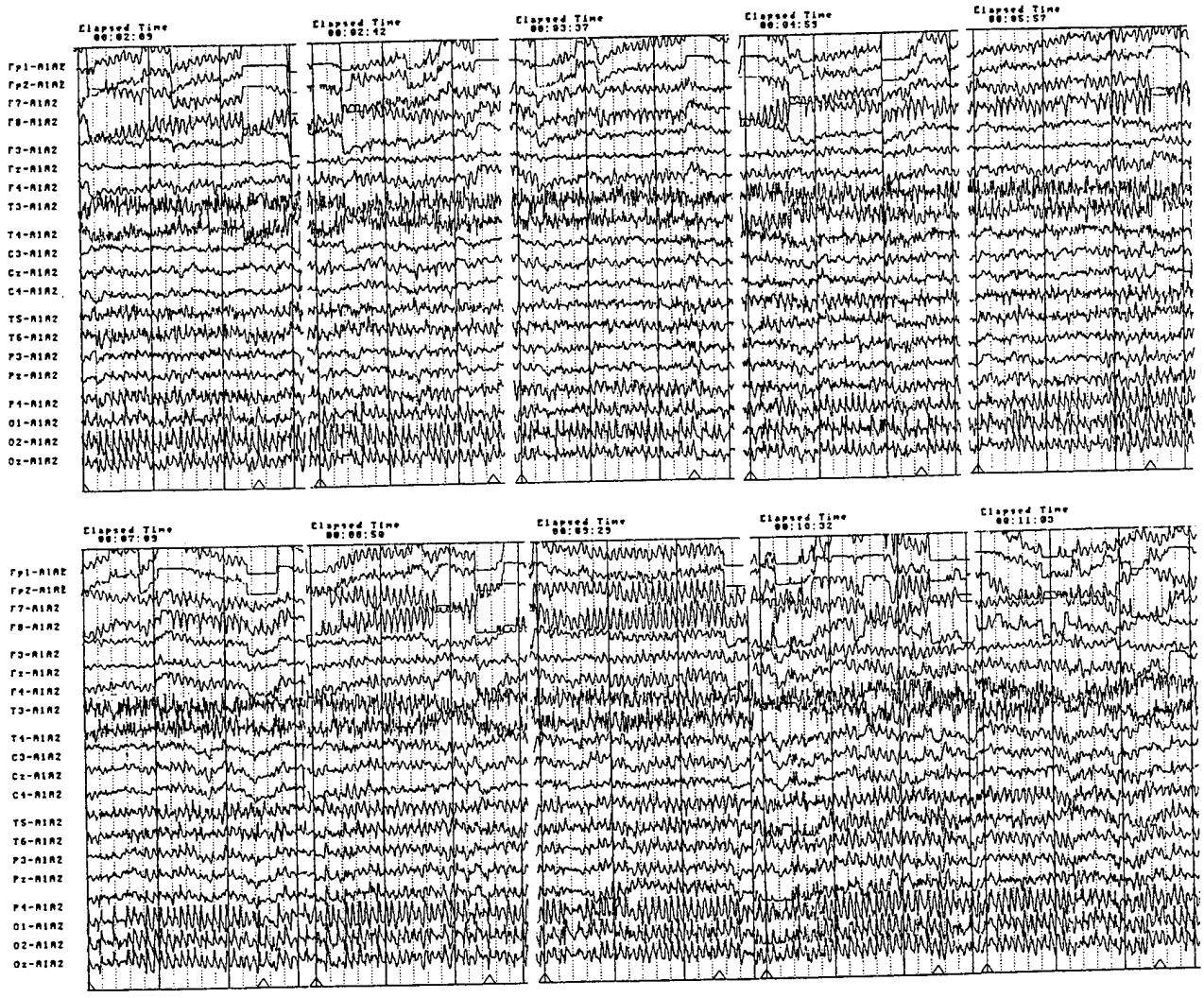

Figure 25. The EEG epochs selected for analysis from flight maneuvers 1-5 for subject 9.

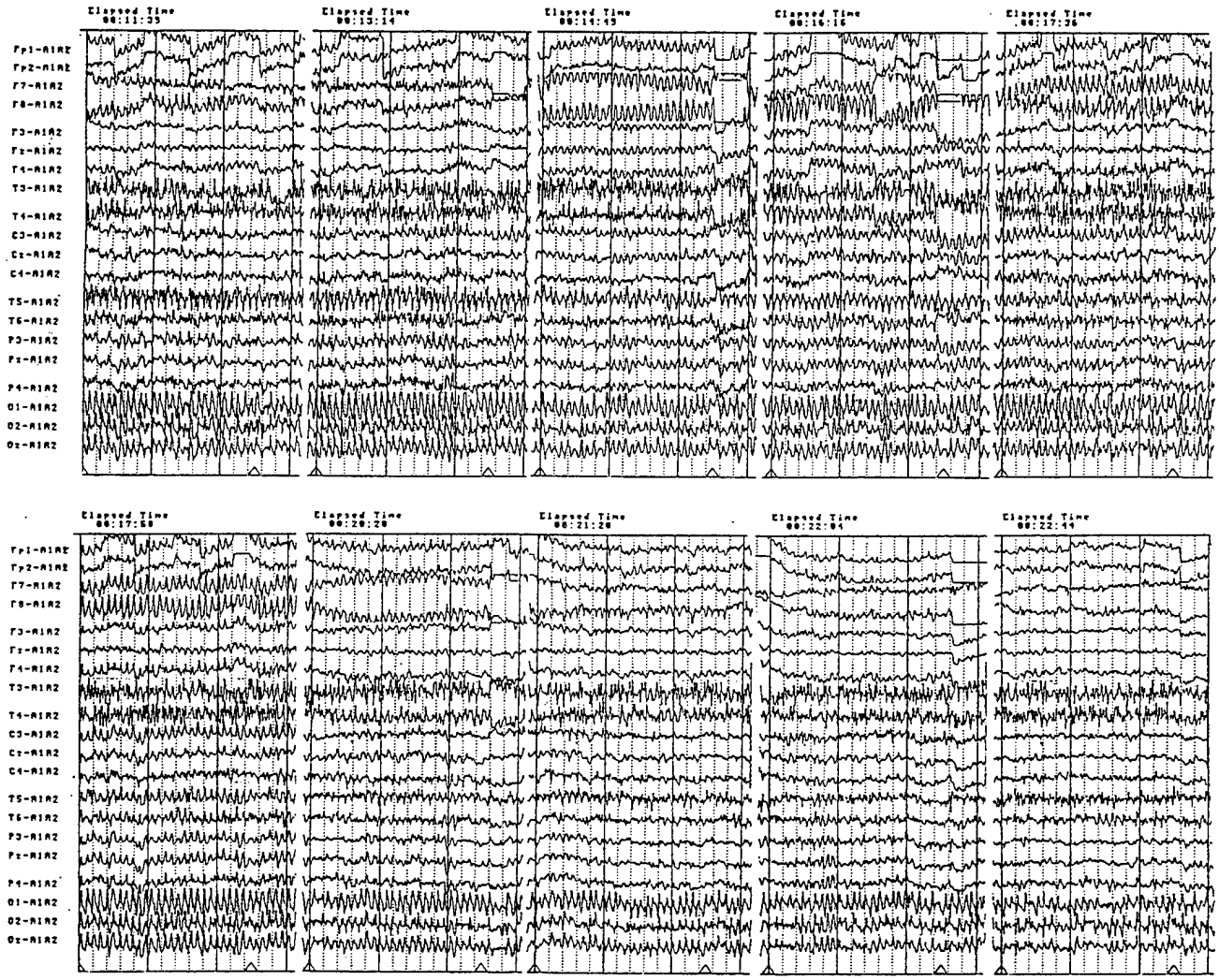

Figure 26. The EEG epochs selected for analysis from flight maneuvers 6-10 for subject 9.

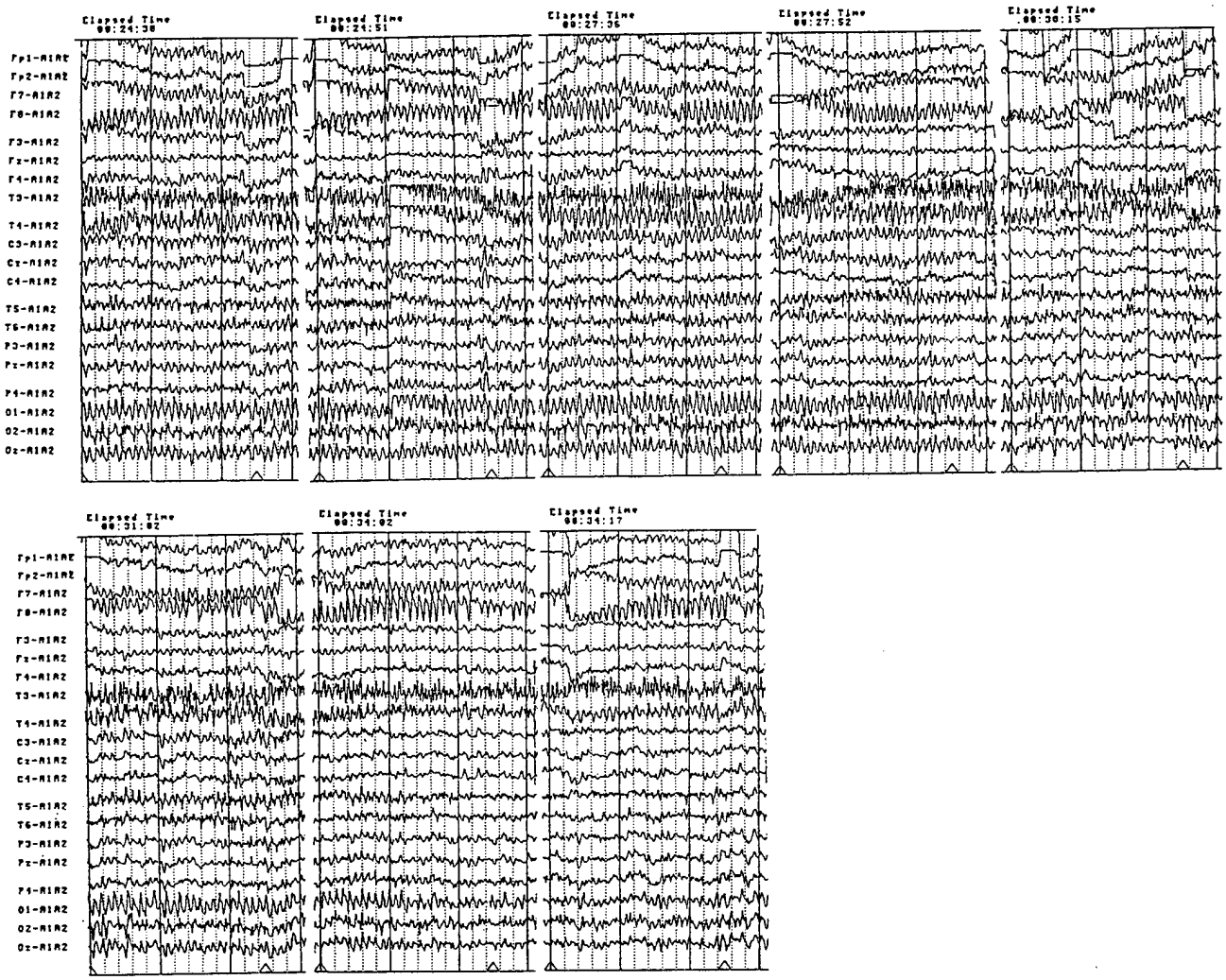

Figure 27. The EEG epochs selected for analysis from flight maneuvers 11-14 for subject 9.

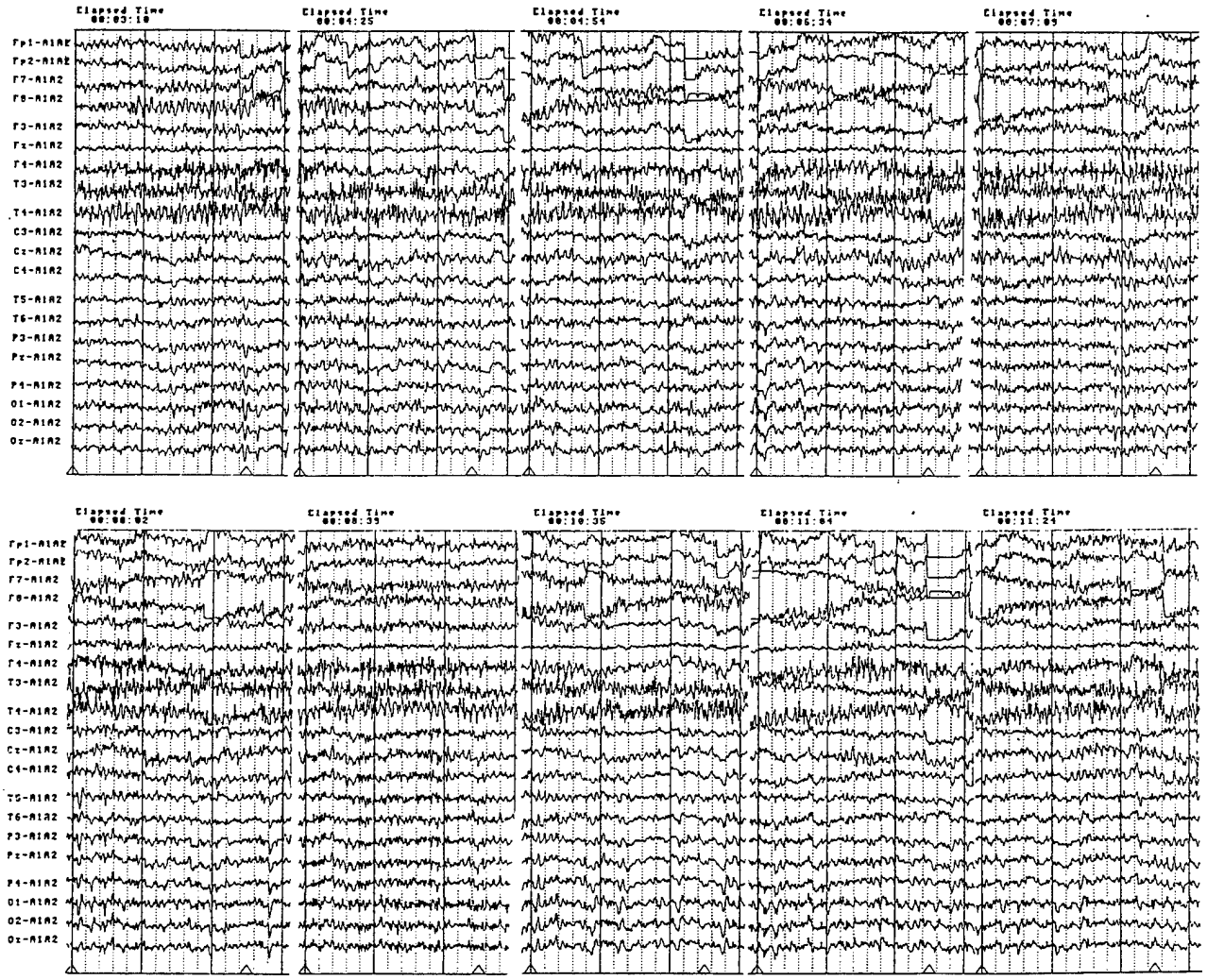

Figure 28. The EEG epochs selected for analysis from flight maneuvers 1-5 for subject 10.

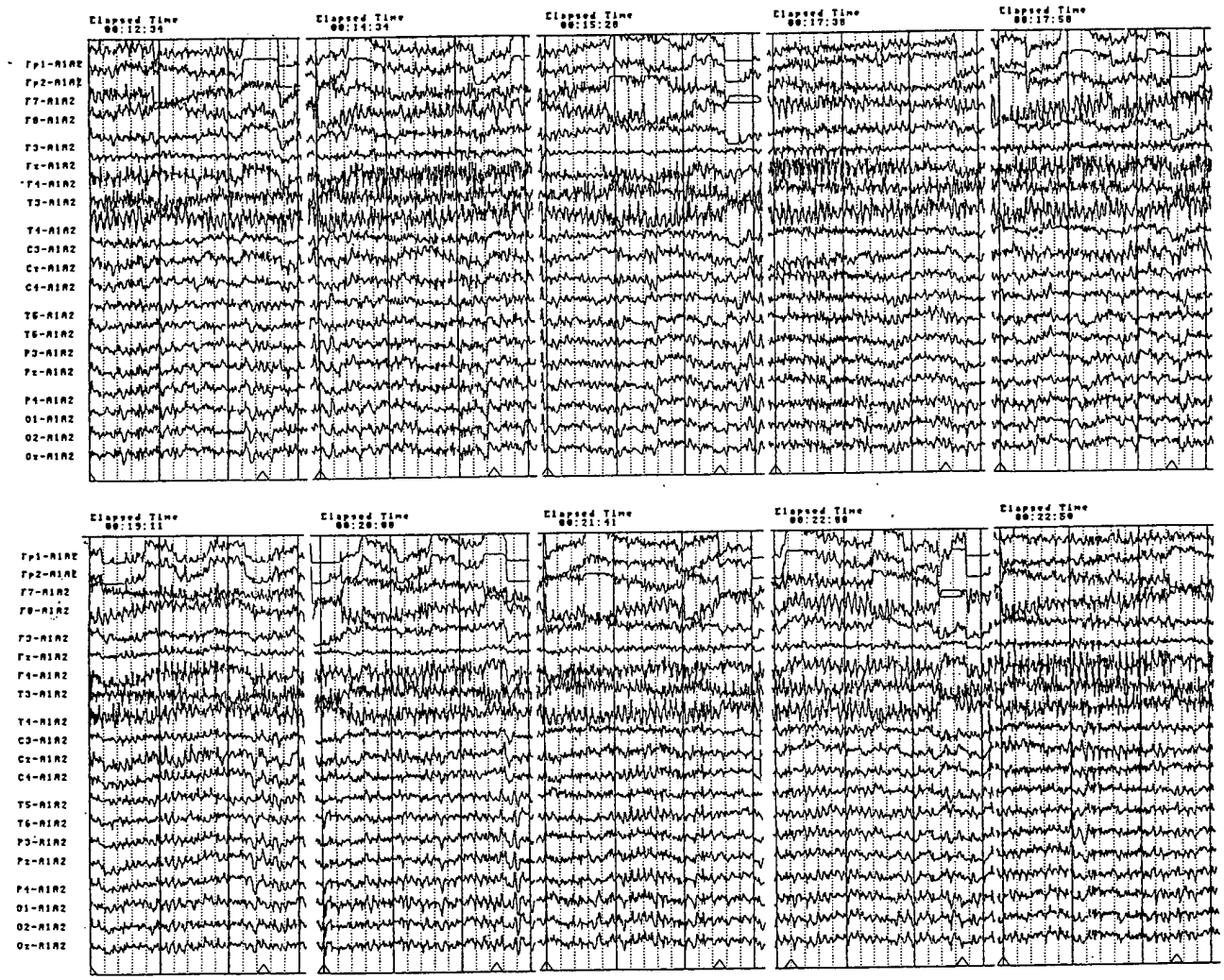

Figure 29. The EEG epochs selected for analysis from flight maneuvers 6-10 for subject 10.

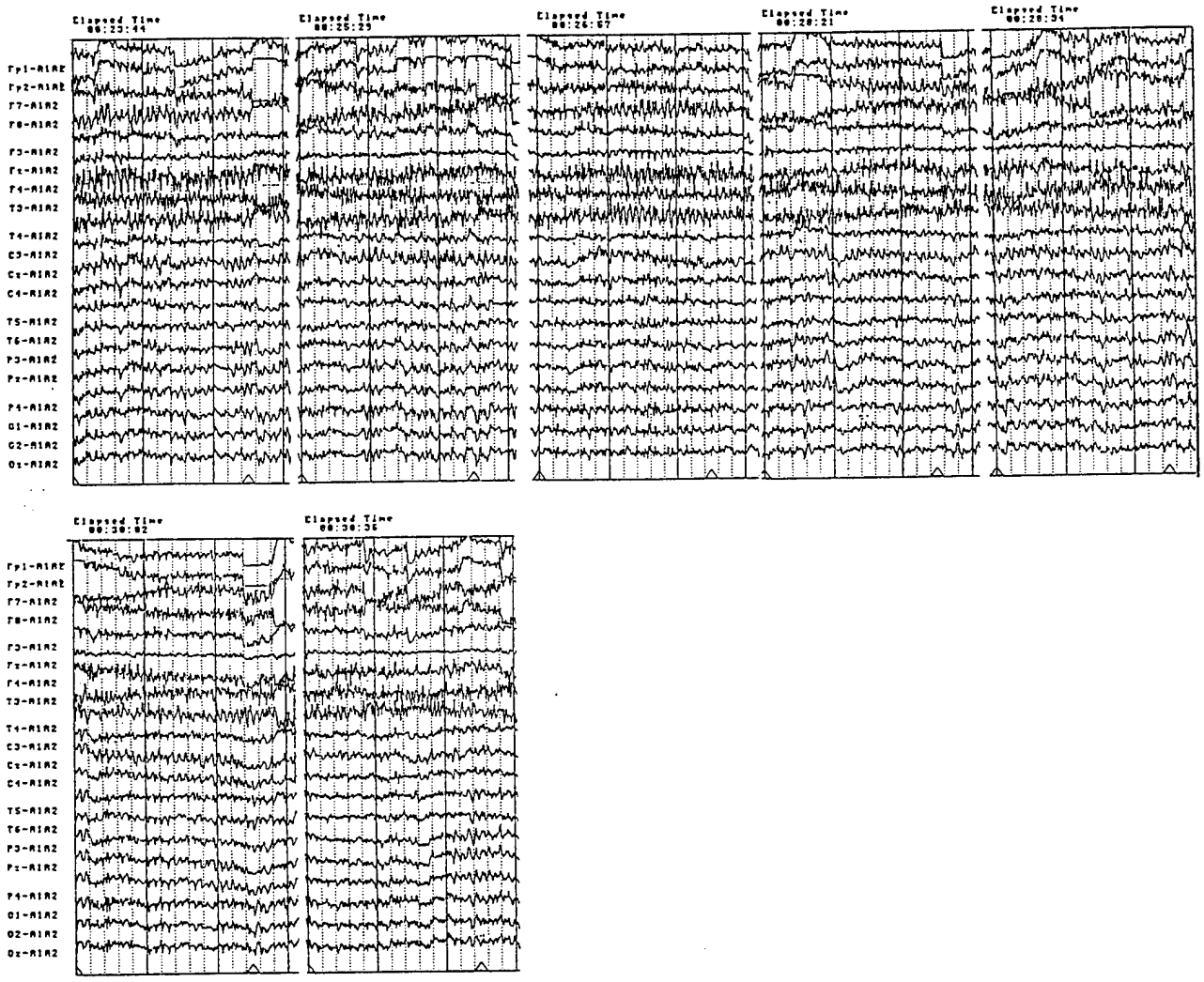

Figure 30. The EEG epochs selected for analysis from flight maneuvers 11-14 for subject 10.