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Task complexity modulates pilot electroencephalographic activity during real flights

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Abstract

Most research connecting task performance and neural activity to date has been conducted in laboratory conditions. Thus, field studies remain scarce, especially in extreme conditions such as during real flights. Here, we investigated the effects of flight procedures of varied complexity on the in-flight EEG activity of military helicopter pilots. Flight procedural complexity modulated the EEG power spectrum: highly demanding procedures (i.e., takeoff and landing) were associated with higher EEG power in the higher frequency bands, whereas less demanding procedures (i.e., flight exercises) were associated with lower EEG power over the same frequency bands. These results suggest that EEG recordings may help to evaluate an operator's cognitive performance in challenging real-life scenarios, and thus could aid in the prevention of catastrophic events.

Descriptors: Descriptors: EEG, Fatigue, Neuroergonomics, Safety, Simulation, Training

Contemporary military and civilian aviation is often stressful and cognitively demanding (Damos, 2014). A high proportion of accidents in aviation (80–85%) are caused by human error, which is directly attributed to failures in cognitive performance (CP; Thomas & Russo, 2007). It is in takeoffs and landings, the most cognitively demanding flight stages (e.g., Di Nocera, Camilli, & Terenzi, 2007; Harmony et al., 1996; Lee & Liu, 2003; Sterman & Mann, 1995; Wilson, 2002; Yao et al., 2008), that most accidents occur (Boeing, 2013). Thus, understanding the impact of in-flight procedures on pilot CP at the various flight stages, and detecting the onset of CP decline, can help to improve air safety. Indeed, the noninvasive monitoring of operator CP and its impairment is a current goal of international organizations worldwide, especially in critical-safety environments (Friedl & Allan, 2004; Friedl et al., 2007; Tracey & Flower, 2014).

Traditionally, risk management experts have used subjective questionnaires as their primary tool for evaluating operator's CP (Di Stasi et al., 2014). Such questionnaires, easy to administer and interpret, have several methodological caveats, however. Their standard offline administration (paper and pencil test), for example, does not allow for continuous evaluation of CP (Di Stasi, Marchitto, Antolí, & Cañas, 2013). Thus, the ability to objectively and sensitively measure operator CP online in real scenarios remains a major challenge (Di Stasi, Catena, Cañas, Macknik, & Martinez-Conde, 2013).

EEG recordings are one of the most reliable contemporary methods to assess operator CP, and they can be collected continuously, without interfering with the tasks at hand (Borghini, Astolfi, Vecchiato, Mattia, & Babiloni, 2012; Tracey & Flower, 2014). Yet, EEG has failed to gain traction in aviation safety, due to the technical and methodological difficulties of measuring EEG in real aircraft and the intrusive and bulky nature of the equipment (Caldwell, Caldwell, Brown, & Smith, 2004; Caldwell, Hall, & Erickson, 2002; Caldwell, Kelly, Roberts, Jones, & Lewis, 1997;

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Dussault, Jouanin, & Guezennec, 2004). Studies relating in-flight EEG data to pilot CP remain scarce (Caldwell, 2004), despite early interest (Sem-Jacobsen, Nilseng, Patten, & Eriksen, 1959). Most of the research to date has taken place in fixed-wing aircraft and been limited to specific in-flight maneuvers; no published EEG studies have addressed complex and dangerous maneuvers such as takeoffs and landings (Caldwell et al., 1997) or pilot performance in rotary-wing aircrafts (i.e., helicopters). Thus, the effects of flight procedural complexity on pilot CP remain unknown, especially in rotary-wing aircrafts; these studies are critical because noise, vibration, and other environmental stressors tend to be greater in rotary than in fixed-wing aircrafts.

Here, we investigated the EEG power spectrum of military pilots in relationship to flight procedural complexity during real helicopter flights. Our results indicate that flight procedural complexity modulates the EEG power spectrum: cognitive-demanding procedures (i.e., takeoff and landing) induced higher EEG power over the higher frequency bands, whereas less demanding procedures (i.e., air work: flight exercises) induced lower EEG power over the same frequency bands. Our combined results indicate that EEG power spectrum is sensitive to variations in flight procedural complexity during real flights.

Method

Ethical Approval

We conducted the study in conformity with the Code of Ethics of the World Medical Association (WMA, 1964). The experiments were carried out under the guidelines of the University of Granada's Institutional Review Board (IRB approval #866) and approved by Spanish Air Force General Air Warfare Command (approval date: 04 January 2013). Written informed consent was obtained from each pilot prior to the study.

Participants

Pilots attended the Spanish Air Force Helicopter School (78th Air Base Wing), in Armilla (Granada, Spain), for aviation training. Eight male pilots (all 2nd lieutenants), constituting the entire rotary-wing pilot course for the 2013/2014 academic year at General Air Academy (San Javier, Murcia, Spain), volunteered to participate in the study. All pilots had normal vision and underwent a full physical examination prior to study participation. All subjects were currently on flight status, indicating recent good health, were nonsmokers, and right-hand dominant. Mean age, height, and weight (with standard deviations in parentheses) were 25.0 (2.0) yrs, 178.0 (4.9) cm, and 80 (6.3) kg. They averaged 160 ($SD = 25$) flight hours—in all fixed-wing aircraft types—and all were qualified to fly the Eurocopter EC 120 helicopter. They reported an average 7.5 h of sleep (range: 7–8) during the night previous to the evaluated flight. Before the experiment, each pilot filled in the Stanford Sleepiness Scale (SSS; Hoddes, Zarcone, Smythe, Phillips, & Dement, 1973), for screening purposes. No participants scored > 3 (had they done so, they would have been excluded from further testing; Connor et al., 2002). To control for the possible effect of chronotype on performance (Del Rio, Diaz-Piedra, Catena, Buela-Casal, & Di Stasi, 2014), subjects also completed the reduced version of the Morningness-Eveningness Questionnaire (MEQ; Adan & Almirall, 1991; Horne & Ostberg, 1976). All pilots were classified as "moderately morning type" (i.e., likely to be most alert in the morning and early evening) according to their reported preferences in sleep–wake and activity levels (as indicated by their MEQ scores). No subjects were excluded from participation based on their MEQ scores.

Experimental Design

Following a repeated measures design, the pilots operated the aircraft under several flight stages (see Study protocol) with different task complexity levels: high (takeoff and landing procedures) and low (air work procedures). Here, we recorded in-flight EEG signals during the entire flight. In addition, pilots completed several standardized questionnaires before and after the flight (see Study protocol).

Study protocol. The 78th Air Wing of the Spanish Air Force houses several training helicopters, which provide newly commissioned pilots with general skills and tactical training, including procedures to use the mission computers, communications, and navigation systems. In this study, pilots flew Sikorsky S-76C school helicopters as part of their training. The Sikorsky S-76C is a medium-sized twin engine, four-bladed helicopter. Pilots sat on the right seat, while the instructor sat on the left one. An aeronautical engineer was always on the flight. The instructor acted as pilot-in-command, supervising each flight and performing instruction tasks. Pilots were required to fly the aircraft and complete an on-air profile performing different maneuvers. Once the pilot received his preflight briefing, he was driven to the aircrew flight equipment room, and the electrodes were placed on his scalp (see EEG recording). Each flight lasted about 60 min, and the flight scenario was divided into four 15-min stages (S), corresponding to the main phases of flight (Taylor, Dixon-Hardy, & Wright, 2014): takeoff procedures (S1), two consecutive air work procedures (S2 and S3), and landing procedures (S4). Both air work stages (S2 and S3) were evaluated by the instructor and included low-speed flights, stall, and constant rate turns. During each maneuver, the pilots were required to maintain precise control over specific flight parameters (i.e., heading, altitude, airspeed, etc.) which varied across maneuvers. All pilots performed the same practical tests (i.e., the maneuvers corresponding to the sixth lesson of the basic instrument flight module from the Joint Aviation Requirement standardized syllabus (available at https://jaato.com/). The instructor evaluated how well the pilot flew (i.e., maintained headings, altitudes, airspeeds, and other parameters) at the end of each flight (see Table 1). The environmental conditions required to allow takeoff were: cloud ceiling at least 6,000 ft above ground level, 4 miles visibility, and wind of less than 10 knots. All flights were performed between 8 am and 2 pm, and under visual flight rules (i.e., a set of regulations under which a pilot operates an aircraft in weather conditions that are clear enough to allow the pilot to see where the aircraft is going).

Approximately 1 day before the experiment, the age, sex, hand dominance, and flight hours for each pilot were recorded, as well as his responses to the MEQ questionnaire. The pilots filled in several additional questionnaires in two different measuring sessions—right before (i.e., preflight) and after (i.e., postflight) the flight. These included the SSS (Hoddes et al., 1973) and an adapted version of the Borg Rating of Perceived Exertion (BORG; Borg, 1998). The SSS provided a global measure of the pilots' sleepiness, and the BORG is indicative of the level of fatigue (Di Stasi, McCamy et al., 2013; Di Stasi et al., 2014).

EEG recording. We recorded the EEG signals using a portable EEG recorder (SOMNOwatch plus EEG-6, Somnomedics, Germany). The device consisted of two small thin boxes (SOMNOwatch and EEG headbox with electrodes) fastened to the chest with flexible belts. This kind of device is generally used to record EEG during sleep (e.g., Diaz-Piedra et al., 2013), thus it is robust to movements and noise (i.e., artifacts from electrode movement that lead to changes in contact impedance or even the generation of a triboelectric response on the wires). The device sampled data at 256 Hz applying a band-pass filter (0.3–30 Hz, 24 db/octave). Recordings were stored in a memory card. We used a monopolar montage with gold cup electrodes (Natus Neurology Incorporated—Grass Products Warwick, U.S.) at five active scalp sites: F3, F4, C3, C4, and Cz placed according to the International 10/20 system (Jasper, 1958), and using the linked mastoids as the reference. We analyzed the EEG activity of channels F3, F4, C3, and C4, but not of channel Cz, whose activity was recorded by default as an internal device requirement. This combination was optimum for avoiding recording errors due to device vibration, electromagnetic interference, and pilot movements (Dussault et al., 2004).

To remove physiological artifacts from eye activity (see EEG analysis), we recorded vertical and horizontal eye movements placing an electrode ~1 cm out from the outer canthus of the right eye and another ~1 cm below the left eye. Before electrode placement, the scalp and areas around the eyes were cleaned with a slightly abrasive paste and alcohol. The electrodes were then filled with conductive paste and attached with collodion. Finally, the head was covered with a lined textile helmet—to hold the electrodes in place during flight and reduce discomfort due to the helmet.

EEG analysis. SOMNOwatch plus EEG-6 automatically subtracted the DC drift artifacts from the time series. The DOMINO Light software (version 14.0, Somnomedics) was used to export raw signals to EDF+ data format. EDF+ data were then imported, preprocessed, and analyzed using EEGLAB software, v12.010b (freely available at http://sccn.ucsd.edu/eeglab/). Finally, we used a semiautomatic artifact rejection procedure: First, a human expert (AC) visually inspected the original flight EEG recordings and detected the artifacts (e.g., muscle activity, electrode noise) by their waveform and frequency features. Eye artifacts were then corrected using an offline procedure (Gratton, Coles, & Donchin, 1983).

The EEG recording was segmented in four large consecutive nonoverlapped epochs of 15 min each, so that the first epoch comprised the takeoff stage (S1), the second and third encompassed the air work stages (S2 and S3), and the fourth the landing stage (S4). The time to walk from the equipment room to the helicopter (approximately 3 min) and then back from the helicopter to the equipment room was discarded. Each epoch was then divided into segments of 4 s in length. Segments with amplitudes out of the [−100, 10 μV] range were considered artifacts and discarded (9.1%). The fast Fourier transform implemented in the EEGLAB software was used to perform spectral analysis and calculate power spectra for the δ (0.5–4 Hz), θ (4.0–8 Hz), α (8.0–13 Hz), and β (13–30 Hz) frequency bands. Then, we computed the average power for each frequency band, channel, and epoch.

Statistical Analysis

Flight stage, channel, and the power of each frequency band were submitted to a 4 (Flight Stage) × 4 (Channel) × 4 (Frequency Band) repeated measures analysis of variance (ANOVA). Thus, data were analyzed using a within-subjects design (i.e., comparing each pilot to himself across conditions), and variability between pilots was part of the error terms. We used the Greenhouse-Geisser adjustment to correct for the violation of the sphericity assumption, thus all p values are reported with this correction. We used the Bonferroni-Holm correction for multiple comparisons (Holm, 1979). For the Borg and SSS scales, we used two separate paired t tests with the two measuring sessions (i.e., preflight vs. postflight) as the within-subjects factor. We used a single-sample t test to describe the pilots' flight performance as evaluated by the instructor. Significance levels were always set at $\alpha = .05$.

Table 1. *Effects of Flight on Pilots' Evaluations and Self-Rating Scales*

	Preflight	Postflight
Subjective assessments	*M* (*SD*), range	*M* (*SD*), range
BORG Score range: 6–20	8.3 (1.5), 6–11	9.0 (2.4), 6–13
SSS Score range: 0–7	2.0 (0.5), 1–3	2.3(0.9), 1–3
Performance evaluation Score range: 0–10	–	7.7 (0.6), 7–8.5

Note. Average, standard deviation, and range of the Borg rating of Perceived Exertion (BORG), Stanford Sleepiness Scale (SSS), and evaluation scores, calculated from all pilots ($n = 8$). Higher scores indicate higher perceived mental fatigue, sleepiness, and better performance. M = mean; SD = standard deviation.

Results

We monitored the EEG power spectrum of pilots during real flights, in relationship to high procedural complexity (i.e., takeoff [S1] and landing [S4] procedures) and low procedural complexity (i.e., air work procedures [S2 and S3]).

Effects of Flight Procedural Complexity on EEG Activity

Flight stage, frequency band, and channel modulated the pilots' EEG power spectra, $F(3,21) = 7.79$, $p < .02$; $F(3,21) = 52.34$, $p < .001$; and $F(3,21) = 7.15$, $p < .02$. Among all possible interactions (Flight Stage × Frequency Band, Flight Stage × Channel, Frequency Band × Channel, and Flight Stage × Frequency Band × Channel), only Flight Stage × Frequency Band was significant, $F(9,63) = 9.91$, $p < .01$ (Figure 1). The analysis of the simple effects of this interaction yielded significant differences between flight stages only for the higher (> 8 Hz) EEG bands (see High-frequency EEG bands). Finally, post hoc comparisons indicated that overall power in S1 was larger than S2 and S3 (all corrected p values < .05; Figure 1 inset).

High-frequency EEG bands. High-frequency EEG bands differentiated between flight stages: α, $F(3,21) = 9.05$, $p < .01$; and β, $F(3,21) = 18.61$, $p < .01$. Post hoc comparisons indicated that power in the α band was larger for S1 than for S2 and S3. Power in β bands was larger for S1 than S2, S3, and S4. Finally, power in the β band was larger for S2 than S3 (Figure 1).

Low-frequency EEG bands. Low-frequency EEG bands did not differentiate between flight stages: δ, $F(3,21) = 2.98$, $p = .11$; θ, $F(3,21) = 2.88$, $p = .11$ (Figure 1).

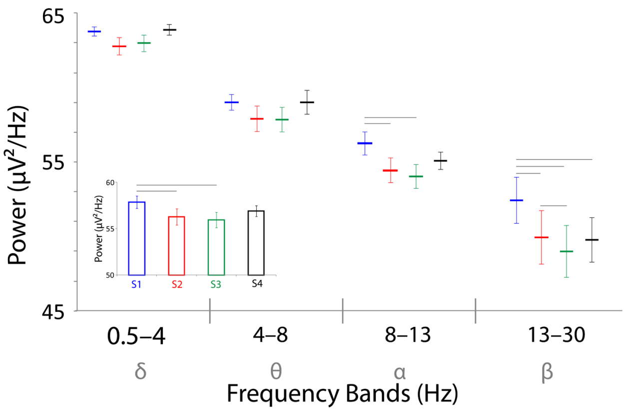

Figure 1. The effects of flight procedural complexity on EEG power spectrum. Average EEG power spectrum for each frequency band at four different flight stages (collapsing across channels): data from the first 15 min of the flight (S1: takeoff procedures) indicated in blue, from the second 15 min (S2: air work procedures) in red, from the third 15 min (S3: air work procedures) in green, and from the last 15 min (S4: landing procedures) in black. A gray horizontal line above the middle of any two means indicates statistically significant differences with a corrected p value $< .05$. Error bars represent the *SEM*. Inset: average EEG power spectrum for flight stages (collapsing across the channels and frequency bands).

To summarize, flight procedural complexity modulated the EEG power spectrum: highly demanding flight stages (i.e., takeoff and landing) were associated with higher EEG power over the higher frequency bands, and less demanding flight stages (i.e., air work) with lower EEG power over the same frequency bands. We observed an overall U-shaped pattern across the EEG spectrum (Figure 1, inset) with high complexity flight procedures—takeoff (S1) and landing (S4)—representing the external points of the pattern (quadratic trend: $F(1,7) = 8$, $p = .025$). (This trend was consistent with the data from individual subjects: 6 out of 8 pilots showed equivalent patterns). Specifically, β but not δ, θ, or α bands differentiated between S1 and S4. In addition, β band differentiated between the first (S2) and second (S3) air work periods.

Effects of Flight on Pilot Evaluations and Self-Rating of Perceived Fatigue and Sleepiness

We examined flight performance, as well as perceived fatigue and sleepiness before and after the flight, to ensure that these factors remained stable across the subjects and experiment.

Flight performance was satisfactory in all pilots (i.e., above the minimum threshold necessary to pass the examination; single-sample t test; reference constant = 5; $t_7 = 11.7$, $p < .01$, Table 1). Pilots performed the assigned tasks within accepted standards, demonstrating a well-developed sense of aircraft control, coordination, and knowledge. Perceived fatigue and sleepiness did not statistically increase from the preflight to the postflight session (Table 1; t values < 1.89).

Discussion

EEG power reflects the amount of neurons that discharge at the same time (Klimesch, 1999). This discharge generates oscillatory activities that are task dependent; that is, oscillations occur more frequently during more than less demanding tasks (Kahana, Sekuler, Caplan, Kirschen, & Madsen, 1999); thus, they are thought to be related to the cortical resources employed for information processing (Klimesch, 2012). Here, we examined how flight procedural complexity affects tonic changes in EEG signals during real helicopter flight maneuvers. Our results indicate a differential representation of high and low task complexity in the in-flight EEG of helicopter pilots.

Today's pilots, due to increased procedural complexity, face several tasks where cognitive skills are more important than physical ones (Schnell, Macuda, Poolman, & Keller, 2006). Among these is the requirement to memorize and recall standardized procedures during the entire flight. Thus, pilot memory load is generally high during flights (Schnell et al., 2006). Previous studies have found a relationship between memory load and low frequency band activity (Harmony et al., 1996; Jones & Wilson, 2005). Thus, increased activation of the hippocampus (a critical area to encoding, consolidating, and recalling memories, e.g., Carr, Jadhav, & Frank, 2011) may lead to increased power in the lower frequency bands (i.e., in the δ and θ bands) throughout the flight, as found here. It is also important to consider how pilot CP may vary across flight stages. Takeoffs and landings are the most unpredictable flight stages and require the execution of highly cognitive demanding maneuvers (Di Nocera et al., 2007; Lee & Liu, 2003; Yao et al., 2008). In contrast, air work procedures require the execution of stereotyped motor maneuvers in which cognitive demands are low (Schnell et al., 2006). Our results indicate that the pilots' CP, as measured by EEG, varied with procedural flight complexity. The following sections describe the effects of flight stage on high- and low-frequency EEG bands.

High-Frequency EEG Bands

Takeoff and landing stages are associated with higher cognitive demands than air work stages (Harmony et al., 1996; Sterman & Mann, 1995; Wilson, 2002; Wilson & Hankins, 1994). Here, we found higher EEG power in the high-frequency spectrum (α and β activity) in the takeoff and landing stages, as compared to air work stages. These results are compatible with the recently observed increase in global EEG power spectral density during airplane takeoff and landing phases, in relation to air work stages (Astolfi et al., 2011). Air work procedures were associated with lower EEG power over most of the high-frequency spectrum. Interestingly, we also found a decrease in β band from the first to the second air work stage, perhaps reflecting the effects of learning and/or time on task. That is, repetition of routine motor procedures from S2 to S3 might have lowered the task demands and thus reduced cortical activation (Fournier, Wilson, & Swain, 1999; Wilson, 2002).

Low-Frequency EEG Bands

There were no significant differences in δ and θ activity across flight stages, although these bands showed similar trends as the high-frequency bands (see Figure 1). Overall power was higher for the δ and θ activity than for the α and β activity, perhaps due to the high memory load required by the flying task (see above). Both δ and θ waves are also affected by variations in arousal levels (Eoh, Chung, & Kim, 2005). Thus, it may be that the lack of significant differences across flight stages for δ and θ activity could reflect a ceiling effect for low-frequency EEG bands in connection with arousal and/or memory load (Eoh, Chung, & Kim, 2005; Jones & Wilson, 2005). Whatever the reason for the lack of effects of flight procedural complexity in these specific bands, it is worth noting that it applied to both δ and θ waves, supporting the hypothesis that these indices behave similarly (Jap, Lal, & Fischer, 2011; Jap, Lal, Fischer, & Bekiaris, 2009).

Effects of Flight Procedural Complexity on EEG and the Potential Role of Arousal

Simultaneous EEG and fMRI recordings have recently revealed the existence of diffuse cortical and subcortical brain networks involved in the variation of the EEG power spectra during complex tasks, such as flying or driving (Astolfi et al., 2007; Borghini et al., 2012). Arousal is known to affect oscillatory brain activity (e.g., Bonnet & Arand, 2001; Shi & Lu, 2013; Steriade, McCormick, & Sejnowski, 1993). Because task complexity modulates arousal (Di Stasi, Catena et al., 2013; Wickens, 2008; Yerkes & Dodson, 1908), procedural flight complexity may modulate pilot arousal levels, which in turn could influence EEG signals. Moreover, accident risk levels—particularly during takeoff and landing stages—might play a relatively important role in arousal and cortical variations (Billeke, Zamorano, Cosmelli, & Aboitiz, 2012). Thus, in our study, the pilots' level of arousal might have adjusted according to the procedural complexity and the accident risk level of the flight stages (Dussault, Jouanin, Philippe, & Guezennec, 2005).

Our data showed an EEG power reduction across all frequency bands with increased time on flight. Previous studies have suggested that decrements in psychophysiological indices (e.g., EEG activity, cerebral blood flow, and saccadic velocity) with time on task during the performance of cognitively challenging tasks (Di Stasi, Antolí, & Cañas, 2011; Di Stasi, McCamy et al., 2013; Di Stasi et al., 2012, 2014; Lim et al., 2010; Paus et al., 1997) result from decreased activation of the sympathetic nervous system; in other words, by reduced arousal (Di Stasi, Catena et al., 2013; Di Stasi et al., 2015). Likewise, increased EEG activity during landings might indicate higher arousal than in the preceding air work flight stages, due to the increased procedural complexity and accident risk levels of landing procedures.

Our combined results indicate that EEG could be used to evaluate online CP in challenging real-life scenarios. These findings may also enhance our understanding of the relationship between brain activity and CP in complex and dynamic situations.

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