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Research article

Effects of age and flight experience on prefrontal cortex activity in airline pilots: An fNIRS study

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ABSTRACT

It is essential for airlines to have a deep understanding of the cognitive impact of aging among pilots. The current literature on executive function indicates that compensatory mechanisms in the brain may counteract age-related cognitive decline, at least up to certain task load levels. However, few studies have been administered to evaluate changes in aircrew competence as they age. The present study focuses on dorsolateral prefrontal cortex (DLPFC) activity as it is implicated in cognitive performance and working memory, which are associated with skill proficiency. We measured the DLPFC activity for airline pilots, including trainees, during maneuvering using a flight simulator. Our preliminary results indicated that only expert (aged) pilots demonstrated higher activity of the left DLPFC than the right one. However, for youth trainees, not only was the error rate high while using the flight simulator, but the activity of the DLFPC was also lower than that of the expert pilots, and there was no statistically significant difference between the left and right DLPFC. Although these findings partially differ from those reported in previous studies on age-related changes, it is evident that training as an airline pilot for over 20 years may affect such results. We believe that this noninvasive approach to objective quantification of skill will facilitate the development of effective assessment competence in aging.

1. Introduction

The number of older airline pilots in Japan is increasing. Since hazard perception is considered one of the most important competencies in aviation operations, the potential cognitive decline associated with aging is perhaps more problematic than the physical decline [1]. Understanding how age affects certain cognitive functions essential to flight crew may help flight operations adapt to age-related variations in cognitive abilities.

Abilities such as working memory, spatial attention or inhibition, which are necessary for aircraft operation, are known to be affected by age [2]. Age-related structural and functional changes in the frontal lobe are known to be a likely contributor to executive dysfunction, and atrophy of the lateral prefrontal cortex has been reported to begin in middle age [3]. Furthermore, differences have been observed between the lateral prefrontal activities of older and younger adults [4,5], which may contribute to age-related changes in performance, although it is difficult to draw causal inferences from cross-sectional studies and should be done with caution [6].

Studies on executive function that take into account the outcomesof both age and task load would be beneficial to understanding

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this issue. Various studies have indicated that, depending on the load of the performance task, comparable performance in old and young adults may be related to over-activation of the prefrontal cortex in old adults, while poor performance in old adults may be associated with comparable or lower levels of prefrontal activity compared to young adults [7–11].

Theoretical models have been advanced to explain age differences in brain activation, including the decrease in hemispheric asymmetry in older adults (HAROLD) model [12], and the compensation-related utilization of neural circuits hypothesis (CRUNCH) [13]. The HAROLD model posits that prefrontal activity has a propensity to be less lateralized in older adults than in younger ones. Meanwhile, the CRUNCH model envisions that more cortical regions would be activated as the task load increases. As pointed out by Causse et al. [11], although these models are useful and simple, the experimental data have occasionally been inconsistent. Therefore, consolidation of these models is still a challenge.

Among all noninvasive functional brain imaging techniques, functional near-infrared spectroscopy (fNIRS) provides the distinctive ability to monitor and quantify rapid functional brain activations without restraining and interfering with whole-body task execution [14]. Various brilliant MRI studies have been conducted on pilot maneuvers. However, all of them have to be subject to behavioral constraints during measurement [15–17]. Therefore, fNIRS is a favorable neuroimaging modality for studying cortical brain activations while maneuvering an airplane. So far, some fNIRS studies targeting aircraft pilots have been reported [11,18–20].

As mentioned earlier, although studies on fNIRS have demonstrated that piloting, thus far, provides beneficial information, experimental subjects have mostly been private pilots. Furthermore, although there are some suggestive reports on some airline captains [20–23], fNIRS studies on them are even fewer. Since expert airline captains are usually 40 years old or older, have a flight time of over 10,000 h, and are well-trained and evaluated regularly, the results of their brain activity may be affected by work experience. Furthermore, the present study uses a full-flight simulator of a passenger plane (Boeing 767-300), which enables the simulation of realistic conditions. We measured the activity of the left and right DLPFC under low and high maneuvers, respectively.

More specifically, this study aimed to determine the differences in brain activity and left-right differences between young and expert (aged) groups by performing fNIRS measurements under low and high task, respectively. Owing to the different age groups, changes due to aging must also be discussed. Clarifying the characteristics of a skilled pilot may lead to facilitating the development of effective aging-responsive training.

2. Results

~ Figs. 1 and 2 ~

Using a full-motion flight simulator (Fig. 1a), brain activity while descending for landing (from 1500 ft to 500 ft) was measured by fNIRS. To ensure adequate experimentation time, taking into account the fatigue for participants (within approximately 30 min), the protocol consisted of five landings: two in low maneuvers (good weather with flight director function [FD]) and three in high maneuvers (bad weather without FD) (Fig. 2).

~ Figs. 3–5 ~

First, the changes in brain activity (average of left and right DLPFC activity) during each task performed by experts (aged) and young trainees were examined. Typical change in brain activity for a single maneuver are demonstrated in Fig. 3. There were statistically significant differences in simulator scores for each task (low task between the captain and trainee: $p = 0.042$; high task between the captain and trainee: $p = 0.038$). This implies that the captain showed higher performance. However, brain activity was not statistically significantly different for each task (low task between the captain and trainee: $p = 0.19$; high task between the captain and trainee: $p = 0.16$). The average of brain activity indicated that high maneuvers showed higher DLPFC activity than low maneuvers in both groups. In other words, brain activity increased as the load increased. Although no statistically significant differences were obtained in the current study, it is interesting to note that the mean brain activity (OxyHb average) of the captain (low task: 0.032, high task: 0.041) was higher than that of the trainees (low task: 0.001, high task: 0.018) in both tasks (Fig. 4).

Second, we examined the left-right difference in DLPFC activity. In the overall result of low and high tasks combined (five landings), expert captains showed significantly more DLPFC activity in the left hemisphere than in the right one ($p = 0.0005$), whereas no significant difference was observed in the young trainees ($p = 0.12$) (Fig. 5). Therefore, the left DLPFC is indicated to be significantly differentially active in expert (aged) captains during task execution regardless of the magnitude of the load. These results may indicate

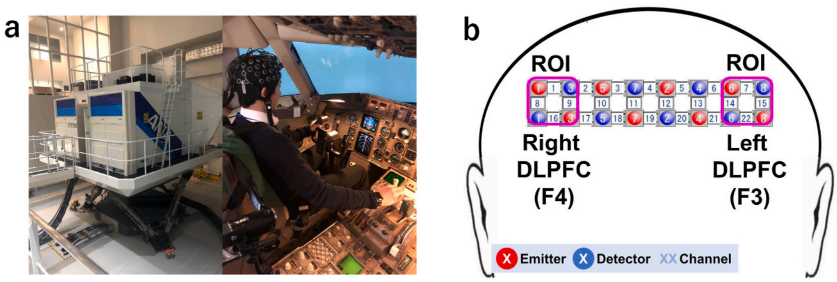

Fig. 1. (a) Boeing 767-300 twin-engine simulator at ANA Blue Base (Tokyo, Japan). Pictures have been used with written consent. (b) Schematic arrangement of the optodes allocation, target ROI (region of interest) and channels (front view). According to the distribution of the target Brodmann area (BA) contribution, the channels 1, 8, 9, and 16 for the right DLPFC (F4), and 7, 14, 15, and 22 for the left DLPFC (F3) were selected.

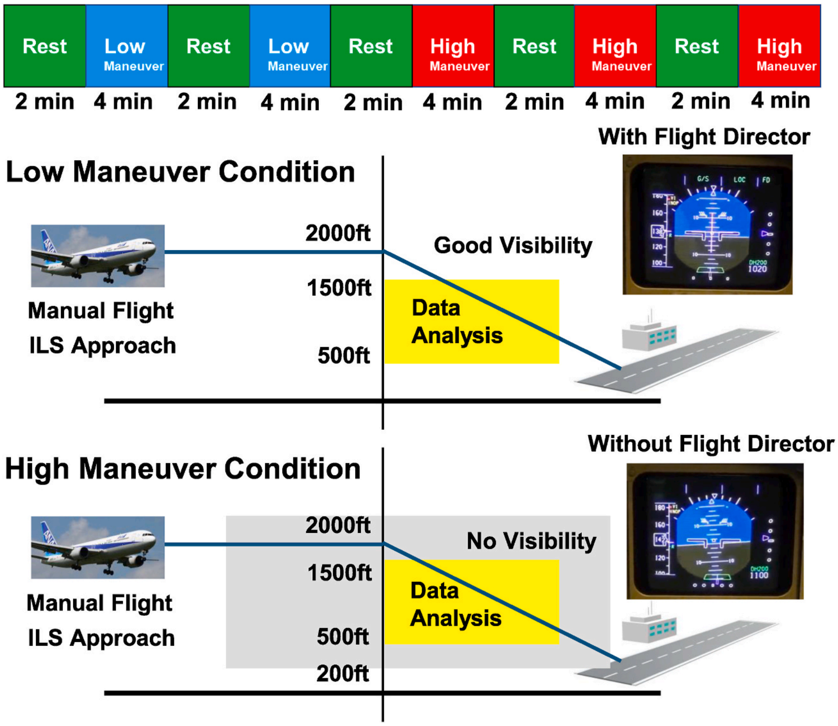

Fig. 2. Overall flow of the experiment with the five landings (two low maneuvers and three high maneuvers). The data from 1500 ft to 500 ft were analyzed (fNIRS and flight simulator scoring). Each measurement took approximately 30 min. A Boeing 767-300 full-motion simulator was used to run the experiment. It simulated a twin-engine aircraft in flight mode. The user interface consisted of a primary flight display (PFD), a navigation display, and an engine instrument display. The scenarios were as follows: After relaxing (this phase was mostly set to serve as a baseline), pilots were asked to fly straight at 2000 ft in manual mode (autopilot and auto-throttle deactivation). When approaching the instrument landing system (ILS) range, they were asked to land using ILS signals (the localizer and glideslope pointers were shown in the PFD). In the low maneuvering experiment, the flight director (FD), the equipment that shows the correct pitch and bank in good weather (i.e., good visibility and no clouds), was used. In the high maneuvering experiment, no FD was used owing to bad weather (i.e., no visibility because of clouds).

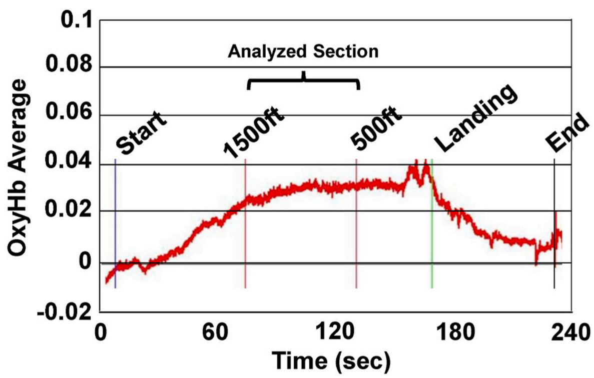

Fig. 3. Diagram of typical changes in brain activity (the average value of the concentration changes in the levels of Oxy-Hb) for a single maneuver. The sequence of changes in brain activity was as follows: After relaxing (this phase was mostly set to serve as a baseline) [Start], brain activity increased gradually, reaching a maximum before landing, and then declining gradually. The analysis interval was set as the recording between 1500 ft and 500 ft in this series of brain activity changes [Analyzed Section].

that, compared to the young trainees, the expert group responded appropriately to task difficulty by activating the DLPFC area.

3. Discussion

With the increase in the number of older pilots, it is important for aviation safety to accurately assess their cognitive abilities. Assessing the effects of aging on a highly skilled person is a matter of tact. In most fields, current metrics are human-administered and

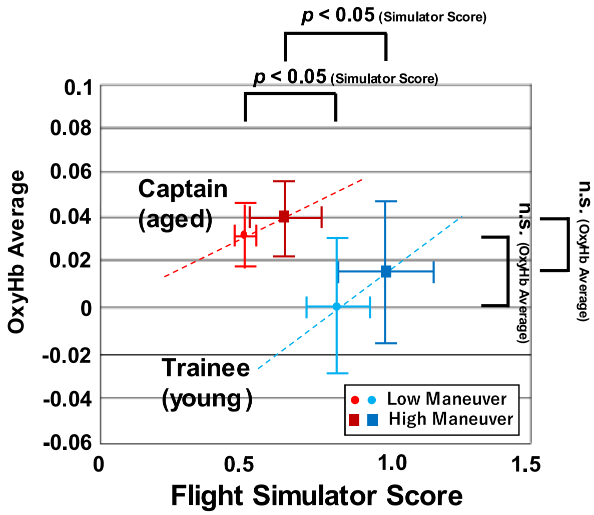

Fig. 4. Relation between averages of mean HbO2 concentration and scores from flight simulators (the lower the score, the better the performance), concerning the two groups across two levels of difficulty. The changes in brain activity (average of left and right DLPFC activity) during each task of experts (aged) and young trainees were examined. Significant differences ($p < 0.05$) in simulator scores for each task were observed. Brain activity was not significantly different for each task. The average of brain activity indicated that high maneuvers showed higher DLPFC activity than low maneuvers in both groups. Furthermore, the mean brain activity (OxyHb average) of the captain was higher than that of the trainees in both tasks, although the difference was not statistically significant. Error bars display ±2 SE mean for all cases. Two sample *t*-tests were conducted for statistical differentiation.

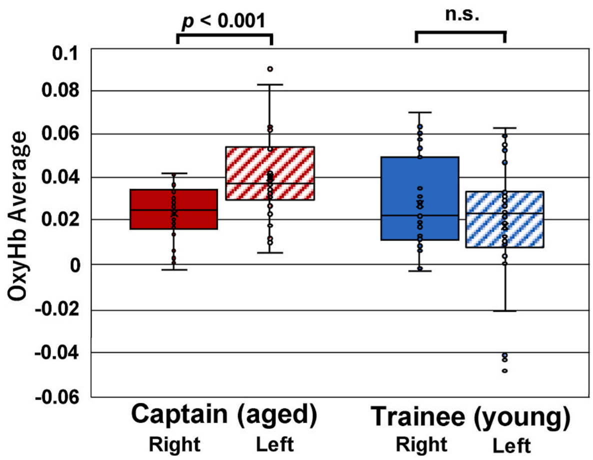

Fig. 5. Average HbO2 concentration changes when compared to the rest in the two prefrontal regions (left and right DLPFC) of interest, concerning two groups across two levels of difficulty. In the overall result of low and high tasks combined (five landings per participant), expert captains (red) showed significantly higher DLPFC activity in the left hemisphere than in the right one ($p < 0.001$), whereas no significant (n.s.) difference was observed in the young trainees (blue). The left DLPFC was significantly differentially active in expert (aged) captains during task execution, regardless of the magnitude of the load. Two sample *t*-tests were conducted for statistical differentiation.

subjective, and they demand significant human resources and time. In aviation training, the concept called "Competency-Based Training and Assessment (CBTA)" was introduced a few years ago and aims to implement effective training and evaluation [24]. Although this CBTA concept is an advanced and meaningful method, this competency evaluation is performed by incorporating the evaluator's subjectivity. The combination with the objection data that are not covered by subjective evaluation, such as biological information, is anticipated to enable us to comprehend the skills of the trainee more precisely [25], and to facilitate the development of effective age-appropriate training. Thus, there must exist some metric of evaluation that is not measured in terms of the evaluator's subjectivity. Proper indicators of aging for airline pilots who wish to be highly skilled are crucial because they are directly related to aviation safety.

The results of fNIRS while maneuvering with a flight simulator showed higher DLPFC activity in the high maneuvers, which was consistent with previous reports [11]. However, the present study showed that the DLPFC activity of expert pilots (older age group) was higher or at least equivalent to that of trainees (younger age group), and the DLPFC activity dominant in the left hemisphere was observed among expert pilots with a significant difference. These results do not support the HAROLD model, but they do support the CRUNCH model to some extent.

In general, past studies that have assessed the relationship between age and brain activity have shown that performance on the tasks used for measurement is better in younger than in older adults (older adults make more errors) [7,8,11]. In the current study, older adults performed better in both maneuvers. Thus, whether the observed difference in brain activity between the two groups (young and old) occurred due to age or performance (ability and habituation developed through training) remain unclear. Nonetheless. older adults can be assumed to be professionals with specialized training and work experience, such as airline captains. In such case, measuring brain activity in a task that is in line with actual training would be appropriate. This study appears to fall into that category.

If we consider older pilots as those with high task performance (equivalent to the young pilots in the previous study) and younger trainees as those with low task performance (equivalent to the older pilots in the previous study) based on the current results, this would also support the HAROLD model. It suggests that one of the lines of evidence is that the HAROLD model is based on ability developed through training, not age.

3.1. Difference in brain activity

The CRUNCH model predicts that more cortical areas are activated as the task load increases. Thus, compensatory activation with aging may be effective while the task is less difficult. However, as the demands increase, the resource limit is reached, processing becomes inadequate, and performance may decline relative to younger individuals [13]. Older adults progress from over-activation at low task levels to under-activation at high task levels owing to resource limits. In the present results, the older participants simulator scores were better than those of the younger participants, suggesting that they were not over-activated. The reason for the higher activity in airline captains may be as follows: The present study was critical in its measurement of the phase before landing because this final approach phase is directly linked to an accident or even a slight mistake. Therefore, expert pilots usually fly an airplane not only by proper maneuvering but also by taking into account various aspects required to prepare for contingencies. This characteristic may lead to increased engagement and high activity in the DLPFC.

Furthermore, studies have shown that older pilots with extensive, lifelong flying experience are inclined to show better preservation of performance than mildly experienced pilots of the same age group [11]. It is likely that a great level of practice can allow maintenance and improvement of proficiency in particular areas such as skills acquired through training [26]. However, young trainees might be concerned with flying an airplane in the ideal position while displaying an immature awareness of the proper engagement required during maneuvers. This may cause various DLPFC activities (recruitment of the other hemisphere) in the young pilots group [27]. The present results found no significant change in brain activity itself between the two groups (Fig. 4), although there was a significant change in the left-right difference between the two groups (Fig. 5). This is because the present results, which are based on two small subsamples, need to be confirmed with a larger group. It is also possible that the low spatial resolution of fNIRS (compared to that of fMRI) did not enable us to detect certain changes in prefrontal activity [11]. Furthermore, implementing even more difficult tasks is necessary, as the captains probably did not use all of their resources under the present conditions. Per the motivational intensity theory [28], because resources are important for survival, individuals tend to avoid wasting them and acquire only what is necessary for the success of the task. The results obtained when dealing with difficult loads, which is a highly sought-after ability for pilots, are considered suitable for testing this theory. Future studies should also compare aging effects between pilots and non-pilots and use the latter as a control group. Furthermore, comprehensive longitudinal studies examining the effects of aircraft piloting experience on brain activity are needed to clarify this hypothesis [11]. Recent breakthrough research in the technical evaluation of surgeons demonstrated that the primary motor cortex (M1) and the supplementary motor area (SMA) had increased activation in the surgical experts' group [25]. The fact that only the DLPFC area was measured in the present study is a limitation. Therefore, brain activity in other regions, such as M1 and SMA, should be investigated, and the number of subjects should be increased.

3.2. Left-right difference in DLPFC

Differences between the lateral prefrontal activity of older and younger adults have been detected [4,5], using spatial delayed-matching-to-sample tasks with varying difficulty levels [7,9,29] or using Corsi block-tapping tests with variable sequence length [10]. In these studies, at the lowest task load, prefrontal activity was left-lateralized in younger adults and either increased [10] or bilateral in older ones [8,9]. An fMRI study, however, demonstrated that DLPFC shows left-lateralization in easy working memory tasks and bilateral recruitment of the prefrontal cortex in working memory is related to task demand but not to age [30]. Therefore, assuming that the left-right difference is task-dependent rather than age-dependent, it is plausible to assume that expert pilots may not need to recruit their right-hemispheric counterparts even when engaging in high tasks. It is possible for years of training to have minimized the effects of aging on these features. One left-handed participant was present among the captains; however, his brain activity did not differ from that of others. This also may be because of the pattern and nature of thinking pertaining to goal hierarchy (the degree to which the configuration of the goal state renders the order of single steps either clearly evident or ambiguous), which shows that high left DLPFC activity may be dominant in expert pilots [31]. The use of goal hierarchy reflects the extraction of information from a problem by structurally examining the goal state. For instance, when a pilot finds a correction while maneuvering, they must consider the causal context before correcting the problem. The corrective methods should be changed according to the circumstances.

Thus, fNIRS data may provide a sound estimate of pilot mental effort, and such measurements of brain activity can provide more granular information about the amount of brain resources needed to achieve a given performance.

3.3. Limitation and future considerations

The present study had some limitations that warrant further attention. First, the study group was relatively small, and the number of trials conducted was limited, making it difficult to establish generalized conditions. This limitation might have been a reason for the lack of statistically significant findings. Nonetheless, the study's strength lay in its use of simulators identical to those used by airline pilots for actual training and screening. Second, recruiting a large number of professional pilots is fraught with difficulties. Third, the absence of a control group (e.g., young experts or old trainees) makes it difficult to interpret the statistically significant findings of DLPFC activation in expert (senior) captains with asymmetry. In this regard, establishing a control group is especially challenging because young skilled personnel are usually not present on the airlines. These difficulties could be resolved by conducting a similar study with a middle-aged group. In any case, further research is needed.

4. Method

4.1. Participants

Six airline captains (six males; mean age 48 ± 4 years; one of them left-handed) and trainee pilots (six males; mean age 24 ± 2 years; all six right-handed) participated in this study. None of the participants reported a history of psychiatric or neurological disorders. All of them belonged to All Nippon Airways, a Japanese airline company. The cumulative flight experience was 120 h (±72 h) and 10,490 h (±1260 h) among the young trainees and experts' group respectively. All methods were performed according to the relevant guidelines and regulations. The participants visible in Fig. 1a provided their informed consent for the publication of their identifying images.

4.2. Experimental design

The protocol consisted of five landings in a flight simulator: two in low maneuvers and three in high maneuvers (Fig. 2). A Boeing 767-300 full-motion simulator at ANA Blue Base (Pilot Training Center in Tokyo) was used to administer the experiment (Fig. 1a). It simulated a twin-engine aircraft in flight mode. The user interface consisted of a primary flight display (PFD), a navigation display, and an engine instrument display. The scenarios were as follows: After relaxing (this phase was mostly set to serve as a baseline), pilots were asked to fly straight at 2000 ft in manual mode (autopilot and auto-throttle were deactivated). When approaching the instrument landing system (ILS) range, they were asked to land using ILS signals (localizer and glideslope pointers were shown in the PFD). In the low maneuvering experiment, FD, the equipment that shows the correct pitch and bank in good weather (i.e., good visibility and no clouds), was used. In the high maneuvering experiment, no FD was used owing to bad weather (i.e., no visibility because of clouds). Before starting the experiment, the participants performed a 30-min training session to familiarize themselves with the simulator's environment. For analysis, data gathered during maneuvering from 1500 ft to 500 ft were used (Fig. 2).

4.3. fNIRS data acquisition

We recorded the hemodynamics of the prefrontal cortex using a multi-channel fNIRS device (LIGHTNIRS, Shimadzu Corporation, Japan) during the simulated landing experiments. Sixteen optodes were placed with a 3 cm source-detector separation in the prefrontal region. Each of these source detector pairs generated one channel. This layout resulted in a total of 22 channels (Fig. 1b). The intensity of light propagating in the brain was acquired at 13.3 Hz using continuous 3-wavelengths (780, 805, and 830 nm). The concentration changes in the levels of oxygenated hemoglobin (Oxy-Hb) and deoxygenated hemoglobin (Deoxy-Hb) were calculated from the changes in detected light intensity based on the modified Beer Lambert law. The data were preprocessed with a low-pass filter and a cutoff frequency of 0.1 Hz to remove noise. We extracted the functional component using a pretreatment and hemodynamic modality separation method algorithm [32]. Baseline correction was performed to set the task starting point of each data to zero. After these processes, the average value of the concentration changes in the levels of Oxy-Hb in the flight from 1500 ft to 500 ft was computed. Fig. 3 demonstrates a diagram of typical changes in the average value of the concentration changes in the levels of Oxy-Hb (brain activity) for a single maneuver.

4.4. Target region of interest and channels

In this study, we identified the target Brodmann area as BA46 (DLPFC). The region of interest (ROI) was set as follows: Channels 1, 8, 9, and 16 for the right DLPFC (F4), and 7, 14, 15, and 22 for the left DLPFC (F3) (Fig. 1b). We digitized each participant's channel position using the Fastrak 3D digitizer (Pohhemus, US) with input to the standard brain model. We also obtained Montreal Neurological Institute coordinate outputs using the NIRS-SPM software Ver. 4 (Department of Bio and Brain Engineering. KAIST, Korea) to collect brain anatomical information from the measurement channel [33].

4.5. Statistical analysis

Three-way repeated-measures ANOVAs were employed to analyze concomitant prefrontal activity (as reflected by HbO2 concentration), with a within-subjects factor of task difficulty, a between-subjects factor of age group, and a within-subjects factor of prefrontal ROI. Post-hoc contrasts were conducted using Fisher's least significant difference (LSD) with Benjamini-Hochberg false discovery rate (FDR) multiple testing correction [34,35]. All results were considered significant at $p < 0.05$.

4.6. Scoring using instruments from a flight simulator

Scoring was done through the instruments of the flight simulator during maneuvers from 1500 ft to 500 ft. Using the capabilities of a flight simulator (The Debriefing System), The deviations from the ideal value of each parameter (airspeed, pitch, heading, bank, glideslope, and N1 (the value of engine thrust setting)) were integrated, and the average and standard deviation values were computed. To compare the different values of units, the sum of the coefficient of variation (CV) was adopted for scoring. For example, the airspeed set in this experiment was 139 knots (kt). The mean and standard deviation were determined by the displacement (delta airspeed) from 139 kt over time (10 plots per second). When we obtained the mean and standard deviation of delta airspeed (0.774 kt and 0.445 kt, respectively), the CV was calculated to be 0.575. Other values were also calculated for deviation from the ideal value determined by the aircraft condition. The lower the score, the better the performance (Fig. 4).

Ethics declarations

This study was reviewed and approved by the ethics committee of Osaka University Hospital, with the approval number G21327. All participants provided informed consent to participate in the study.

Data availability statement

The datasets generated and/or analyzed during the current study are not publicly available because the participants did not consent to the sharing of data with third parties.

CRediT authorship contribution statement

Kenji Kawaguchi: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Data curation, Conceptualization. **Yohei Nikai:** Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Satoshi Yomota:** Visualization, Validation, Methodology, Investigation. **Akisato Kawashima:** Methodology, Investigation, Conceptualization. **Yoshihiro Inoue:** Visualization, Validation, Methodology, Investigation, Data curation, Conceptualization. **Makoto Takahashi:** Visualization, Validation, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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