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OBJECTIVE EVALUATION OF HUMAN PILOT OPERATIONS IN WIND SHEAR USING PSYCHOPHYSIOLOGICAL MEASUREMENTS

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Abstract

With the development of onboard Light Detection and Ranging (LIDAR) systems, it will be possible to measure the wind velocity field up to several miles ahead of an aircraft when flying in clear air. We investigate how this information can be relayed to the pilot in a meaningful way, in order to reduce accidents, incidents, or inconvenience caused by strong turbulence and wind shear. In this paper, we will focus on the objective evaluation of the pilot's use of such a new interface, through analyses of the pilot's control actions, as well as psychophysiological data obtained from an eye-mark camera, an electrocardiogram (ECG; heart rhythm) and electroencephalogram (EEG; brain waves). We present two preliminary experiments with 3 subjects each. The first experiment showed promising results, but suffered from significant artifacts due to the fact that subjects were expecting the occurrence of a discrete event (windshear). The second experiment used a secondary task, which provided additional and valuable data, but probably obscured part of the changes in the measured psychophysiological parameters.

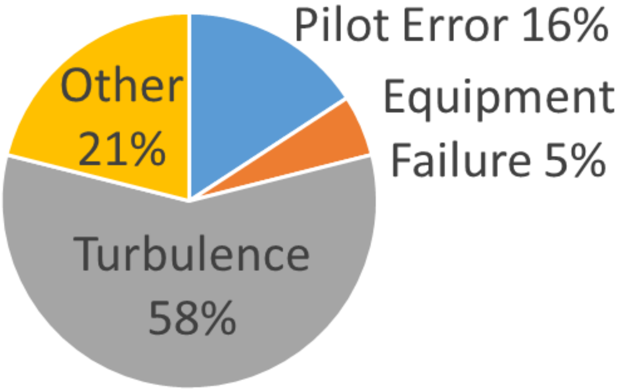

Fig. 1 Main accident causes in Japan between 2004 and 2013 (by domestic air carriers that operate aircraft with 100 or more passenger seats or with a maximum takeoff weight of more than 50,000 kilograms) [1].

1 Background

More than 50% of the Japanese domestic airline accidents over the past 10 years were caused by turbulence (Fig. 1) [1].

1.1 The SafeAvio project and LIDAR technology

The Japan Aerospace eXploration Agency (JAXA) is carrying out a project under the name "SafeAvio", which focuses on "Research and development of onboard safety avionics technology to prevent turbulence-induced aircraft accidents" [2]. Whereas turbulence accompanied by rain clouds can be detected to some degree by weather radar, it is still difficult to foresee clear air turbulence. To change this, JAXA has been developing an onboard Doppler light detection and ranging (Doppler LIDAR) system that uses laser beams to detect clear air turbulence ahead of the aircraft [3][4].

The LIDAR system can measure wind changes up to ca. 15km (±1 minute) ahead at cruise altitude and even farther during the landing. However, since it relies on the Doppler-effect, only wind speed changes in the direction of measurement can be detected. It is therefore difficult to predict vertical and lateral wind components.

The LIDAR system provides an extension

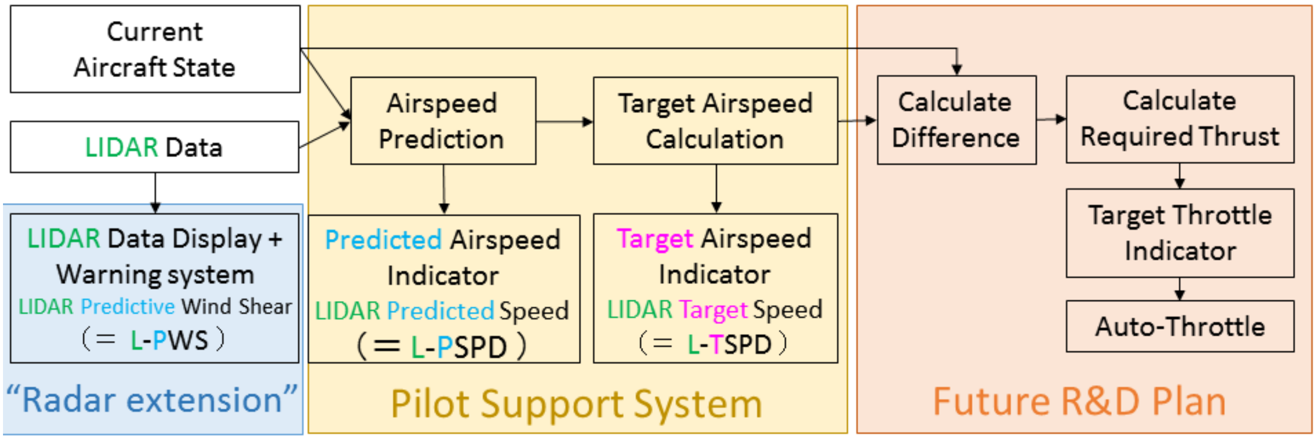

Fig. 2 Overview of the proposed SafeAvio systems using data measured by the onboard LIDAR.

to the current RADAR system by supplying additional information in clear weather. A "Predictive Wind Shear (PWS)" caution/warning system using LIDAR data can be developed analogous to the current RADAR-based PWS system. However, since the LIDAR data is more detailed (albeit with less coverage), it can also be useful to guide the pilot through areas with rough air (Fig. 2).

The SafeAvio project considers two main scenarios: strong turbulence during the cruise phase of flight, and windshear, downbursts, or other strong turbulence during the landing approach. In the former case, the pilot can instruct the cabin crew and turn the seatbelt signs on. In the latter case, the pilot will have to decide to land or go-around depending on the severity of the situation. In both cases, the pilot (or an automated control system) should try to stabilize the plane as best as possible during the turbulence.

The University of Tokyo (UTokyo) works in collaboration with JAXA on the development and evaluation of pilot support systems and automatic flight control algorithms utilizing the data measured by the onboard LIDAR system (Fig. 2). An important part of such support systems is to visualize the LIDAR data in such a way that the pilot can easily obtain and understand the most relevant information.

1.2 Human Factors

A pilot's ability to safely operate an aircraft is not limited to the pilot's skill, but includes for example also the availability of information and the human-machine interface design. In the evaluation of this operational safety (which depending on the cases compared can be an evaluation of the pilot, or an evaluation of a new human-machine-interface) we can distinguish the following 3 levels:

1) **Performance.** This is the minimum requirement. If safety-limits are exceeded, it is evaluated worst. If performance is within reasonably narrow limits, a small performance improvement won't affect the safety evaluation score.
2) **Situational Awareness.** This reflects the pilot's level of understanding of the current aircraft state, and his/her ability to "look ahead" (predict the future state; foresee problems before it is too late). If performance is within reasonable limits, maximizing situational awareness will be beneficial to ensure future performance, and thus increase safety margins.
3) **Spare Capacity.** This is how much (cognitive, mental, memory) resources the pilot still has available for other tasks. If the base workload is already high, an additional emergency is likely to saturate the pilot's capabilities and badly affect Situational Awareness and Performance.

In short: given sufficient performance, we want to maximize situational awareness and spare capacity. This justifies time spend on additional practice and training after meeting the minimum requirements.

Performance is relatively easy to measure objectively and quantitatively, as long as the simulator or aircraft outputs its state at a sufficiently high frequency and resolution. Still, from the wealth of data available, often only a single parameter, such as the path tracking error, is used. This ignores the fact that flying an aircraft safely is a multi-objective optimization problem, and the pilot often has to deal with vague, implicit, and conflicting objectives. We therefore advocate evaluating a variety of aircraft states, as well as the pilot's control input patterns.

Situational Awareness is more difficult to evaluate. Evaluations are often subjective, through rating scales, questionnaires, or interviews. Smart experiment design might measure the effect of (a lack of) awareness of a specific piece of information through an analysis of an (expected) behavioral change. In some cases, the performance on an (artificial) secondary task can be used as a measure of situational awareness.

Spare Capacity, or actually the opposite: workload, is generally assessed subjectively through ratings. This may work with professional test pilots, who have been selected for their meta-cognitive skills and trained to be (self-)critical, and have a large knowledge base to make relative comparisons, but at best this still is only a single, subjective aspect of workload. Adding secondary tasks of increasing difficulty until performance degrades is another method to measure spare capacity, but it may lead to complex or unrealistic scenarios. Psychophysiological measurements can add an objective evaluation.

1.3 Ongoing Research

Traditionally, both trainee pilots and new human-machine interfaces have been evaluated mostly subjectively, sometimes in combination with a few simple performance measures. Such evaluation looks only at a small part of the factors influencing flight safety. At the UTokyo, we have been developing objective measures of pilot control style and workload using control input data and psychophysiological measurements. We previously presented an early report such techniques applied to curved versus straight-in approaches [5]. The current research develops these ideas further and aims to apply them to evaluate the pilots' use of our proposed LIDAR data based pilot support systems in the case of (predicted) windshear landings.

The current research collaboration with JAXA, a 2.5 year project that started in the summer of 2014, consists of the following 4 phases:

1) Develop & propose new "SafeAvio" display designs
2) Develop & propose evaluation methods for the SafeAvio display designs
3) Evaluate the appropriateness of these evaluation methods
4) Evaluate the SafeAvio display designs

At the time of writing of this paper, we are in phase 3.

In section 2 we briefly outline the proposed display design. In section 3 we discuss an early experiment where we measured pilot's reactions to audio warnings of a reactive (not predictive) windshear alert system. Section 4 deals with the proposed evaluation methods and a preliminary experiment to evaluate the appropriateness of those methods. We conclude this paper in section 5.

2 SafeAvio LIDAR Based Pilot Support Displays

Figure 3 shows an impression of the Primary Flight Display (PFD) and Navigation Display (ND) as they can be found in any modern airliner cockpit. The leftmost part of the PFD shows the airspeed information. A "speed trend vector"[1] is typically displayed next to the

[1] a vertical arrow of varying length that indicates what the airspeed will be in 10 seconds if the acceleration or deceleration trend continues

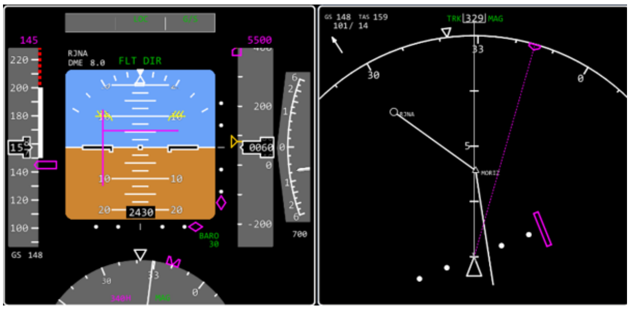

Fig. 3 Primary Flight Display (PFD, left) and Navigation Display (ND, right).

current airspeed value. The currently set target airspeed is indicated numerically in magenta at the top of the speed tape, and as a magenta "bug" at the respective value on the tape. Radar data is displayed on the ND.

In clear weather no radar data will be available, but the LIDAR may provide wind speed data. This data will be visualized on the ND, similar to the way Radar data is shown, but recognizable as being LIDAR sourced. The LIDAR data will be further processed and predicted airspeed fluctuations will be shown in between the airspeed indicator and the virtual horizon display on the PFD. In case pilot action is required, a target airspeed is calculated and displayed similar to the current target airspeed indications, but recognizable as being LIDAR sourced. Figure 4 summarizes the functions of each display.

Further details or illustrations of the proposed SafeAvio displays cannot be presented at this time, because we are preparing for a patent application.

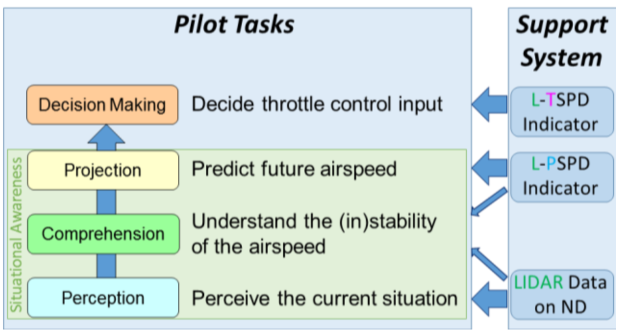

Fig. 4 Intended support functions of the SaveAvio display features.

3 Windshear Warning Experiment

We performed an initial experiment to see how pilots react to the current reactive windshear warning system. In clear air, no radar data can be obtained, so the predictive windshear system will not be able to give any alert. Therefore, our reference case to compare the LIDAR based system against, will be the reactive windshear system.

3.1 Materials & Methods

For the experiment we used the fixed-base Boeing 747-400 simulator at the UTokyo (Fig. 5). Three subjects flew 8 approaches each with severe low-level windshear. They flew 4 approaches without warning callout on the first day, and 4 with warning callout on the second. All 3 subjects were male. One had relatively little experience flying the simulator (UTJ), the other two had much experience (UTM, UTU), of which one (UTU) is a retired airline pilot with real 747-400 experience. .

Fig. 5 Boeing 747-400 simulator at the University of Tokyo and the Takei TalkEyeLite and NAC EMR8 eye-mark cameras, ParamaTech EP-301 portable ECG recorder, and eMotiv EPOC+ eeg headset..

The simulator states were logged at 20Hz, eye-mark data (pupil diameter, gaze direction, blink detection) was taken at 60Hz using the NAC EMR8, and electrocardiogram (ECG) data at 256Hz using the ParamaTech EP-301 (Fig. 5). Brainwave data (electroencephalogram, EEG) were not recorded in this experiment.

Before and after the experiments, reference eye and heart data were taken while relaxing

3.2 Results

Analysis of the psychophysiological data showed very different patterns for the cases with and without warning callouts. A typical example is shown in Fig. 6. If we look at the pupil diameter, a measure for (cognitive & memory) workload [7][8], we can note the following. In the case of no warning, the pupil diameter steadily increases, reaches a high during the windshear and then decreases. In the case an audio warning is present, the pupil diameter doesn't change much except for a short jump at the warning callout.

For the heart rate (stress, arousal [9]) we see the opposite: little variation in the case without warning, and a clearly increasing heart rate in anticipation of the warning. Since both experiments were on different days, absolute values should not be compared.

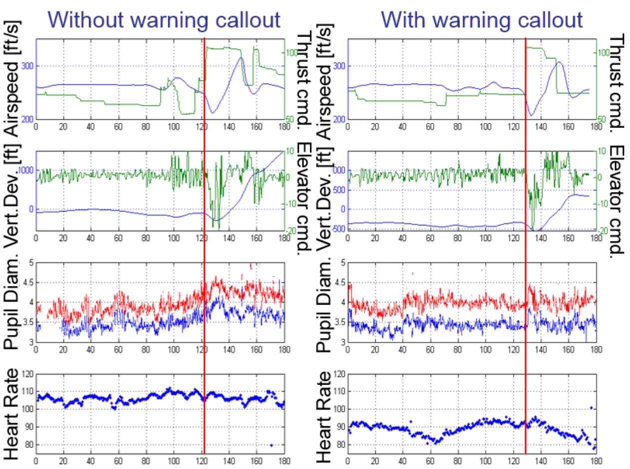

Fig. 6 Typical results of severe windshear landing experiments with and without audio warning. From top to bottom:Airspeed(blue) and Throttle setting(green), Vertical deviation (blue) and Elevator command (green), Left/Right pupil diameters (blue/red), and Heart rate. The vertical red line indicates the onset of the windshear.

3.3 Discussion

The results indicate that these psychophysiological measures are sensitive to changes in the experiment conditions, and are therefore potentially useful for the evaluation of pilot behavior and the effectiveness of a pilot support system. However, the current experiment setup, where the pilot knows to expect windshear and even knows whether or not he will be warned when to initiate the go-around procedure, is clearly visible in the results. This could obstruct a meaningful evaluation (although this setting is similar to the routine checks pilots do in airline simulators).

The pilot's pupillary response in the "without warning callout" case could be explained from the pilot's prior knowledge of the experiment case. Knowing that there will be windshear, and knowing that there won't be a warning, the pilot actively searches for (visual) cues that he can use to decide when to take action. Similar pupil behavior was reported by Privitera et al. [5].

The increasing heart rate in advance of the audio warning is thought to reflect the increased arousal/readiness of the pilot. Without any specific workload increase (just wait until the warning sounds, then execute the trained response), there is not much more to it than that.

4. Evaluation Methods and their Evaluation

This section will describe the proposed objective evaluation methods and discuss the preliminary experiment we carried out to verify their appropriateness. In the experiment, we focus on the evaluation of the LIDAR-based predicted airspeed indicator (L-PSPD) in a continuous task. That is, there is no discrete event such as a windshear alert, but the pilot has to maintain steady flight in rough air.

Subjective evaluations, including a modified version of the Situation Awareness Rating Technique (SART) [11] and a rating using the Bedford Workload Scale [12], are also considered. However, these are coordinated by JAXA and will be discussed in another publication.

4.1 Equivalent Task for Evaluation

To evaluate the validity of the proposed evaluation methods, we developed an experiment with an information display change similar in nature to the addition of the SafeAvio display. The L-PSPD display is intended to support the pilot's ability to "look ahead" and predict the future airspeed. Not dissimilarly, pilots use the pitch indicator (artificial horizon) as an inner loop "look ahead" control for vertical deviation (see e.g., [13]). The artificial horizon is a well-established and proven useful instrument. We therefore decided to use "Without/With artificial horizon pitch display" as an equivalent of "Without/With SafeAvio L-PSPD display" (Fig. 7). If our evaluation methods would not work on this equivalent task, it would be unlikely that they would on the actual SafeAvio evaluation task.

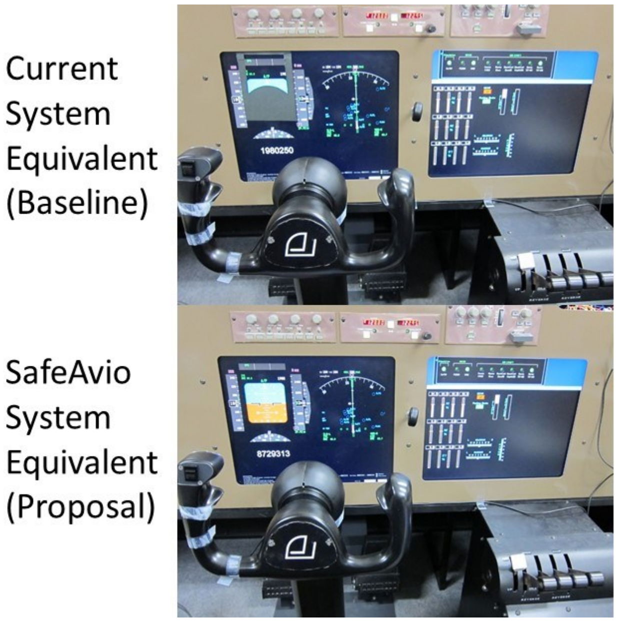

Fig. 7 Experiment setup with obscured pitch display (above) as equivalent to the current display where "looking ahead" control is impossible, and the improved display design with pitch as equivalent for the proposed SafeAvio display.

4.2 Materials & Methods

4.2.1 Primary Task

We used the Boeing 747-400 simulator (fixed base training device) at the UTokyo (Fig. 5).

The subjects were asked to manually control the simulated aircraft to maintain level flight at 2000±50ft altitude and 180±5kt airspeed. They could only use the cockpit instrument displays (the outside visuals were turned off). There was light random turbulence. In half of the trials, the pitch display was obscured, in the other half it was visible.

4.2.2 Secondary Task

We used a classic Sternberg task [14] as secondary task in 6 of the 8 trials per subject. No secondary task was used in the remaining 2 trials. The flow of the task is shown in Fig. 8.

The subject has to remember 7 digits shown at random intervals, respond with a button click whether or not a test digit shown later was contained in the original series, and the call out loud the original 7 digits as well as he remembers. At the time the test digit was shown, a beep sound was played. At least 10 numbers were shown in each trial. Two pushbutton switches were attached to the back of the yoke for the user to respond whether (upper switch) or not (lower switch) the test digit was contained in the original number.

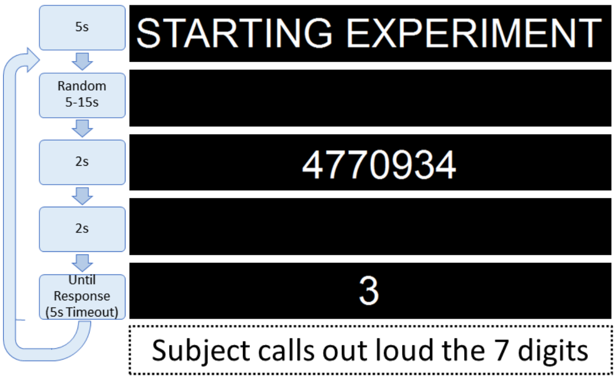

Fig. 8 Flow of the secondary task.

4.2.3 Measuring Equipment

The simulator states were logged at 20Hz. Eye-mark data (pupil diameter, gaze direction, blink detection) was taken at 30Hz using the Takei TalkEyeLite. Electrocardiogram (ECG) data was recorded at 256Hz using the ParamaTech EP-301. Brainwave data (electroencephalogram, EEG) were recorded using the eMotiv EPOC+ at 128Hz. All are depicted in Fig. 4.

4.2.4 Participants

3 male subjects participated in this experiment. One had simulator experience in another

simulator (JXC), the other two had much experience in this simulator (UTM, UTU), of which one (UTU) is a retired airline pilot with real 747-400 experience.

4.2.5 Trials

Each subject flew 8 trials of 3minutes each. Two subjects flew the first 2 trials with pitch display, then 2 without, then 1 with, and 1 without respectively. Finally they flew trials without secondary task: 1 without and 1 with pitch display, respectively. The third subject flew the trials with the with/without pitch display trials inverted. After each set of 2 trials, there was a short break, where subjective data were collected.

4.2.6 Analysis

Primary task performance was calculated as the root mean square (RMS) of the airspeed deviation (difference from 180kt) and the RMS of the altitude deviation (difference from 2000ft). We also calculated these RMS values considering dead-bands of ±5kt and ±50ft respectively, and dead-bands of ±10kt and ±100ft respectively.

Secondary task performance was expressed as the number of correct clicks, number of timeouts, average time between the appearance of the test digit and the subject's button click, and the total number of wrong or missing digits in calling out the 7 digit numbers. If more than 10 numbers were shown during the 3minute trial, the evaluation was limited to the first 10 numbers.

From the eye camera data we calculated the blink rate and average pupil diameter after filtering the data around blinks.

From the ECG we calculated the average and standard deviation of the heart rate (HR), and an index of mental effort (ME) based on the power spectrum density of the sinus arrhythmia (heart rate variability) in the frequency band from 0.06 to 0.14 Hz (see [5]).

From the EEG we calculated the activity in the various power spectrum bands, and specifically the average frontal theta activity. All analysis were performed after applying a 1-40HZ bandpass filter and removing the baseline using EEGLab, and additional filtering of blink and muscle related signals using the AAR plugin.

Control style analysis was performed by visualizing the subject's elevator control inputs using a power spectrogram.

4.3 Hypotheses

An overview of our hypotheses is given in Table 1.

If there would be a discrete event, we would expect the increased situational awareness due to SafeAvio indicators leads to higher arousal/readiness and thus increasing heart ahead of the actual event or alert (according to the results presented in the previous section).

Table 1 Hypotheses

		With SafeAvio L-PSPD			
OBJECTIVE	Main Task Performance	⇧	Simulator data	RMS error	⇩
	2nd Task Performance	⇧	2nd task data	Score	⇧
	Visual Workload (Scanning)	⇧	Eye data	Dwelling time	⇧
			Eye data	Blinks	⇩
	Average Workload	⇩	EEG	Frontal Θ	⇩
			ECG	HRV	⇧
	Peak Workload	⇩	EEG	Frontal Θ	⇩
			ECG	HRV	⇧
			2nd Task	Timeout	⇩
SUBJ.	Situational Awareness	⇧	Modified SART	Score	⇧
	Workload	⇩	Bedford scale rating	Score	⇩

4.4. Results

An overview of the objective performance results of primary and secondary tasks is shown in Fig. 9. As expected, the RMS of airspeed and altitude deviation are smaller in the SafeAvio-equivalent "with pitch display" trials. A one-way ANOVA of the differences between "with" and "without pitch display" was significant at

1%-level for the first subject (UTU, the retired airline pilot) (F(1,6)=17.13, p= 0.0060 for airspeed and F(1,6)=17.33, p= 0.0059 for altitude) From the analyses with dead-band, we can also that the most extreme altitude deviations occurred in the "without pitch display" trials.

The total number of correct responses on the secondary task is also slightly higher in the "with pitch display" trials. For UTU and JXC, timeouts only occurred in the "without pitch display" trials. The average response time (excluding timeouts) is slightly faster in the "with pitch display" trials for UTU and JXC, and unchanged for UTM. The number of mistakes or omissions in calling out the remembered numbers varies widely (see also the discussion section).

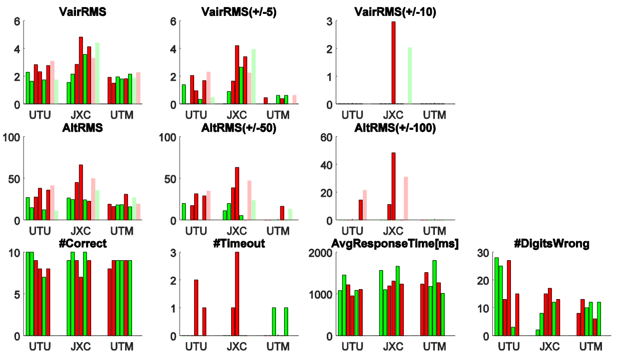

Fig. 9 Objective performance data of primary and secondary task for all 3 pilots and all cases. Green/Red: With/Without pitch display. Pastel colors indicate experiments without secondary task.

A quick analysis of the eye data did not show any significant results. However, in several trials the reported blink rate is so high that we suspect other reasons for missing data points, for instance calibration or data synchronization errors. Further analysis of the data and equipment verification will have to clarify this.

No significant differences were found in the average heart rate (none were expected). The average heart rate variability (HRV) was higher (meaning lower effort required) in the SafeAvio-equivalent "with pitch display" trials for all 3 subjects. Only for JXC this difference was significant (at 1%-level; F(1,6)=14.38, p= 0.0091). This is in line with our hypothesis.

Analysis of the brainwave (EEG) data showed higher activities in various power spectrum bands for several subjects in the "with pitch display" trials. However, these differences did not reach significance.

The control elevator inputs and spectrograms of UTU and JXC are shown in Fig. 10 and Fig. 11, respectively. The pattern for UTM is similar to that of UTU. For UTU, we see more and larger control inputs when the pitch display is available. For JXC we see that the control input period changes remarkably from 4-8s to 8-12s cycles.

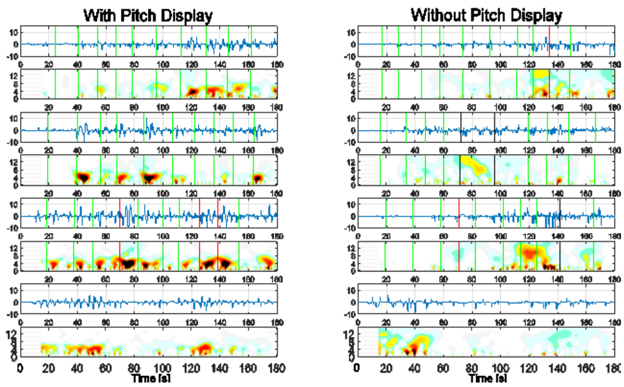

Fig. 10 Elevator control input time histories and spectrograms of veteran pilot UTU. Left/Right: With/Without pitch display. Colored vertical lines indicate correct(green), incorrect(red), or timeout(black) secondary task responses. The bottom trials are withyout secondary task.

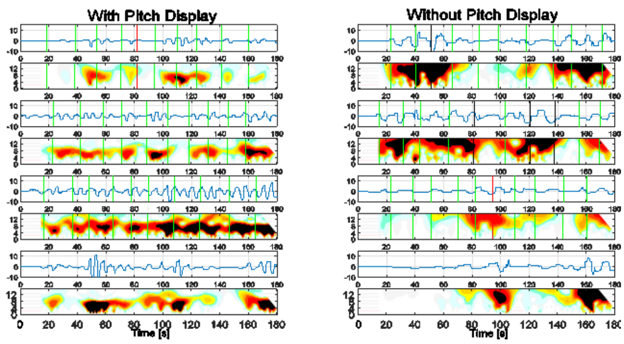

Fig. 11 Elevator control input time histories and spectrograms of JXC. Left/Right: With/Without pitch display. Colored vertical lines indicate correct(green), incorrect(red), or timeout(black) secondary task responses. The bottom trials are withyout secondary task.

Finally, Fig. 12 shows an overview of the main result parameters over one of the 180s trials. It is interesting to see how the various parameters such as deviations, control actions, and second task response times, timeouts, and recall performance correlate with each other.

Subjective ratings were in line with the hypotheses.

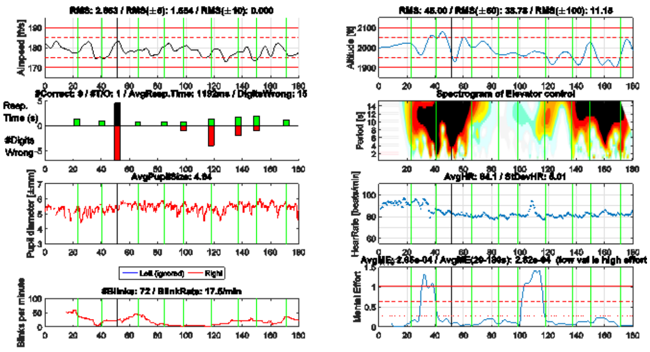

Fig. 12 Part of the analysis results of JXC's first trial without the pitch display.

4.5 Discussion

4.5.1 Secondary Task

Calling out the remembered numbers in the secondary task seems to be a significant burden for the subject. It also requires careful note-taking of the numbers called out, preferably by multiple people. This may have been a problem in the first 2 trials of the first subject (UTU). The score of wrong digits or omissions is also sensitive to the way interchanged digits are dealt with for example.

Another problem of a demanding secondary task is that the subject will use up all his “spare capacity” to perform well on the secondary task. This obscures the possible psychophysiological effects of changes in the primary task. Therefore, we are considering to use a simpler task where we only record response time in future experiments.

4.5.2 Control Style Changes

We noted changes in control style observed from the spectrograms. We believe the fewer and smaller control inputs of UTU (and UTM) in the “without pitch display” case may have been because they were careful to over-control while they had insufficient information. This may have been an effective approach since the turbulence in the experiment was relatively weak. Stronger turbulence should be considered in future experiments.

The changes of JXC's control, with a clear decrease of control input frequency, are closer to the expectation, since “inner loop” pitch control has become impossible, and altitude and airspeed changes only become visible at longer time spans.

4.5.1 Psychophysiological Measures

Eye and brainwave data did not provide clear results. This is partly due to measurement errors that could have been reduced with more careful calibration and taking proper reference data after each re-calibration. We will also have to review data to more carefully remove artifacts due to body movements, talking, etc.

5 Conclusion

We proposed new systems to support the pilot when encountering clear air turbulence. We also proposed various objective measures for the evaluation of the pilot's use of such new systems. The two experiments showed useful results and we discussed some issues to be kept in mind for future experiments.

We note that the number of subjects in the experiments was small, and that only one subject had actual professional flight experience. However, the addition of a variety of objective and psychophysiological data to the evaluation human-machine interfaces can provide new viewpoints. One interesting benefit of objective data is that it can be obtained continuously, in contrast to subjective ratings, which essentially give an overall evaluation over the whole trial.

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