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Analysis of Pilot's Cognitive Overload Changes during the Flight

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Abstract:

In this article, the research aimed at determining the impact of the intensification of actions on the pilot's cognitive load in a simulated flight is presented. The tests were divided into two groups: pre-flight verification tests and flight tests of increasing intensity. The work was carried out at flight simulator CKAS MotionSim5. Based on the collected data, it has been proved that along with the intensification of the tasks imposed on the pilot, the level of his cognitive load also increases. Further inference leads to the conclusion that cognitive overload is one of the main reasons for pilots' mistakes. The linear relationship between experience and cognitive load has also been proven in the studied group.

Keywords:

cognitive overload, flight simulator, flight time

1. Introduction

An increase in world air traffic is observed annually. The forecasts of aircraft manufacturers and aviation authorities indicate a trend in which the annual increase is about 5-10%. A gradual growth in flight operations in the Warsaw FIR has also been noticed [1, 2].

Undoubtedly, the key benefits of air transport are speed, accessibility and safety. With the increase in demand for aviation-related services, the entire air transport market has faced the problem of a shortage of trained staff. This deficiency is most evident in the case of aircraft pilots. As a result, the shortage of qualified pilots enhances high complexity, difficulty and cost of training of crews. The second aspect limiting the number of candidates for future pilots are rigorous medical examinations resulting from high health (physical and psychological) requirements.

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In order to reduce the risk related to the personnel, a number of technical improvements are made in the aircraft cockpit. The combination of inexperienced pilots with a technically and IT complex aircraft results in the risk of pilot overload by working on overseeing all aircraft on-board systems. Similar work conditions can lead to cognitive overload involving too many stimuli received by pilots.

A common thesis is that the highest percentage of aviation accidents and incidents is caused by pilot errors [3]. Therefore, it was decided to examine the impact of pilot load represented by an increase in the number of tasks to be performed on the level of pilots' cognitive load. The impact of experience on the occurrence of load symptoms in flight will also be analysed.

In the initial part of the work, theoretical foundations on the basis of which the thesis was formulated will be presented. Next, the research methodology will be presented. In addition, the results of the work presented earlier will be analysed.

2. Cognitive Processes in Pilot's Work

The analysis of operations, sequence of actions performed, and reaction control constitute the starting point for research on reducing the risk of threats during activities performed in the human-machine system [4]. This applies to both the operator's safety and, above all, the safety of operating environment of this system.

In the case of piloting, there is the issue of a large amount of information reaching the pilot through a huge number of on-board systems. However, no systems monitoring the psychophysical state of the pilot that could assess his fatigue, stress and load are used [5, 6]. On the other hand, piloting less complicated aircraft (especially light aircraft) burdens the pilot with additional aspects related to the lack of any technical assistance in piloting. This increases the number of human duties at the controls associated with the need for independent, manual control of more flight parameters. For these reasons, cognitive abilities in the work of the pilot play a very important role, especially in an emergency situation. In such cases, quick decision making under highly stressful conditions is crucial. Therefore, to successfully manage an emergency situation, flawless perception and fast analysis of information from many different sources (mainly visual and auditory) are necessary.

The number of tasks performed by the operator increases the cognitive load which uses pilot's resources needed to properly perform the task, the so-called cognitive resources. Depending on the level of complexity of the task, the consumption of cognitive resources increases, and the efficiency of human organism is initially constantly high. When the maximum consumption of resources is achieved, the cognitive system, which deals with coding, processing and finally reproducing information, is unable to compensate for available task requirements by available resources [7]. Such a situation leads to so-called cognitive overload (Fig. 1).

The workload of the pilot has a great impact on flight safety, as illustrated by the accident statistics which shows that a significant proportion of the accidents occur during the most difficult and stressful stages of the flight. At such times, the time needed to complete the task is important. When performing one task, it often happens that the pilot needs to do additional work. This might result in skipping some activities or performing them imprecisely. Everyone has their own maximum load point depending on their psychophysical condition. Crossing this limit is associated with an increased risk of making a mistake. The longer the pilot is subjected to an increased load, the faster his fatigue progresses. In order to fight it, the human body adapts to workload. In other words, it modifies the task in such a way as to cover the load that it poses [8].

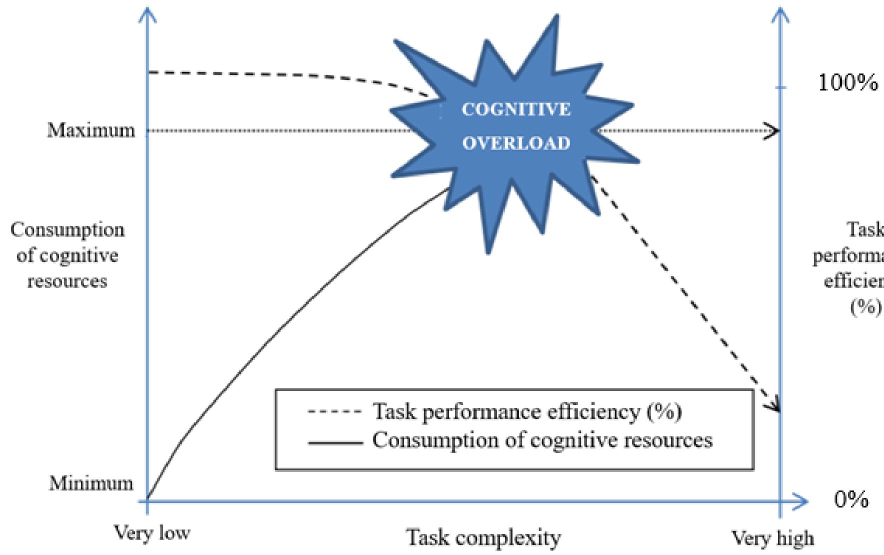

Fig. 1 Cognitive overload [9]

3. Research Methodology

3.1. Description of Tested Subjects

The tests were carried out on a group of pilots authorized or completing the course to obtain a PPL (Private Pilot Licence (Airplanes)) licence. All subjects belonged to the 20-25 age group. This work summarizes the results of three pilots with similar aviation experience. Importantly, each of them knows the Simulator CKAS MS5 used during testing well, so the occurrence of errors caused by the pilot's inexperience was avoided. All listed volunteers took part in preliminary and simulator tests in the same place, in the same simulator and under the same conditions. Tab. 1 summarizes the basic information about pilots participating in the study.

The interview with the respondents prior to the trial indicated that they were all in good physical and mental conditions, did not take stimulants (coffee and/or energy drinks) immediately before the test, were not sleepy, and rated their well-being at 9/10 on a 10-point scale.

3.2. Flight Simulator

The research was conducted in the Simulation Research Laboratory using a flight simulator CKAS MotionSim5 (Fig. 2). This device was produced by Australian company CKAS Mechatronics Pty Ltd. It is a system that uses software and hardware that combines the reliability of a modern desktop computer equipment on a custom built motion platform, with a cockpit that provides control devices identical or similar to those found on the real aircraft.

Tab. 1 Basic information about pilots participating in the study

	Experience	**Real flight time**	**Flight time on CKAS MS5 Simulator**	**Licence**
Testee A	aircraft engine mechanic and completed trainings and practices in the field of aircraft construction	– light aircraft – 205 hours, – glider – several hours	5 hours	PPL for 1 year
Testee B	air transport engineer and completed training and practices in the field of aircraft construction	– light aircraft – 70 hours, – glider (3 years of training without obtaining a licence) – 25 hours,	20 hours	PPL for 3 years
Testee C	air transport engineer and completed training and practices in the field of aircraft construction	– light aircraft – 19 hours, – pilot in command – 3 hours	10 hours	During PPL exams

Fig. 2 CKAS MotionSim5 simulator [10]

The CKAS MotionSim5 trainer is designed to simulate four generic types of light aircraft: a piston single-engine aircraft, a piston twin-engine aircraft, a light twin-engine turboprop aircraft, and a light jet [11]. It is not intended to simulate a particular aircraft model, but rather to represent a typical aircraft of each class in its handling qualities and features. The Flight Simulation Training Device can be certified as an EASA FNPT II MCC Flight Trainer (Flight Navigation and Procedure Trainer Multi Crew Coordination). It means that FSTD allows to train two pilots at the same time. The MotionSim5 is a four-seater platform with two sets of flight controls. It requires at least two persons to operate: a pilot and an instructor, seated behind the left pilot seat at the Instructor Station. The Instructor Station provides control over the flight simulator environment such as weather, positioning, malfunctions, as well as real-time tracking and flight recording. Additionally, it is possible to take operations from and to almost every airport in the World.

The MS5 Visual System provides a wide 200° × 40° viewing angle with high resolution. It consists of three full-HD (1920 × 1080 pixels) front surface DLP projectors, three high-end PCs for image generation, and the screen. An additional PC is used to drive flight instruments and to simulate general flights [12]. The movement of the simulator cab is enabled by the electrical motion system with six degrees of freedom. This makes it possible to obtain high accuracy in performing of movement. The system tilts the hull in every possible direction at an angle of 18° and moves it 150 mm [13].

For the purposes of the simulation, the flight simulation starting at the airport in Zielona Góra (EPZG) was used. The simulated flight was a flight under VFR (visual flight) conditions. After take-off, the test pilot's task was to achieve the set altitude, speed and course, and to maintain these parameters despite being distracted by on-board alarms, as well as the tester's questions.

3.3. Research Instruments

Initial research only considers the two most important information receptors for the human brain – vision and hearing. With the help of these two senses, virtually all information stimuli accompanying the piloting process reach the pilot. Thanks to the vision, the pilot is able to read all the indicators located in the cockpit in order to obtain information on the course of the flight; in addition, thanks to the observation of space, he is able to orient himself as to his position. However, thanks to hearing, he can communicate with both the co-pilot, cabin crew and air traffic control. In addition, he is able to communicate with the machine itself by receiving the sound signals it sends.

The pilot's concentration was checked by verifying the correctness of the flight carried out on the simulator, i.e. monitoring the deviations of flight parameters such as altitude, speed and keeping the set course. By monitoring these three parameters, it is possible to determine the exact movement of the aircraft in all three dimensions. By assessing changes in altitude, it is possible to determine the vertical position of the aircraft, while by analysing speed and course, he can verify its horizontal movement.

The tests consist of two parts: preliminary tests and relevant simulator tests. The purpose of the preliminary tests was to verify and assess the psychophysical state of each of the volunteers studied. To achieve this, tests were carried out for each of the subjects, which concerned testing the speed of response to stimuli, eye tests and hearing tests.

Two devices were used during the response rate testing (Fig. 3): the Piórkowski Apparatus (AP) and the Response Parameters Meter (MPR). Piórkowski Apparatus is a device, which can measures eye-hand coordination. It is a mental activity taking place at the subconscious level involving the visual and motor system [1]. MPR is a device which measures response time. It is the time it takes to perform an external response in response to a stimulus. This time consists of two components: psychic response time and motor reaction time [14].

The reaction time consists of:

- stimulus reception time,
- perception (time of admission to consciousness),

- Identification (determination) reaction.

For most populations, the average response time values are within the following range:

- 0.7-0.9 s for a simple signal,
- 1.2 s for the expected signal,
- 1.3-1.5 s for an unexpected situation.

Fig. 3 Piórkowski Apparatus and MPR device

The reaction delay was measured using simple MPR program: 30 pulses, only red light. The task for the tested subject is to correctly respond to each stimuli. The complex program 1 consists of: 10 yellow lights – footswitch, 8 red – manual button, 5 green lights – no reaction, 7 beeps – no response.

The second stage of the testing was eye examination. In this case, the check consisted of two tests: “Point to centre” and “Where to land”. The first test consisted of indicating on the displayed board consisting of circles the one which is exactly in its centre (Fig. 4a). The whole test consists of 8 consecutive boards of increasing difficulty. The second test was to find the specified fragment throughout the board. The subject had twenty seconds to indicate on the board the coordinates that correspond to the fragment cut out from it and presented next to it (Fig. 4b). In the whole test, 6 specific pieces cut out from the same board should be identified. Owing to the visual tests, it was possible to check not only cognitive skills such as concentration and processing speed, but, in addition, attention span, visual perception and analysis, or field of view width.

During the hearing test, two verification tests were carried out - the test related to the range of audible frequencies and the one related to spatial hearing. The first of them began with a 20 000 Hz sound and a gradual slow-down to 20 Hz. The test was carried out through/via headphones, and the subject himself held a button enabling him to stop lowering the tones. Thanks to this, at the moment when he began to hear the sound, he could stop its emission, and the displayed frequency was an accurate result illustrating the upper audibility range of the subject. For certainty, each subject carried out this measurement several times, and the average was drawn from the result. The second hearing test was the spatial hearing test of each subject. Four loudspeakers arranged in a square pattern in such a way that they were equidistant from the testee were used for this test. The subject, sitting in the centre of this square, was supposed to identify which loudspeaker was emitting at a given moment. This sound was the sound of an alarm clock (easy to recognize and unambiguous in reception). In addition to the correctness of the answer about the direction from which the sound came, the time to answer was also checked. Thanks to hearing tests it was possible to check cognitive skills such as short-term auditory memory, concentration, spatial orientation and auditory perception. During the relevant simulator tests, the cognitive load measurement represented by the change in pilot pulse was used measured by a finger pulse oximeter. The pulse oximeter (Fig. 5) enables precise, stable and fast measurement of oxygen saturation (SpO_2), pulse (PR) and perfusion index [PI], as well as it has the ability to send data via Bluetooth.

a) b)

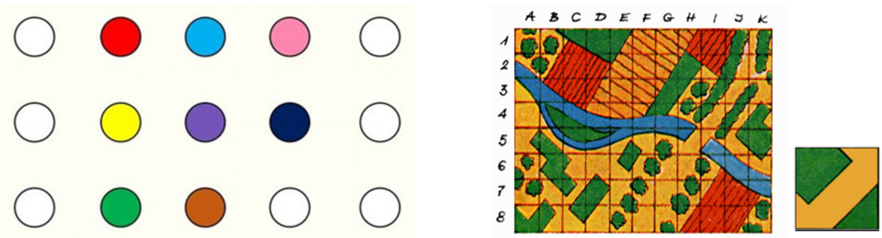

Fig. 4 Tables used for eye tests, a) "Point to centre" and b) "Where to land"

Fig. 5 One of research device – pulse oximeter

Pulse measurement was conducted by measuring the amount of haemoglobin in the designated measuring fragment of the human body. This is due to the fact that the capillaries dilate slightly with each heartbeat to accommodate more of the blood pumped by them, and return to their smaller size between beats. Thus, by analysing these changes, the heart rate of the pilot can be determined. During the flight, the intensity of the pilot's tasks was changed. Detailed characteristics of the analysed blocks will be included in the further part of the work. This chapter only presents the types of activities performed by pilots. The tasks were characterized by a low level of difficulty because their purpose was not to prevent the flight, but only to divert attention from the main task. All these tasks can be divided into the following categories:

- tasks involving the spelling of words – they absorb the pilot's thoughts and force him to use basic memory resources,
- simple mathematical calculations – they pose the necessity of using the working memory and the ability of logical thinking,

- identification of sound signals – the pilot must name the sounds played by the examiner. The ability to quickly analyse sound stimuli and the use of long-term memory are involved in this process,
- tasks involving the reading of on-board instrument readings – for this task, the pilot must correctly interpret visual stimuli. This requires quick analysis of data from the sense of sight and additionally reaching for memory resources (remembering the location of appropriate indicators),
- eye-hand coordination – this category includes tasks involving the use of appropriate switches (fuse and engine extinguishing system switch) after hearing a sound signal (in the case of a fuse, the sound of the fuse being turned off, and in the case of an extinguishing system, the sound of an engine fire alarm). These tasks absorb the pilot's attention and force him to distract the visual and auditory attention from the flight parameters indicators,
- general questions – these are questions about, for example, providing the current date, providing the name of the city, the name of the university, the colour of something, etc. These questions are about absorbing memory resources, logical thinking and attention of the respondent.

3.4. Research Assumption and Conditions

The research consisted of the following stages:

- flight preparation and take-off – flight preparation involves determining the main flight parameters, i.e. altitude, speed and course, after setting these parameters, take-off takes place,
- stable flight phase – during this phase, the test pilot should raise the machine to a designated altitude, make a turn to the set course, and level the speed. After notification of readiness by the pilot, the next stage of the test begins,
- proper examination – during this phase, the task load of the examined person increases at an even pace, doubling every two minutes over time. This is the key measuring phase,
- termination of measurements – the termination of measurements takes place immediately after the pilot has finished task by stopping the simulation during the flight. This is not a full flight, because there is no landing, which is one of the most difficult manoeuvres, and would cause too much load on the pilot and, as a result, would disturb the test results.

The relevant test phase (proper examination), which is the main element of the whole simulator test, focuses on the pilot's task load. These tasks consist in answering the examiner's questions or performing some action asked by him. The tasks for the tests were selected in such a way that they do not cause difficulties in answering, because the purpose of the test was not to assess the correct answer to complex issues, but only to divert attention from the main task, which is the correct performance of the flight. In addition, there is a time schedule of how they were commissioned to the volunteer. The test tasks were divided into four equal (two-minute) time blocks, differing in the number of tasks per each. The number of commands in each of them was:

- green block – 4 tasks, 30 seconds to perform each,
- yellow block – 8 tasks, 15 seconds to do each,
- orange block – 12 tasks, 10 seconds to do each,
- red block – 25 tasks, 5 seconds to complete each.

4. Research Results

4.1. Preliminary Research Results

During the preparation for flights, pilots were asked to perform tests on instruments testing their visual-motor coordination – the Piórkowski Apparatus (100 impulses test, 60 seconds) and the Reaction Parameters Meter (30 impulses test, 60 seconds). As can be seen in Fig. 6 the vast majority of the results were correct, and the response time was normal each time, which allowed to state that there were no contraindications to perform the tests.

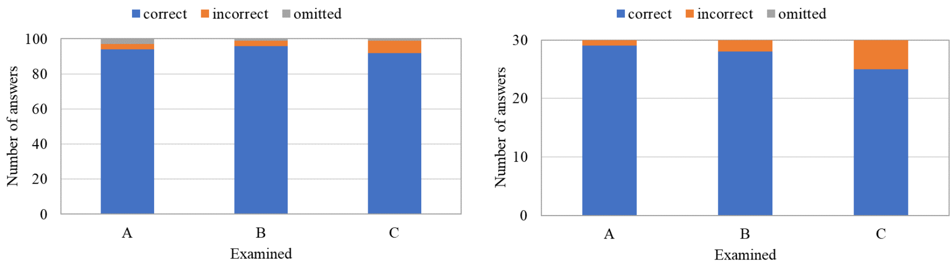

Fig. 6 Number of correct, incorrect and omitted answers achieved before the flights, a) AP, b) MPR

In the "Where to land" test, subject A obtained 50% efficiency, subject B gave 4 out of 6 correct answers, and subject C was only mistaken once. This proves his greatest perceptiveness. The "Indicate Centre" test, which aimed to check perceptiveness, spatial orientation and field of view width, proved to be the easiest for the examined B (100% correct answers). Testees A and C made 2 mistakes in 8 attempts. The upper frequency of the sound heard by the respondents is summarized in Fig. 7. Minimal error bars indicate reproducible results. The higher the frequency, the higher the sound the volunteer could hear, and thus it was easier for him to hear the high-frequency sounds characteristic of alarms. In this case, it can be seen that all examined subjects achieved results above 16 000 Hz.

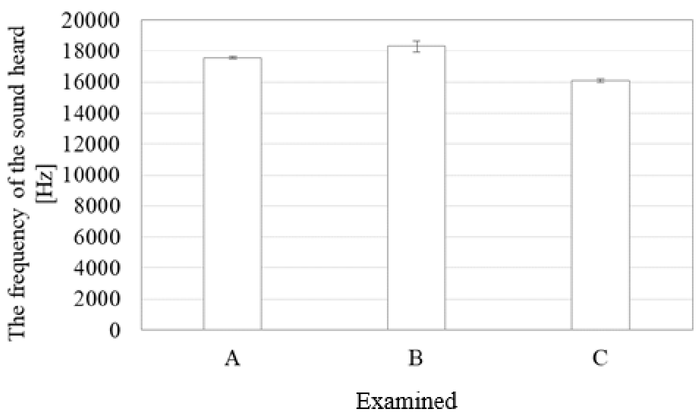

Fig. 7 Upper frequency of sound heard by pilots in preliminary tests

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Such results can be explained by the fact that all respondents are young people (in the range of 20-25), therefore they did not experience the phenomenon of hearing impairment consisting in limiting the hearing of high frequencies, which increases with age. Studies of spatial hearing showed no disturbance. Participants in most cases gave correct answers, and the response time was always normal.

4.2. Research in Flight Simulator

In order to present the results, it was decided to average the pulse value in individual test phases. Therefore, the graph shows the average value and deviations from this value are shown by means of error bars. The decrease in the average value is directly related to the reduction of the body's internal organs' demand for oxygen-saturated blood, which means that they no longer have to work so hard. The same relationship also applies to the human brain. However, the increase in heart rate indicates an increase in the organs' need for oxygen necessary for their proper functioning. Changes in the value of this parameter directly inform about the increase or decrease of such parameters as: stress, load and fatigue level [3, 15]. The figures show 6 phases (Fig. 8):

- phase 1 (so-called purple) was the period of initial tests and preparation for the flight,
- phase 2 (so-called grey) represented free flight (without any parameters, i.e. speed, altitude and course). It was supposed to be a period of adaptation and habituation of the subjects to the conditions in the flight simulator,
- phase 3 (so-called green) is the first of those involving test tasks. In accordance with chapter 3.4., it contained 4 tasks, 30 seconds to perform each,
- phase 4 (so-called yellow) – in accordance with chapter 3.4. contained 8 tasks, 15 seconds to do each,
- phase 5 (so-called orange) – in accordance with chapter 3.4. contained 12 tasks, 10 seconds to do each,
- phase 6 (so-called red) – according to chapter 3.4. contained 25 tasks, 5 seconds to complete each.

Phase marked as 1 (purple) was the period of initial tests and preparation for the flight. At that time, pilots performed tests on stationary testing devices (AP and MPR), as well as eyesight and hearing tests. It was the time immediately before entering the flight simulator. The highest fluctuations in the pulse level were observed in pilot A. Very similar results were observed in pilot's B results. Both had an average pulse of 85 bpm. Pilot C during preliminary tests achieved a pulse lower than the normal pulse for people at this age of about 70 bpm. Increased values in pilots A and B are caused by excitement and nervousness caused by the test (this is additionally confirmed by the irregular course of the characteristic).

The second phase of the study (grey) represented free flight (with no parameters, i.e. speed, altitude and course). It was supposed to be a period of adaptation and habituation of the pilots to the conditions in the flight simulator. It should be noted that all of them had an increase in heart rate compared to tests carried out outside the simulator. The largest differences can be seen in pilot A – numerous jumps in the pilot's pulse reached 115 bpm. In the case of pilots B and C, an increase in pulse by about 10 bpm was noted.

The next phase of the study (No. 3 – green) is the first of those involving test tasks. During its duration, the pilot was asked to solve 4 easy tasks (described in chapter 3.3) within 30 seconds for each of them. No significant pulse changes were observed, because the tasks were not difficult, their frequency did not cause pressure, and the pulse level stabilized after the increases noted after the start of the simulator flight. It should be mentioned that while examinee C has similar range variability in all previous phases, the results of pilots A and B are much more stable.

Phase four – despite increasing the intensity of tasks (8 tasks, 15 seconds to do each), there are no changes compared to the third phase. The only significant difference is the stability of results – in pilots A and B the opposite trend was observed in relation to phase 3.

Phase 5 (orange one) shows significant changes in pilot's A pulse (lower stability). In the case of pilot B, a sharp pulse drop (by 15 bpm) was observed. It still occurred in significant drops in value during the phase. Pilot's C results are very similar to those obtained in phase 4.

The last analysed phase – No. 6 (called red one) are the most intensive tasks assigned to the subjects. The tests were planned so that in this phase it would be difficult for the pilot to reconcile the maintenance of flight parameters with the implementation of additional commands. However, no significant differences were observed compared to the previous, fifth phase.

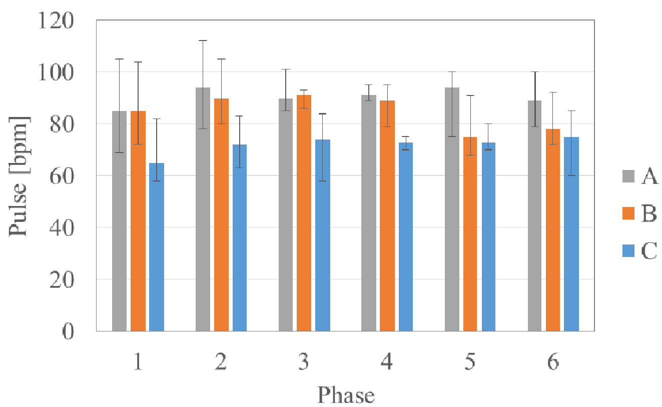

Fig. 8 Pulse changes for A, B and C pilot in individual phases of the investigation

5. Summary and Conclusions

Due to the individual psychophysical conditions of each of the volunteers, it is impossible to accurately compare the data obtained from each of them, therefore it is more reliable to search the graphs for characteristic trends and points related to the relevant moments of the study.

The tested subjects were young people authorized to perform flights. The initial survey also indicated that there were no contraindications related to illness or malaise. The research was divided into preliminary tests and tests in a flight simulator.

The aim of the preliminary research was to obtain measurable results describing each of the pilots, so as to obtain a comparative point for further research. Thanks to these tests, it was found that all tested people have a similar response time to visual stimuli. Similarly, there were only slight differences when comparing their hearing tests.

The key stage was the part of the research using the CKAS MotionSim5 flight simulator, which is the equipment of the Simulator Research Laboratory at the Poznan

University of Technology. The analysis of pilot's pulse changes during loading their minds by tasks indicated that in all cases cardiac arrhythmias occurred during the stage of preparation for the flight and in its final stage, at the highest task load. It follows that they were most stressed at the very beginning of the investigation while reading information about its further course and at the time when it began to overwhelm their number of activities performed.

This was also confirmed by the results of devices for monitoring bioelectrical brain activity. These results were not shown in this article, but on its basis, it has been proved that as the load on the pilots increases, the level of attention they need to devote to completing tasks increases with increasing task complexity. An important factor determining the degree of this growth was the experience of the volunteers. It can be clearly seen here that the most experienced volunteer could boast the most stable readings of the concentration level, and the most irregular results of the concentration measurements belonged to the least experienced member of this group. None of the subjects experienced an extreme phase of cognitive overload characterized by inability to make decisions by which subjects could not correctly answer control questions.

Based on the collected data, it was proved that as the complexity of the task progresses, the load on pilots also increases. Due to the individual nature of each person, this increase occurs in different ways. The load characteristics can change linearly or stepwise at different rates. In addition, overload will affect their cognitive function in each individual.

It follows that cognitive overload is one of the main reasons why pilots make mistakes. It should not be understood only as an extreme condition in which the pilot cannot find himself in the given situation because of too much information reaching him. Temporary loss of attention and individual omissions of important details can also be classified as cognitive overload. Such omission can occur through a momentary (even microsecond) superimposition of two stimuli from different sources of information, e.g. sight and hearing, which may cause an overlook of the entire message or part of it derived from one of these sources. Such momentary overloads due to low detection (also by the person experiencing this phenomenon) are the cause of pilot errors. The omissions indicated here, caused by the inflow of large amounts of information, which the pilot must analyse in a short time, are one of the most serious sources of danger. They often lead, in combination with other factors such as pilot's inexperience and atmospheric conditions, to a "domino effect", which can, in extreme cases, result in an aviation accident.

The pilot's experience and skills acquired during training are of key importance in reducing the impact of cognitive overload on the pilot's work. This could be observed even in the case of such a narrow control group included in this work. With the same assumptions and conditions for all volunteers, the smallest psycho-cognitive burden was given to the pilot with the highest level of experience. In addition, after comparing the results of all tested, a linear relationship can be observed between the experience and cognitive load. This relationship shows that the greater the experience in piloting and the better knowledge of the piloted aircraft, the lower the load on the person under the controls.

The research presented in this article will therefore be an introduction to the development of analyses regarding the impact of experience on pilot load.

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