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ORIGINAL ARTICLE

WORKLOAD OF HELICOPTER PILOTS AND ITS IMPACT ON FLIGHT PERFORMANCE

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Introduction: Various working conditions affect pilots' physiological and psychological state, directly impacting their flight performance. The present study shows the relationship between workload and pilot performance. The study aimed to evaluate performance in a slalom maneuver task under various workload conditions.

Method: Twenty Polish Air Force Academy pilots participated in the study. The experiment was performed on the SW-4 helicopter flight simulator. Task A involved no additional workload; task B involved mental workload, including distraction of the pilot; task C involved very poor weather conditions, representing physical workload. Performance was measured based on the recorded flight parameters. Workload was measured using the NASA TLX questionnaire. The structure of the survey provides detailed information about the types of workload and their impact on the subject's performance.

Results: The results analysis was performed for both performance and pilots' workload. The highest workload was recorded for task B (56.930), a medium workload for task C (48.842), and the lowest workload for task A (29.860). Finally, performance decreased significantly for tasks B and C.

Discussion: The presented study demonstrates that various workload conditions yield different performance levels. It also emphasizes the need to monitor both pilot performance and psychological state to obtain a more comprehensive understanding of their characteristics.

Keywords: workload, NASA TLX, ECG, helicopter pilots, flight simulator

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INTRODUCTION

Research on man-machine systems involving human factors is currently one of the most extensively developing fields worldwide. Analyzing human parameters and their performance during task evaluation can improve systems and increase operator safety. In aviation, the man-machine system – the pilot-aircraft combination – has been widely investigated to identify the most critical factors that may affect pilot safety [17]. Despite increased automation and the implementation of more autonomous systems, the human operator, represented here by the pilot, remains a crucial element in man-machine systems. An operator typically makes key decisions during the process, which in many cases are correct.

On the other hand, humans are the primary cause of most accidents and incidents in aviation [4]. The pilot's psychological state directly affects their efficiency. Identifying the pilot's state can help predict their reactions and avoid some errors. The challenge lies in collecting these data, analyzing them online, and interpreting the results.

In the training process, performance is mainly considered [2,3,14]. Despite medical examinations at the beginning of a pilot's career, physiological aspects during training and practice are mostly overlooked [13]. The analysis of both performance and the effort required to achieve results provides many more details about the candidate/pilot. Some systems monitor the operator's actual state; however, this still needs to be combined with onboard systems capable of using that information to adapt to the pilot's condition [5,18]. The performance rate is based on predetermined parameters that the pilot must achieve (time, precision, procedures, etc.). Such results are objective and comparable across different subjects [8,26]. A problem that arises is individual variability and differing resistance to workload, stress, and fatigue among subjects [11]. Each subject reacts differently to external stimuli. That is why the analysis of the results was performed individually.

In the literature, numerous methods and tools exist for assessing human psychological state and workload. One of the techniques that has undergone several modifications is the Cooper-Harper (C-H) scale [20]. This ten-point scale provides a reliable measure of handling qualities and indicates human-machine performance. One variation of the C-H scale is the Bedford scale, which focuses on task evaluation by the operators. The Bedford Scale is a uni-dimensional rating scale designed to identify an operator's spare mental capacity while completing a task [12,19]. The Situation-Awareness Global Assessment Technique (SAGAT) was developed to assist in this process by providing an objective measure of a pilot's situation awareness with any given aircraft design [11]. Another commonly used method is the Subjective Workload Assessment Technique (SWAT), in which subjects rate the workload of a task on the dimensions of time load, mental effort load, and psychological stress load [7]. One of the most popular techniques for measuring operator workload is the NASA Task Load Index (NASA TLX) [1]. This tool not only allows for the determination of workload in a measurable way but also enables the distinction of its type [9]. Questionnaires are a subjective form of workload assessment used in the present research. Electrocardiography (ECG) and galvanic skin response (GSR) were applied to enhance the reliability of subjective measurement. These types of objective physiological measurements have been used in previous similar research and have proved reliable, especially heart rate (HR) analysis [19].

Research on human factors, human performance, and psychological state during operations is highly challenging because the experiments involve humans working in high-risk environments. For this reason, research is often conducted in simulators and virtual reality. Such an approach enables experiments that would otherwise be too hazardous for pilots to perform in real flight. In the present study, the pilot had to perform a flight under various work conditions that would have been too difficult to execute in a real-life environment. The study aimed to evaluate slalom maneuver task performance under various workload conditions. In this research, pilots performed a multiple maneuver – low-altitude slalom – under different workload conditions. The flight was conducted as a nap-of-the-earth (NOE) flight, which requires high effort and skill. The experimental conditions included mental distraction and poor visibility.

MATERIALS AND METHODS

Participants

A group of 20 pilots (mean age M=21.5 years, 19 males, 1 female) from the Polish Air Force Academy performed a set of maneuver tasks under different workload conditions. All pilots had similar flight experience (second- and third-year students) with a minimum of 20 hours of actual flight time and additional hours on flight simulators. The pilots trained on the same rotary-wing aircraft (SW-4) during their everyday training. None of the subjects suffered from any disease or cardiac dysfunction.

All pilots agreed to participate in the research and signed all required forms. They also completed all the documents required for this type of study. The study received a positive recommendation from the appropriate bioethical commission.

Procedure

All participants were informed of the aim of the research and the procedure before the tests. The pilot's task was to follow a predefined trajectory (slalom maneuver) according to the criteria provided below. The slalom maneuver used in the research was adopted from the Mission Task Elements, which are basic maneuvers for testing the handling qualities of helicopters, as outlined in the ADS-33 report, namely: constant forward velocity, constant altitude, and coordinated turns. The flight criteria were the same for each of the tasks [5]. However, the pilots performed the tasks in a random order so that task difficulty would not be suggested to them.

The elements that differentiated the flights were the working conditions [4]. Three task conditions were defined as follows:

– Task A – good weather conditions,
– Task B – good weather conditions with test questions during the flight,
– Task C – bad weather conditions.

Task B involved mental workload. The need for greater concentration significantly affects cognitive demand. Task C affected physical demand, as operating in challenging work conditions requires increased focus. Visual criteria are the most critical for pilot performance; thus, this task was implemented [6]. This variety of work conditions was discussed in detail and approved by pilot instructors from the Polish Air Force Academy. The experiment was conducted at Warsaw University of Technology using the SW-4 helicopter flight simulator, as shown in Fig. 1 [5]. Because the pilots train on the same helicopter model, the time required to become familiar with the helicopter's dynamics was relatively short. During each flight, objective and subjective measurements were collected. The purpose of data registration was to assess both pilot performance and workload under various conditions. The slalom maneuver was adapted from the ADS-33 report [2], consisting of five pylons, input and output gates (see Figure 2). The distance of the pylons from the y-axis was 20 meters, while the distance between the pylons along the x-axis was 450 meters. The trajectory resembled a sine wave and was mathematically formulated (Eq. 1). Based on the fixed slalom trajectory, reference values for flight parameters were calculated. These values were used as a baseline for performance assessment. The slalom was created in 3dsMax software and then transferred to the virtual environment.

Fig. 1. SW-4 helicopter simulator.

$$\gamma_{ref}(x)=\begin{cases} A_{se}*\sin\left(Lx-\frac{\pi}{2}\right), & for \quad x\le 450 \\ A_{si}*\sin\left(Lx+\frac{\pi}{2}\right), & for \quad 450<x\le 2250 \\ A_{se}*\sin\left(Lx+\frac{\pi}{2}\right), & for \quad x>2250 \end{cases} \tag{1}$$

After receiving the necessary approvals and instructions regarding the experiment, the pilots had a relaxation period before the tasks to measure and establish the HR and GSR baselines for each pilot. After completing all three tasks, a 5-minutepost-experiment relaxation session was also conducted.

Hardware

The SW-4 helicopter (PZL Świdnik) flight simulator is a fixed-base simulator with a convex screen and a 180-degree field of view. The helicopter's cabin is based on real-life dimensions, and the cockpit exactly replicates the original set of controls and indicators as they appear in the real helicopter (see Figure 1). During the flight, the supervisor could adjust various settings, including weather conditions, simulation time, and damage scenarios for the helicopter subsystems. The instructor was also able to change the flight conditions so that the scenarios met the requirements set as inputs to the experiment (A, B, and C).

Software

The open architecture of the software supporting the flight simulator enables the registration of flight data during task performance. Over 125 flight parameters are stored. Additional software was developed in MATLAB version 2013a (The MathWorks, USA) for further parameter analysis. Detailed analysis of the parameters enabled definition of the performance levels that pilots needed to achieve during each task variant (A, B, or C). Another advantage of the simulator is its ability to integrate additional elements into the existing environment.

Workload conditions

The research aimed to verify pilot performance while completing a selected maneuver under three different workload levels. Task A, a non-stress task, was performed in excellent weather conditions – no wind, clear visibility, no clouds, and at 12:00 flight time. Task B, involving mental stress, was performed under the same weather conditions as task A. During the flight, however, the instructor asked a set of 46 questions to verify knowledge of flight procedures and general information. The questions were asked quickly, and the pilot had only three seconds to answer each one. If the subject did not answer within the time limit, the following question was asked, and the lack of an answer was considered a failed response. There was no option to skip a question or correct an answer. A correct answer was equal to 1 point; a wrong or incomplete answer resulted in 0 points. Pilots were informed that their answers would directly affect their overall flight score, which served as an additional stimulus to increase engagement. Finally, task C was performed in harsh weather conditions; no questions were asked during this task. Horizontal visibility was less than 450 meters.

Performance measurement

Based on the trajectory (Eq. 1) and the defined flight criteria, a set of reference flight parameters was obtained. Each value was calculated individually for each pilot. The performance ratio was calculated for all parameters for each pilot under three conditions (A, B, and C). The matrix represents the set of four main parameters: roll angle, forward velocity, y, and z values along the x-axis (Eq. 2).

$$M_{ref}(x)=\begin{bmatrix}\Phi_{ref}(x)\\ U_{ref}(x)\\ \gamma_{ref}(x)\\ Z_{ref}(x)\end{bmatrix} \tag{2}$$

where:
$\Phi_{ref}(x)$ – roll angle,
$U_{ref}(x)$ – forward velocity,
$\gamma_{ref}(x)$ – longitudinal values,
$Z_{ref}(x)$ – altitude values.

These parameters were used to calculate and present pilot performance. The simulator

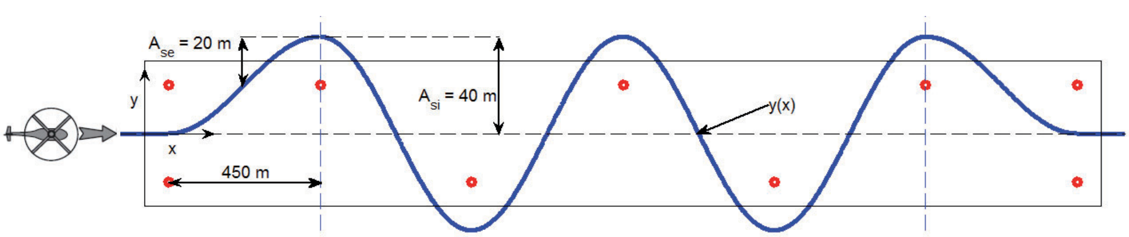

Fig. 2. Slalom maneuver.

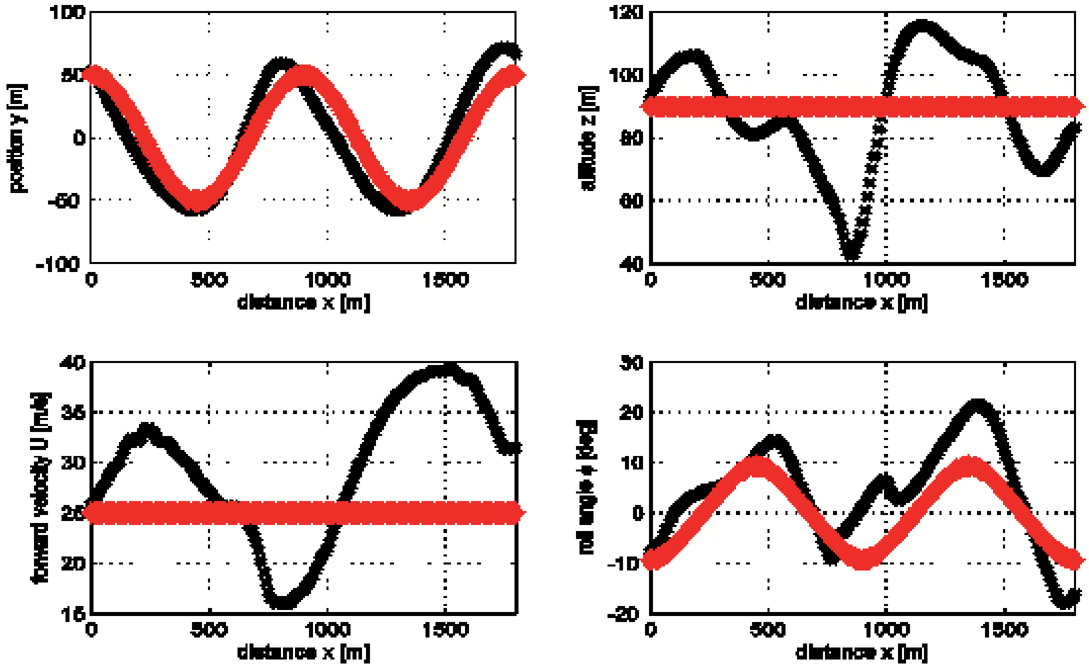

Fig. 3. Reference (red line) and realized (black line) flight parameters.

software returned a similar matrix containing the set of parameters for each flight condition (A, B, and C). The reference parameters obtained from the trajectory (Eq. 1) were used as a baseline for each flight to assess pilot performance. Four flight parameters were selected as the most important.

Having established the baseline and registered the data from individual flights, the error for each parameter was calculated as follows:

$$M_{err}(x)=\begin{bmatrix}\Phi_{err}(x)\\U_{err}(x)\\\gamma_{err}(x)\\Z_{err}(x)\end{bmatrix}=\begin{bmatrix}\Phi_{ref}(x)\\U_{ref}(x)\\\gamma_{ref}(x)\\Z_{ref}(x)\end{bmatrix}-\begin{bmatrix}\Phi_{real}(x)\\U_{real}(x)\\\gamma_{real}(x)\\Z_{real}(x)\end{bmatrix} \tag{3}$$

To assess the performance index, the criterion of the “integral of the squared error function” was used (Eq.4), and the errors were calculated as follows:

$$M^2_{err}(x)=\begin{cases}e^2_{\gamma}(x)=\left(\gamma_{ref}(x)-\gamma_{real}(x)\right)^2\\e^2_{Z}(x)=\left(Z_{ref}(x)-Z_{real}(x)\right)^2\\e^2_{U}(x)=\left(U_{ref}(x)-U_{real}(x)\right)^2\\e^2_{\Phi}(x)=\left(\Phi_{ref}(x)-\Phi_{real}(x)\right)^2\end{cases} \tag{4}$$

The parameters are compared in Figure 3, which presents the reference (red) line and the realized (black) line. Based on these, the performance parameter for each flight was calculated.

$$J=\int_{xp}^{xk}e^2(x)dx \tag{5}$$

Since each pilot had different characteristics, individualized data analysis was required. One of the most important aspects of the experiment was the change in performance relative to subsequent work conditions. Therefore, an additional parameter was introduced (Eq. 6) to indicate whether performance was lower or higher compared with the baseline. This approach enabled performance assessment to remain independent of individual differences between subjects.

$$J^B_A=\frac{J^B}{J^A},\quad J^C_A=\frac{J^C}{J^A} \tag{6}$$

where:

J^B_A – normalized parameter comparing the result from task B to the results from task A,

J^C_A – normalized parameter comparing the result from task C to the results from task A,

A, B, C – different task conditions.

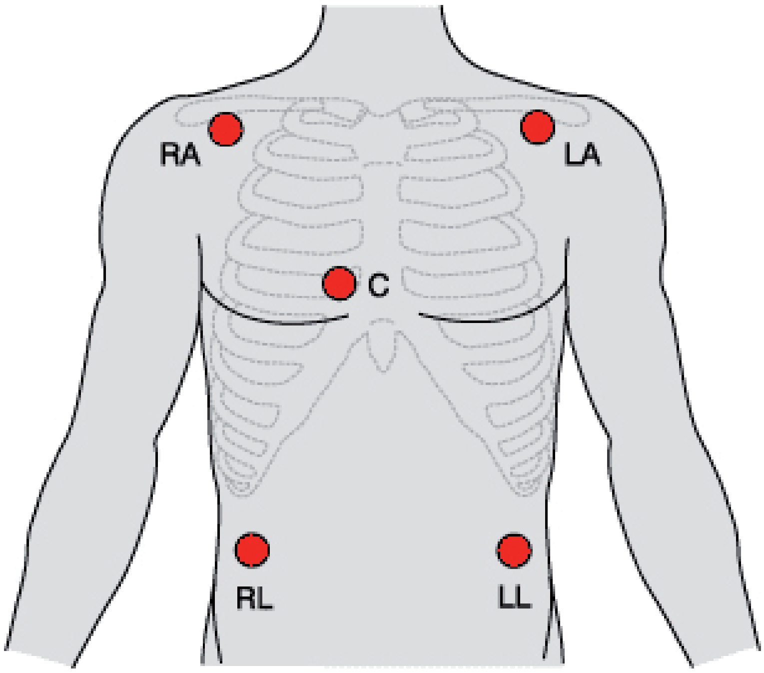

Fig. 4. Electrodes over the pilot's body.

Workload measurement

The pilot's workload, measured by both objective and subjective assessments, was evaluated to determine the operator's engagement. Electrocardiography (ECG) and Galvanic Skin Response (GSR) were used to estimate the objective level of engagement [16, 16]. The small, portable device that recorded ECG and GSR signals was attached to the subject's hip. The electrodes [25] were attached to the subject's skin in appropriate places (see Figure 4). According to [10], the selected areas are the left arm (LA), right arm (RA), center (C), and left/right leg (LL, RL).

A subjective analysis with the NASA TLX questionnaire assessed the workload. The questionnaire captured six aspects of workload:

- mental demand,
- physical demand,
- temporal demand,
- performance,
- effort,
- frustration.

The NASA TLX questionnaire can be divided into two groups. The first group focuses more on the pilot's mental aspects: mental demand, temporal demand, and frustration. The second group focuses more on the pilots' physical parameters: physical demand, performance, and effort. Such a wide range of parameters allows for a more detailed assessment of the tasks assigned to the pilots.

In the first part, the pilot rates the level of each parameter by giving a score from 0 to 100. In the second part of the questionnaire, the pilot selects the parameter with the most substantial effect from the table of all 15 possible parameter pairs to set the appropriate weights for each parameter. The algorithm calculates the scores for all six parameters and provides the final workload rating. The questionnaire was administered directly to each pilot in the helicopter cabin, allowing them to remain in the simulator throughout the experiment.

Statistical Analysis

For the workload assessment, the data from the NASA TLX were analyzed using a repeated-measures ANOVA method, with the independent factor being the test condition (A, B, or C). When the sphericity assumption was violated, the Huynh-Feldt correction was applied to the degrees of freedom. Simple and main effects were analyzed using post hoc comparisons with the Bonferroni correction. Effects were considered significant at $p<0.05$. Effects within the range (0.05-0.1) were interpreted as statistical trends. Values of partial eta² (η^2p) were reported to indicate the strength of the examined relationship's effect. All analyses were performed using Statistica software ver. 11.0 (Statsoft, Tulsa, USA).

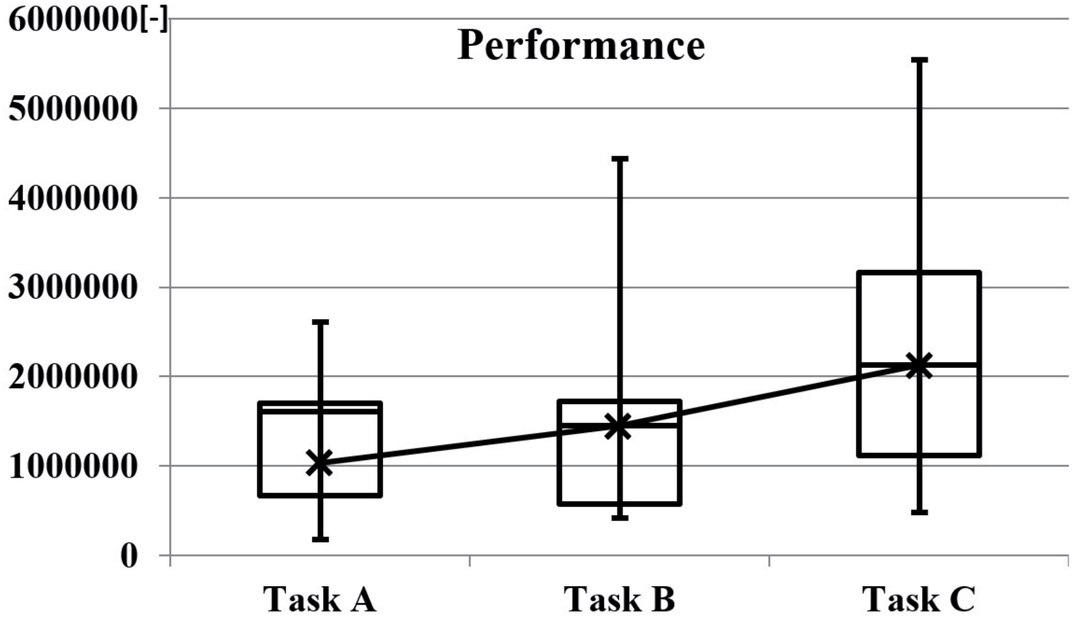

Fig. 5. Pilots' flight performance. The box represents the interquartile range, the whisker indicates the range of data from the minimum to the maximum value that are not outliers, the asterisk indicates the mean value, and the line inside the box denotes the median.

Tab. 1. ECG and GSR parameter results for one of the subjects.

Parameter		Relax before	Task A	Task B	Task C	Relax after
HR [beats/ min]	M	92.43	92.22	111.42	100.38	88.13
	SD	6.30	3.81	11.09	7.86	5.35
	min.	76.92	79.78	87.20	64.10	88.67
	max.	106.38	103.44	141.51	136.36	101.09
IMP [mV]	M	201.64	156.95	103.97	72.44	64.65
	SD	7.59	12.17	17.69	6.62	2.95
	min.	181.20	130.14	78.02	59.95	57.63
	max.	213.58	185.59	139.92	86.02	71.87

HR – heart rate, IMP – impedance, M – mean value, SE – standard error, SD – standard deviation

RESULTS

The overall flight performance results (Eq. 5) derived from the data registered via the simulator software are shown in Figure 5, where mean values for all subjects are presented. The value of the performance is dimensionless. The error analysis is relative to reference values; thus, the lower the number presented, the closer to the reference value. Consequently, the mean values increased for tasks B and C. The analysis of individual pilot data confirms that pilot efficiency drops in the subsequent tasks. Accordingly, based on the normalized parameter (Eq. 6), the increase for task B compared with task A was 70%, and for task C compared with task A was 100%.

The GSR data were too blurry, and the signal contained substantial noise and artifacts. Thus, the data were not reliable, and analysis of this parameter was not pursued further. However, the ECG measurement proved that the pilot's heart rate (HR) increased across the tasks (Table 1).

Relaxation periods before and after the tasks were also recorded to establish a reference level for each pilot. It is worth mentioning that all measurements are calculated within subjects, as various pilots may have different baseline HR levels. For this research, the trend (increase or decrease) in HR was of primary interest, rather than the exact HR values. The interesting part is that the HR parameter increased more in task B. The results of the performance analysis indicate that increased HR levels are associated with poorer performance. In the literature, increased HR is the human body's reaction to stress [24]. Thus, the workload

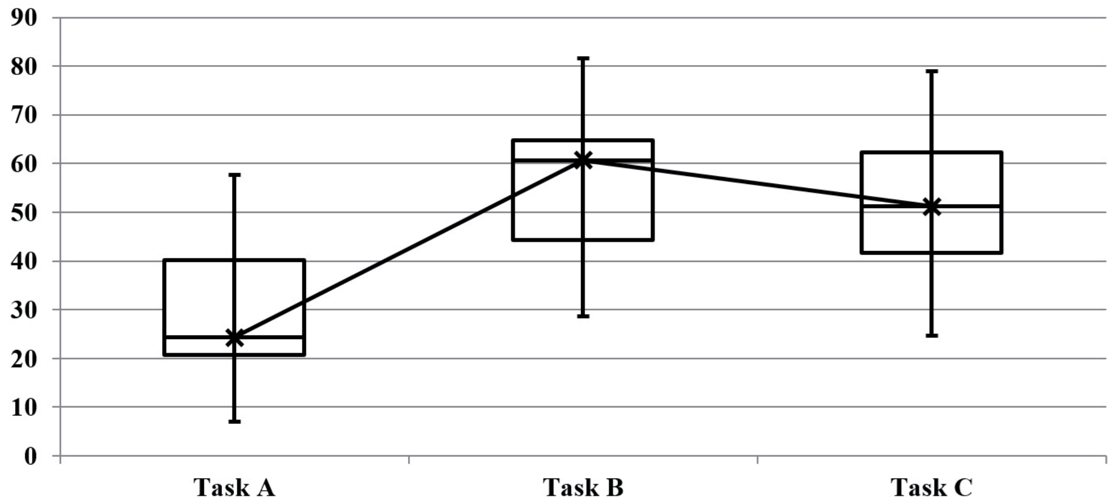

Fig. 6. Total workload for different flight conditions. The box represents the interquartile range, the whisker indicates the range of data from the minimum to the maximum value that are not outliers, the asterisk indicates the mean value, and the line inside the box denotes the median.

conditions affected the pilots' physical state. In table 2, the HR ratios and (Eq. 6) are presented, showing the overall tendency of HR increase.

Tab. 2. HR parameter coefficient for all pilots.

Pilot number	HR Parameter	
	$J^{\frac{B}{A}}$	$J^{\frac{C}{A}}$
1	1.01	0.97
2	1.05	1.07
3	1.21	1.09
4	1.08	1.11
5	1.07	0.96
6	1.16	1.06
7	0.96	0.94
8	1.08	-
9	1.12	1.11
10	1.21	1.13
11	-	-
12	1.06	0.97
13	0.98	0.90
14	0.98	1.18
15	1.14	0.99
16	1.08	1.07
17	1.05	1.00
18	1.15	1.07
19	1.02	0.98
20	1.02	1.00
Coefficient increase	84%	61%

$J^{\frac{B}{A}}$ – normalized parameter comparing the result from task B to the results from task A,

$J^{\frac{C}{A}}$ – normalized parameter comparing the result from task C to the results from task A

The changes in total workload level, as measured by the NASA TLX questionnaire (Figure 6), were analyzed across various simulator tasks. The results indicate that performing multiple tasks significantly influences the perceived workload level, $F(2,36)=33.229$, $p<0.001$, $\eta^2p=0.649$. Subjects reported a significantly lower workload level in task A (M=29.860, SE=2.986) compared to task B (M=56.930, SE=3.411), $p<0.001$, and task C (M=48.842, SE=2.904), $p<0.001$. In addition, in task B (M=56.930, SE=3.411), the level of perceived workload was significantly higher than in task C (M=48.842, SE=2.904), $p<0.05$.

An identical analysis was performed on all six parameters. The four main parameters are presented in this study. As can be seen in Figures 8-10, the differences in task difficulty are clearly distinguishable. In both figures (7 and 8), for task B (where the pilots were questioned), the results clearly indicate increased workload. The values for both parameters, temporal and mental demands, are much higher in task B compared to tasks A and C; for example, temporal demand of 0.83 compared to 15, and temporal and mental demand of 3.33 compared to 15. These results clearly show the impact of task conditions. The mean value for the temporal parameter in task C compared to task A is also slightly higher, but not significantly so (0.83 compared to 1.17). For task C, the results for physical demand and effort parameters are clearly higher than those in tasks A and B. Statistical analysis showed that these results depended significantly on the task condition.

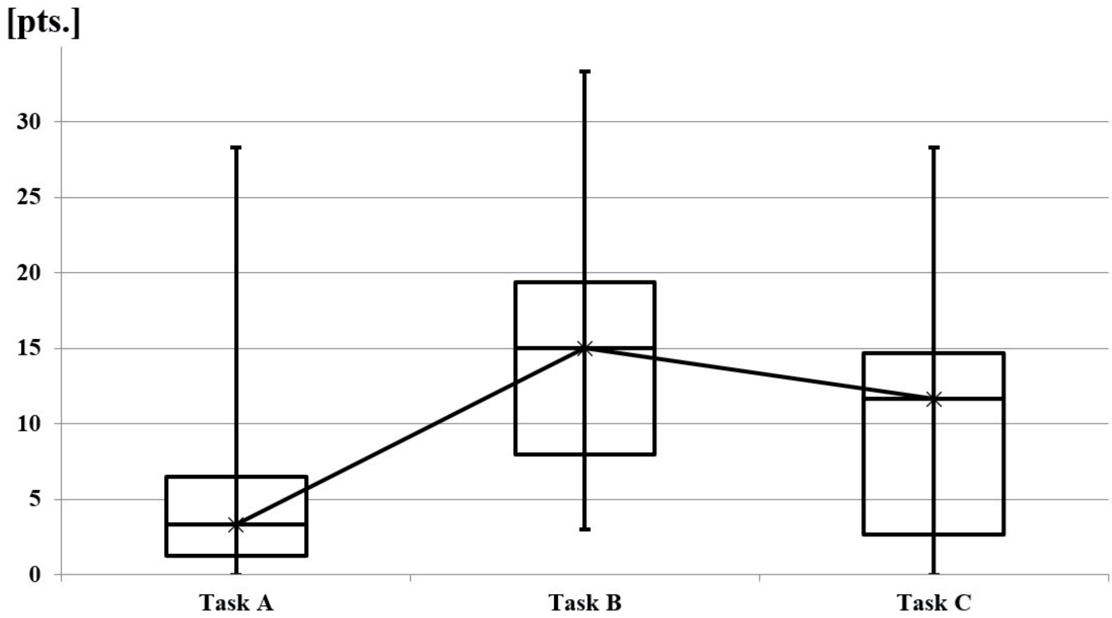

Fig. 7. Mental workload for different flight conditions. The box represents the interquartile range, the whisker indicates the range of data from the minimum to the maximum value that are not outliers, the asterisk indicates the mean value, and the line inside the box denotes the median.

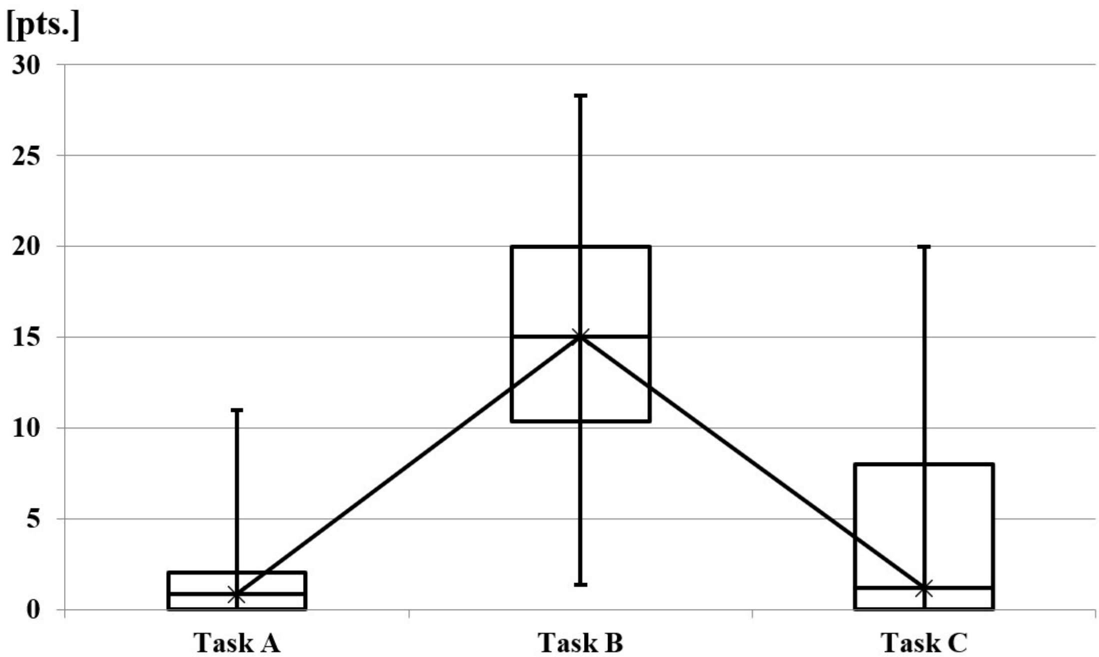

Fig. 8. Temporal workload for different flight conditions. The box represents the interquartile range, the whisker indicates the range of data from the minimum to the maximum value that are not outliers, the asterisk indicates the mean value, and the line inside the box denotes the median.

DISCUSSION

The analysis of the pilot's results revealed a decrease in flight performance in the two subsequent tasks, B and C. Both tasks had different types of impact on the pilot. Task B imposed a greater mental demand and stress on the pilots, which aligns with expectations. Task C exerted a greater impact on temporal and physical demands, as the task itself (with limited visibility) was more challenging. The distraction in task B significantly affected the pilots' flight performance, as indicated in Table 2. The question test made pilots focus more on the flight itself than on the flight instruments, which directly lowered their performance. The

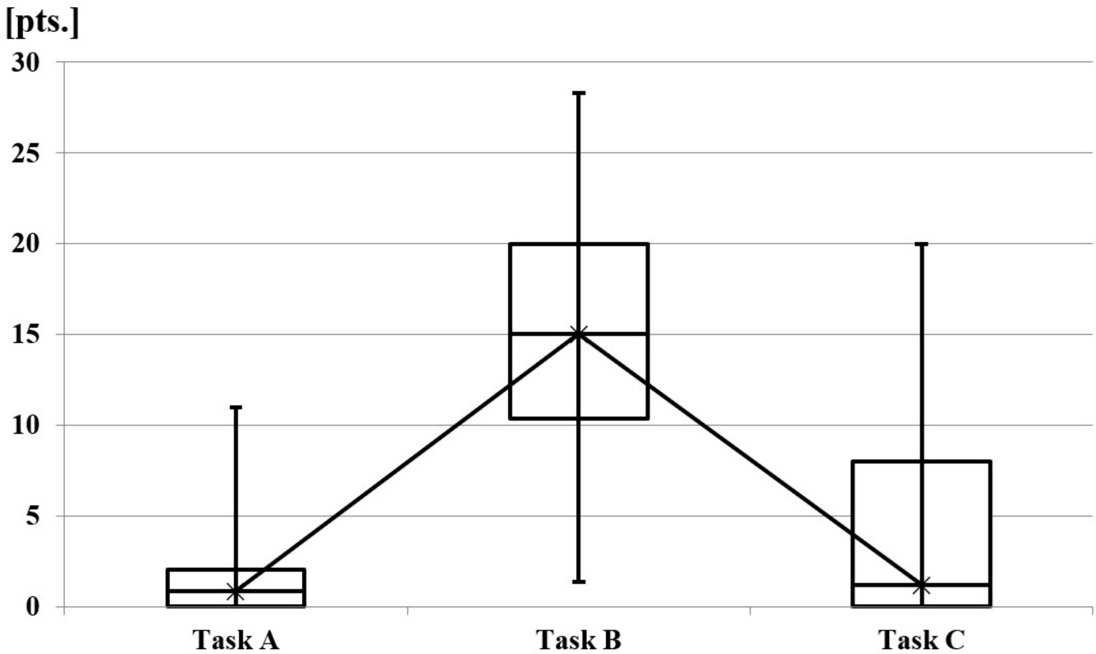

Fig. 8. Temporal workload for different flight conditions. The box represents the interquartile range, the whisker indicates the range of data from the minimum to the maximum value that are not outliers, the asterisk indicates the mean value, and the line inside the box denotes the median.

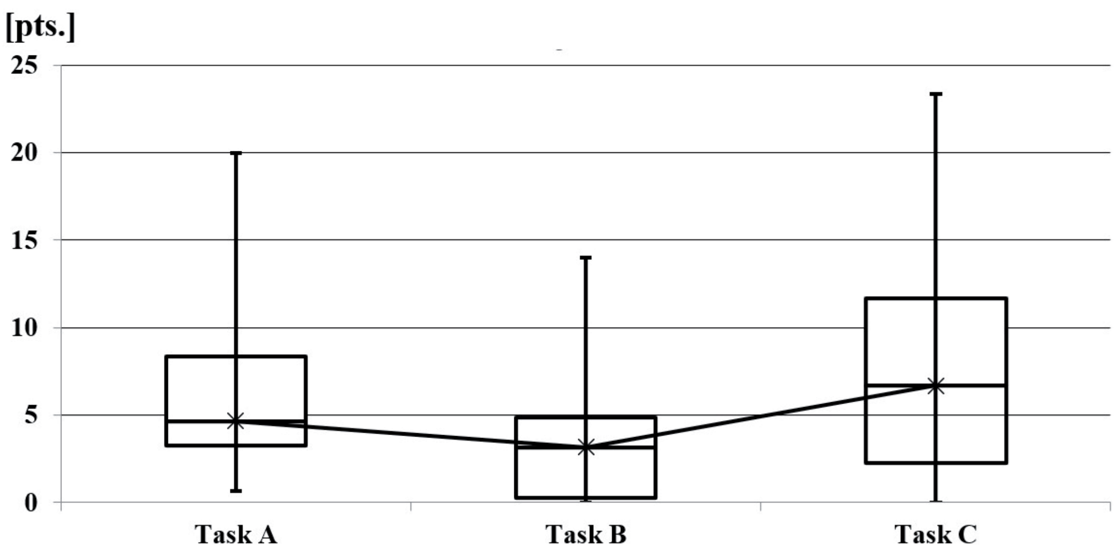

Fig. 9. Physical workload for different flight conditions. The box represents the interquartile range, the whisker indicates the range of data from the minimum to the maximum value that are not outliers, the asterisk indicates the mean value, and the line inside the box denotes the median.

performance results in task C are also unsurprising, as visibility was limited to 300 meters. Thus, the pilot was forced to estimate the trajectory to the next pylon. This significantly affected flight performance (trajectory). As a result, the flight conditions in task C did not allow pilots to meet the same requirements as in task A. Low visibility required the pilots to adopt the fly-on-instruments style of flying. Consequently, the pilots could not follow the indicated trajectory as precisely as in task A.

The increased HR parameter may be interpreted as an indication of increased mental/physical stress, as higher HR is a response of the human body to external stimuli [24]. The most significant increase can be observed in task B. The differences between task C and task B are not substantial. However, the HR parameter itself does not indicate the origin of the stress. The objective results confirmed the increased workload imposed on the pilots.

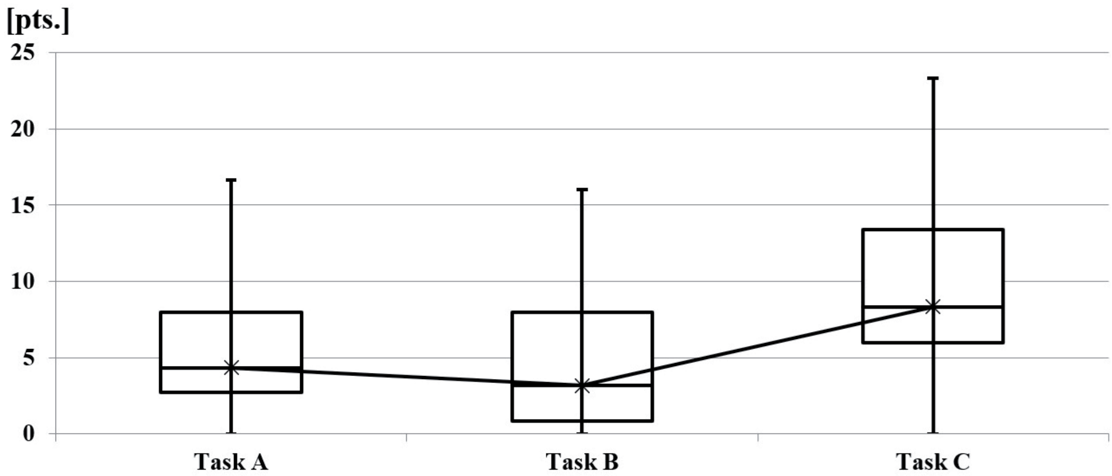

Fig. 10. Effort workload for different flight conditions. The box represents the interquartile range, the whisker indicates the range of data from the minimum to the maximum value that are not outliers, the asterisk indicates the mean value, and the line inside the box denotes the median.

The NASA TLX questionnaire results show that different types of workload can be clearly distinguished after appropriate data analysis. The six different parameters allow for a detailed assessment of the pilots' subjective workload. The result is noteworthy and suggests that, in this experiment, the tests and mental workload were more challenging for the pilots to cope with than the difficult flight conditions.

CONCLUSIONS

The presented experiment demonstrated that external stimuli have a direct impact on pilot flight performance. Using the NASA TLX questionnaire provides a broader spectrum of information about the pilot's subjective workload; however, the use of objective measurements is also crucial for generating more reliable results. Such a tool could be used to distinguish how pilots react to different tasks. Thus, it may be used for more in-depth pilot analysis when combined with the performance results.

One potential use of the present research is to implement a stress factor into a pilot dynamics model in future simulations, where most existing models do not include this parameter [15,21,23]. That would be a step towards developing a tool that could reduce the stress associated with maintaining an appropriate level of performance efficiency.

The experiment showed that different external stimuli (different task conditions) affect different aspects of the pilot's functioning (mental, temporal). However, both types of impact increase pilot stress and, in general, lead to decreased performance efficiency. Such an approach leads to the conclusion that during the process of training or verifying the pilot's skills, not only is performance itself valuable, but so is the effort required to achieve it.

The presented paper demonstrates that the performance parameter is insufficient to fully understand pilots' actions during flights. The external factors that significantly affect the state of pilots also affect their actions. One solution to cope with distractions, stress, and other challenges during flight operations is to utilize Human Adaptive Systems [22]. Such a system would have to collect and identify multiple signals to assess the pilot's psycho-physiological state. Based on that information, the system would adjust the workload level, ensuring that pilot efficiency remains at an optimum level.

AUTHORS' DECLARATION

Study Design: Antoni Kopyt. **Data Collection:** Antoni Kopyt. **Statistical analysis:** Antoni Kopyt. **Graphical representation of results:** Antoni Kopyt. **Manuscript preparation:** Antoni Kopyt. The Author declares that they have no conflicts of interest.

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