CZECH TECHNICAL UNIVERSITY IN PRAGUE
FACULTY OF TRANSPORTATION SCIENCES
Department of Air Transport

Effects of Analog to Glass Cockpit and Opposite Transition on Pilot's Performance

Bachelor thesis

Study program: Technology in Transportation and Telecommunications
Study branch: Professional Pilot

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Ing. Lenka Hanáková

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ZADÁNÍ BAKALÁŘSKÉ PRÁCE
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Jméno a příjmení studenta (včetně titulů):

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B 3710 – PIL – Profesionální pilot

Název tématu (česky): **Vliv přechodu z analogového na glass kokpit a naopak na výkonnost pilota**

Název tématu (anglicky): Effects of Analog to Glass Cockpit and Oposite Transition on Pilot Performance

Zásady pro vypracování

Při zpracování bakalářské práce se řiďte následujícími pokyny:

- Cílem této práce je zhodnotit vliv přestupu jak z analogového do glass kokpitu, tak z glass kokpitu do analogového kokpitu na výkonnost pilota.
- Vypracujte analýzu současného stavu v oblasti přechodu mezi analogovým zobrazením letových, navigačních a motorových údajů do glass kokpitu.
- Navrhněte experiment pro reprezentativní a uniformní skupiny účastníků s ohledem na přestup mezi dvěma typy ergonomie kokpitu.
- Navrhněte metodologii hodnocení výkonu pilotů na základě přímých měření, např. na základě chyb pilotáže, a implementujte tyto principy do navrženého experimentu experimentu.
- Vyhodnoťte sesbíraná data a diskutujte o experimentálních výsledcích v kontextu limitací současného stavu.
- Formulujte závěry práce.

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Rozsah průvodní zprávy: minimálně 35 stran textu (včetně obrázků, grafů a tabulek, které jsou součástí průvodní zprávy)

Seznam odborné literatury: Socha, Vladimir, et al. "Pilots' Performance and Workload Assessment: Transition from Analogue to Glass-Cockpit." Applied Sciences 10.15 (2020): 5211.

Wright, Stephen Joseph. The Human Factors of Cockpit Transitions Between Analog and Digital Displays. Diss. University of Otago, 2013.

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b) v případě odkladu odevzdání práce následující datum odevzdání práce vyplývající z doporučeného časového plánu studia

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V Praze dne .... 9. října 2020

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BACHELOR'S THESIS ASSIGNMENT

(PROJECT, WORK OF ART)

Student's name and surname (including degrees):

Artur Luchkov

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Guides for elaboration

During the elaboration of the bachelor's thesis follow the outline below:

- The aim of this thesis is to evaluate the transfer of both from analog to glass cockpit and glass to analog cockpit to performance.
- Elaborate an current state of the art analysis in the field of transfer between analogue flight, navigation and motor data visualization to a glass cockpit.
- Set up an experimental design for representative and uniform groups of the participants, taking into account the transfer between the two types of cockpit ergonomy.
- Propose a pilot performance assessment methodology based on direct measurements, e.g. piloting errors, and implement these principles into the proposed experiment.
- Evaluate collected data and discuss experimental results in the context of the current state of the art limitations.
- Formulate the conclusions of the thesis.

Graphical work range: According to the instructions of the supervisors.

Accompanying report length: At least 35 pages of text (including pictures, graphs and tables included in the accompanying report)

Bibliography:

Socha, Vladimir, et al. "Pilots' Performance and Workload Assessment: Transition from Analogue to Glass-Cockpit." Applied Sciences 10.15 (2020): 5211.

Wright, Stephen Joseph. The Human Factors of Cockpit Transitions Between Analog and Digital Displays. Diss. University of Otago, 2013.

Bachelor's thesis supervisor: **doc. Ing. Bc. Vladimír Socha, Ph.D.**
Ing. Lenka Hanáková

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b) in case of postponing the submission of the thesis, next submission date results from the recommended time schedule

L.S.

doc. Ing. Jakub Kraus, Ph.D.
head of the Department
of Air Transport

doc. Ing. Pavel Hrubeš, Ph.D.
dean of the faculty

I confirm assumption of bachelor's thesis assignment.

Artur Luchkov
Student's name and signature

Prague .... October 9, 2020

Declaration

I hereby declare that I have completed this thesis with the topic "Effects of Analog to Glass Cockpit and Opposite Transition on Pilot's Performance" independently, and that I have attached an exhaustive list of citations of the employed sources.

I do not have a compelling reason against the use of the thesis within the meaning of Section 60 of the Act No. 121/2000 Sb., on copyright, rights related to copyright and amending some laws (Copyright Act).

In Prague on 09.08.2021

……………………………...

Artur Luchkov

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Název bakalářeké práce

Vliv přechodu z analogového na glass kokpit a naopak na výkonnost pilota

Abstrakt

Oblast designu kokpitu letadla je v současné době zastoupena 2 odlišnými rozvrženími: analogovým a digitálním (glass cockpit) zobrazením údajů. Během své profesionální cesty může pilot občas muset mezi těmito rozvrženími přecházet. Tato změna v ergonomii kokpitu je považována za faktor nepříznivě ovlivňující výkon pilota. Tato práce se zabývá problémem přechodu mezi oběma zobrazeními, a to v obou směrech, a zkoumá specifické efekty tohoto přechodu společně s jejich příčinami. 20 pilotů – studentů s různou úrovní zkušeností bylo rozděleno do 2 skupin podle jejich počáteční zkušenosti: Gr. A (15 subjektů) – piloti, kteří mají zkušenosti výhradně s analogovým zobrazením a Gr. B (5 subjektů) – piloti, kteří létali pouze s digitálním zobrazením údajů. Během 2 simulovaných letů byli účastníci podrobeni přechodu mezi kokpity, přičemž byl sledován výkon pilotáže ve formě odchylek od předem stanovených parametrů pozorovaných před přechodem a po něm. Údaje o srdeční aktivitě byly zaznamenány pro účely hodnocení psychofyziologického stavu. Studie identifikovala obecně mírné negativní efekty přechodu kokpitu z hlediska přesnosti pilotáže, které byly spojeny s umělým horizontem, zatáčkoměrem, gyrokompasem a variometrem. Přechod z glass cockpitu na analogový kokpit se pak zdá být problematičtější. Z hlediska psychofyziologického stavu subjektů nebyly pozorovány žádné významné odchylky.

Klíčová slova: bezpečnost v letectví, kokpit, přesnost pilotáže, variabilita srdečního rytmu, výkonnost

Bachelor Thesis Title

Effects of Analog to Glass Cockpit and Opposite Transition on Pilot's Performance

Abstract

The field of aircraft cockpit design is currently represented by 2 distinct layouts: analog and glass. Throughout their professional path, a pilot may occasionally have to transition between the two. This change in cockpit ergonomics is believed to be a factor adversely affecting piloting performance. The present thesis addresses the issue of cockpit transition in either direction and investigates its particular effects, along with reasons behind them. 20 student pilots with varying levels of experience were split into 2 groups depending on their initial experience: Gr. A (15 subjects) for pilots possessing experience exclusively with analog cockpits and Gr. B (5 subjects) for participants who have flown only with glass cockpits. Within 2 simulated flights, the participants were subjected to a cockpit transition with their respective piloting performance in the form of deviations from predetermined parameters observed before and after. Heart rate data was recorded for the purposes of psychophysiological state assessment. The study identified generally mild negative effects of the cockpit transition in terms of piloting precision and attributed them to the attitude indicator, turn-slip indicator, heading indicator, and variometer. Transition from glass to analog cockpit appears to be more troublesome. No significant variations in the psychophysiological state of the participants were observed.

Keywords: aviation safety, cockpit, piloting precision, heart rate variability, performance

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List of Abbreviations

AI	Attitude Indicator
ALTM	Altimeter
ANOVA	Analysis of Variance
ASI	Airspeed Indicator
CDP	Concurrent Duration Production
EASA	European Aviation Safety Agency
ECG	Electrocardiography
EEG	Electroencephalography
EFIS	Electronic Flight Information System
Gr. A	First group of test subjects
Gr. B	Second group of test subjects
HF	High Frequency power in HRV
HI	Heading Indicator
HRV	Heart Rate Variability
HRVAS	HRV Analysis Software
IFR	Instrument Meteorological Conditions
IMC	Low Frequency power in HRV
LF	Maneuvers 1-6
M1-6	Mean of R-R intervals
mRR	National Aeronautics and Space Administration
NASA	National Transportation Safety Board
NTSB	Primary Flight Display
PFD	Root Mean Square of Successive R-R intervals Differences
RMSSD	Standard Deviation of successive N-N intervals
SDNN	Task Load Index
TLX	Turn and Slip Indicator
TSI	Visual Flight Rules
VFR	Virtual Reality

VMC	Visual Meteorological Conditions
VR	Virtual Reality
VSI	Vertical Speed Indicator

Introduction

With no doubt, flying is one of the greatest technological marvels ever achieved by the humanity. Even today, over a century after the Wright's brothers first powered flight, a sight of an airplane lifting off the ground would take away the breath of many. However, what is typically hidden from the eyes of some casual observer watching a winged machine seamlessly overcome the Earth's gravity is efforts of countless professionals and thousands of parts flawlessly working together in an immensely complex architecture largely built around one person who has the privilege to guide this metal bird up into the skies – the pilot. In fact, in a controlled flight, the pilot and their airplane can possibly be viewed as a single, united entity rather than two separate elements. It is made even more amazing by the fact that the human body is not exactly adapted to this process – we, obviously, have no senses for airspeed or altitude, cannot perceive the horizon without external cues, and generally have no clue about the position of the magnetic north. Thus, the element serving as the facilitator and mediator in this symbiosis is the cockpit and specifically the instrument panel representing an extension of our natural perceptual systems. Therefore, it comes as no surprise that the ergonomic flight deck is of a paramount importance for aviation and its safety.

Ergo, its standardization was expected: after a relative chaos of the early days of flying, following numerous theoretical studies and tragic practical lessons learnt, a universal required instruments' arrangement was legally secured in 1957 [1]. It took the form of the so-called "six-pack" or "basic six" consisting of two rows: airspeed indicator, artificial horizon, and altimeter at the top, along with turn-slip indicator, direction indicator, and vertical speed indicator at the bottom. The "basic six" practically forged the analog cockpit layout and, despite the aviation's impressive progress rates, had predominantly defined a typical airplane's cockpit for decades [2].

Therefore, when within a span of just 3 years a new cockpit type made its way from being certified in a general aviation airplane for the first time to practically becoming "default" on 90% of newly produced piston-powered aircraft in the 2000s, it can be considered a full-fledged technical revolution. Thus, the glass cockpit rapidly entered the world of general flying and a subsequent competition with the aforementioned "steam gauges". While being of no particular novelty to the industry in general (its first implementations appeared in the 1970s with bulky cathode ray tube displays in large commercial aircraft), this design tremendously increased the number of pilots exposed to it after the introduction to light flying. The glass cockpit, with no doubt, has firm ergonomic grounds and was engineered largely to resemble the analog cockpit and follow similar principles. A side-by-side comparison of these two typical cockpits is given in Figure 1. A typical PFD (primary flight display) is composed of an airspeed tape on the left, attitude indicator in the center, altimeter with vertical speed indicator on the right, and heading indicator at the bottom. It is evident that they both are optimized for the same T-shaped scan pattern.

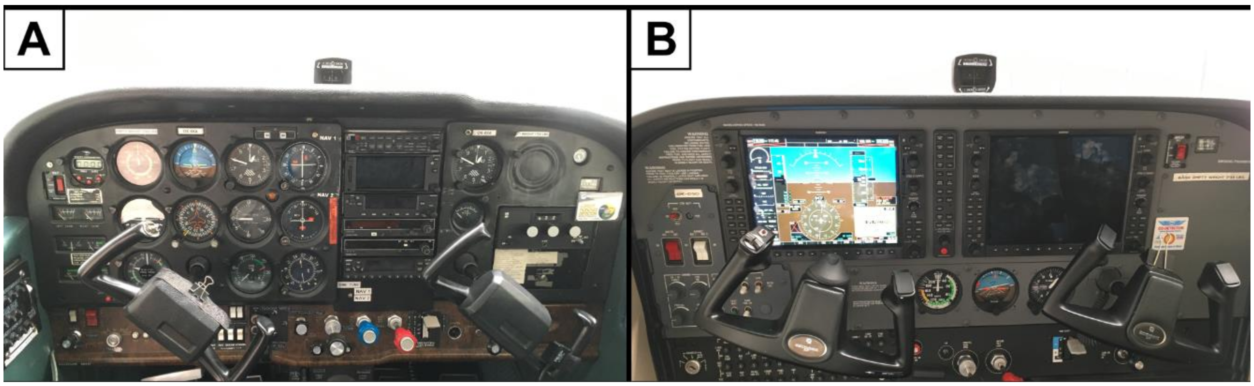

Figure 1. A typical analog cockpit (A) next to a typical glass cockpit (B)

Now that practically any pilot can occasionally face them both, despite a degree of similarity they share, as National Transportation Safety Board of the US (NTSB) notes in their review, transitioning from the analog cockpit to the glass cockpit is associated with certain perception and interpretation risks [2]. The opposite transition raises identical questions. Despite appearing significant, it is evident through the following literature review this issue has gone largely unnoticed by most of researchers and stays relatively understudied. Nonetheless, the same NTSB study indicates that situations involving cockpit transition have led to loss of human life.

Thus, the present thesis will comprehensively review the field of cockpit transition from analog to glass and vice versa, focusing on the avionics primarily used in the general aviation environment. It will assess its effects on the piloting performance, along with addressing the psychophysiological state of the pilots involved. This thesis aims to lay a pathfinding framework to analyze and isolate the reasons behind any effects such observed.

Chapter 1 – Current State of the Art Analysis

1.1. Literature Review

The issue of transitioning between analog and glass cockpit designs contains a substantial number of variables requiring a comprehensive review of the topic. Thus, apart from factors concerning the fact of the transition itself, the general performance and characteristics of the concepts are worth being assessed. Nevertheless, the limited amount of available scientific literature describing the problem imposes certain constraints with regards to the present review.

1.1.1. Comparison of the two cockpit designs

In terms of the general safety of the given instrument panel designs, an NTSB study in 2010 (the latest comprehensive study publicly available within the field to this day) determined that an aircraft equipped with a conventional cockpit is, normally, more likely to be involved in an accident [2]. However, despite a lower accident total rate, airplanes fitted with glass cockpits demonstrated a greater fatality rate per the accumulated flight time. The research found significant discrepancies within the nature of the mishaps in terms of purpose and planned length of the accident flights, the pilot age, certification, and experience, number of the flight crew. According to the publication, accidents involving aircraft with glass cockpits installed typically happened to older and more experienced pilots engaged in single-pilot operations who were more likely to hold an instrument rating and were performing a private or business flight. Meanwhile, practically the opposite situation was observed around airplanes fitted with conventional cockpits: the average pilot age was younger, the operations typically involved two pilots on shorter flights, which is consistent with flight instruction and training, historically showing a lower accident fatality rate. However, even when accounted only for private or business flights, the tendency of a lower general accident rate but a greater fatality remains valid for aircraft with glass cockpits. Additionally, the study also indicated a glass-cockpit-equipped airplane to be more likely to experience an accident in instrument meteorological conditions and at night despite featuring design elements specifically intended to improve spatial orientation and the flight crew holding higher levels of certification. Although, it is worth noting that the difference is only marginally significant. Interestingly, the same report states that most pilots prefer the glass cockpit design and believe it enhances flight safety.

Notably, one study suggests this counterintuitive tendency to be an example of the so-called performance-preference dissociation [3]. This phenomenon has been observed to occur to certain computerized systems up to an extent where the interface offering the worst performance was top-rated by the users [4]. In the specific case of analog and glass cockpits, it can be partially attributed to the colorfulness of the latter. This experience is rather prominent throughout certain other research papers. Thus, one publication compared perceived and measured effects of the glass cockpit for 12 relatively experienced pilots (the median number of flight hours was 3950, 3 pilots holding air transport pilot license and 9 commercial pilot license holders), specifically the performance and the workload [5]. The participants flying in the glass cockpit were performing steadily worse in terms of the number of piloting errors during all 4 test phases of flight: setup, en-route, approach, and missed approach. All the subjects are claimed to have had previous experience with advanced cockpits, therefore, the identified trend should not be fully attributed to possible transition effects. The workload measurements were inconsistent: the glass cockpit decreased it at some phases while increasing it during the other. Nevertheless, once again, the pilots reported a lower workload at the post-flight survey. Thus, even though one of the pilots' main arguments in favor of the glass cockpit is its workload-lowering effect, the results, according to the author, "offer little support for the idea that advanced cockpit systems reduce workload or the incidence of error among experienced pilots during normal flight operations".

Another research compared upset condition recovery times between simulated glass and analog cockpits [6]. While not indicating any statistically significant difference in the recovery response time, the study found a substantial disparity in the time it took to return the airplane to a straight and level flight. On average, an unusual attitude recovery in the glass cockpit could take up to 5 seconds longer than in the analog cockpit. The paper interpreted the results to suggest that a glass cockpit itself might not be as beneficial for the pilot's performance as previously claimed. However, despite the participants possessing private pilot licenses and flying both cockpits within the study, the factor of the cockpit transition was not considered. Since their previous experience with the aforementioned designs and any possible previous transition was not described, it can be disputed whether the decrease in performance was caused exclusively by fundamental flaws of the glass cockpit layout or could have been partially contributed to by operating an unfamiliar instrument panel. Another unknown within this publication is the use of airspeed and altitude trends - it is not specified by the authors and could have affected the validity and current credibility of the results in case they were not used.

Nevertheless, as to what can potentially cause this lower performance, the researchers' opinions across the realm differ and very limited information is available. Specifically within this publication, based on feedback from the participants, the researchers attributed the increase in recovery times for the glass cockpit to the usage of vertical tape displays instead of the round dials for the indication of airspeed and altitude, one of the most distinct differences from the analog cockpit. The vertical tapes were criticized by the subjects for requiring more attention for the specific number read-out and not displaying the whole values range. Round dial instruments were found to be more suitable for quick instrument scanning, where, for instance, the airspeed indicator's needle observed at the 3 o'clock position with a peripheral vision would indicate a low airspeed. The same principle can be applied to the analog altimeter, where the long needle at the 12 o'clock position would indicate the level at thousands of feet. Based on the findings, the paper recommended changing the altitude and airspeed indication type on glass displays. These conclusions correspond to certain other studies comparing round dials and vertical tapes.

Furthermore, a study by USAF specialists seeking the most efficient method for displaying the aforementioned parameters for HUD standardization determined moving round pointers to perform better in terms of piloting precision, not necessarily influenced by the previous experience of the pilot [7]. However, it is also worth noting that this study involved relatively experienced navy pilots who had accumulated approximately 2800 flight hours on average and, therefore, may not be directly applied to the area of civil and especially general aviation flying. In addition, it is also notable that the round-dial display format used within this research still involved a digital speed readout in the center of the indicator and the scale represented only the last two digits and not the whole airspeed range, thus, being different from conventional airspeed indicators. Nonetheless, findings of this research may suggest that a moving pointer might have a potential to perform better in terms of trend identification than trend lines present in modern glass cockpits. As the researchers noted, "rotating pointers are probably more effective because their position and movement are relatively easy to detect in parafoveal and peripheral vision".

Undoubtedly, this topic was a subject of numerous studies at the time of the massive industry transition towards the EFIS (Electronic Flight Information System) in the late 20th century. While the designers' decisions made definitely had certain ergonomic grounds, unfortunately, very limited information is available detailing them. Thus, a paper on the development process of the 747 PFD notes that the Boeing company came to generally negative results in their human factors investigations on vertical tapes: "They lacked relationships that were used extensively by pilots in performing flight tasks. This perception was strengthened by human factors research, which also concluded that, in general, moving scale displays are not as effective as moving pointer displays. The design constraints for the 747-400 PFD and the controversies that surrounded the vertical tape presentation provided a significant challenge to the display design engineers" [8]. It notes that the whole development process of the moving-scale fixed-pointer displays was driven by explicit customer requests, which, in turn, were motivated by the maintenance and space savings demonstrated by Airbus in its A320 cockpit. Interestingly, according to the same publication, Boeing still considered a hybrid glass display design containing digital round-dial airspeed and altitude indicators, but this somewhat exotic solution did not make it to the final design.

Another research publication from the same timeframe offers some support to the idea of round-dial instruments' superior performance. Thus, a NASA study in 1987 investigated different options for integration of vertical airspeed and altitude tapes within the PFD [9]. A number of options were considered and experimentally verified with different variations in high-to-low and low-to-high displays, indicators with and without trend information, etc. Yet again, a slightly better piloting performance and lower workload were observed within the deviations from the vertical path when electromechanical round-dial altitude and airspeed indicators were used. The paper offers a different explanation for such findings: the authors suggest that the electronic display formats providing exact and continuously updated airspeed and altitude read-outs encouraged the pilots to perform unnecessary corrections for small and insignificant deviations. Notably, a factor the research does not mention is a possible influence of the test pilots' experience on this deviation on performance, which, given the year of the research, can be expected to have been limited. Similarly to the aforementioned publications, the pilots yet again expressed their clear preference for the moving tapes and a fully glass cockpit. In order to quantify the remaining capacity of the test subjects, the study implemented a secondary task represented by reacting to arrows appearing on a screen. Performance within the secondary task led to some unexpected conclusions with regards to the trend information representation: while no significant difference in primary task performance was observed with and without the trend information (airspeed and altitude trend lines) on the PFD, the secondary task performance turned out to be better for screen layouts without any trend indication. The researchers attributed these findings to sensitivity of trend display to path tracking errors making pilots adjust the flight path in response to insignificant errors and thus taking up their capacity. It is also crucial to note that the experimental setup involved airspeed and altitude selection bugs.

Ergo, the aforementioned 4 studies and their conclusions can be summarized as the following: there are reasons to believe that round dials present in the analog cockpit might deliver superior performance in the realm of trend identification, maintenance of the required parameters, and workload when compared to the glass cockpit despite the latter, for example, explicitly displaying trend information and reference values.

Nevertheless, the materials still leave a number of unknowns and the conclusions, along with their significance, shall be subject to further investigation and discussion. The issues described partially belong to a 30-year-old timeframe and, given the amount of operational glass cockpit experience accumulated, might have been mitigated. At the same time, while the ergonomics of moving tapes can be questioned to an extent, other components of the glass cockpit have a potential to deliver better performance. For instance, a study from 1990 comparing the pilots' interaction with the analog Boeing 747 cockpit and the partially glass cockpit of the Boeing 767 came to a conclusion that an integrated electronic display is preferable when it comes to quick scan and information acquisition [10]. Apart from that, studies report a number of other ergonomic advantages of EFIS over their electromechanical counterparts [11].

1.1.2. General issues of cockpit transition

In terms of studies specifically concerning the issue of transition, most publications indicate a decrease in the pilots' performance. Thus, the latest comprehensive research in the field examined 20 participants divided into two groups transitioning from the analog cockpit to the glass design [12]. One of the groups received additional training covering aspects of the new instrument scanning techniques related to glass cockpits. Importantly, unlike most previous studies, this research included measuring piloting precision along with collecting physiological data in the form of Heart Rate Variability (HRV), shedding light on pilots' workload and stress. Furthermore, a part of the data collection was performed on real aircraft, contributing to the credibility and applicability of the research. The analysis confirmed transitioning between the ergonomics of the analog and glass cockpits to be a potentially stress-inducing and performance-impairing factor. However, according to the publication, the increased stress does not necessarily lead to piloting precision deterioration. Additionally, the workload was determined not to have been influenced by the flight data displays change within the research despite the authors' expectation. It is believed that adequate transition training could mitigate the performance decrease associated with the transition. These conclusions are, generally, consistent with the findings of the previous studies. Thus, a publication by the Technical University in Kosice acknowledged the negative impact of the cockpit transition and the potential of special training to diminish it [13].

Another well-controlled study investigated the issue of transition on 62 participants without any previous flying experience [3]. Notably, subjects demonstrated a significantly lower flight performance upon being tested on glass cockpits. Interestingly, the previous training with the initial instrument panel before the transition was determined to have had little effect. However, according to the publication, it can be attributed to a relatively young mean age of the participants and their better computer adaptation capabilities. The researchers observed no significant deviations in the workload between the two designs. Nevertheless, the following trend was identified: the participants who were trained and tested using the glass cockpit had the highest subjective workload and the lowest performance. One of the possible explanations for these results the publication suggests is an increased fixation time for the glass instruments compared to their analog counterparts. Nevertheless, the authors noted the restricted applicability of their findings since the subjects had no flight experience and their training sessions were substantially shorter than those undergone by actual pilots.

A publication from 2006 detailing practical experience of the glass cockpit implementation in a flight school with previously analog fleet serves as another important source of information concerning the issue [14]. Thus, 17 instructors (14 of whom later underwent familiarization training) were offered questionnaires detailing their new experience. One of the problematic areas reported was adjusting the instrument scan to the newly introduced instrument panel. Thus, one instructor made a remark about flying at the altitude of 1480 feet with the target of 1500 feet, which caused confusion as to why he cannot precisely hold the required level. This 20-feet difference would otherwise not be noticed in an analog cockpit. 8 instructors expressed concerns in the similar realm of getting the right information from the PDF at the required time, with one of them claiming to have mistaken the altitude for the vertical speed. Similar comments were replicated on several flights (their difficulty rating stayed low) after the introduction of the glass cockpit, however, they eventually disappeared as the pilots gained greater experience in operating technologically advanced aircraft. Therefore, the study concluded that, with extensive preparation, such airplanes can be successfully implemented into the process of flight training (along with the required cockpit transition involved) and that the aforementioned issues can be mitigated. In terms of transition training, the authors suggest that additional ground sessions with computerized training covering the use of the PFD and other systems may be of considerable use.

The literature review has been able to find a rather limited amount of empirical evidence concerning specifically the transition from the glass cockpit to the conventional instrument panel. Thus, a study in 2012 investigated 6 student pilots receiving their training in glass-cockpit-equipped aircraft [15]. They were split into two groups (control and treatment) one of which had to undergo a transition from the glass to the conventional instrument panel while flying in cruise and approach phases of flight. A substantial decrease in pilots' performance was observed within the experiment, which is especially concerning, according to the authors, with regards to the approach since it is a critical phase of flight. However, since only 6 subjects were involved in data acquisition, the specific results should be taken as preliminary. Another study focused on two groups of low-hour instrument-rated pilots executing simulated instrument approaches applying the instrument landing system, using either the conventional or glass cockpit [16]. Half of the participants received their instrument training in glass-cockpit-equipped aircraft (it is important to note that some of the subjects had up to 40 hours of instrument time in analog cockpits), while the other half was trained using the conventional instrument panel. Surprisingly, the pilots' performance in the glass cockpit was substantially better than in its analog counterpart. It was interpreted by the authors as an indication that transition back to flying with analog instruments after the glass cockpit can be especially troublesome. Nevertheless, some reviewers noted that the research involving two different simulators, no random participants' training assignment, and the unaccounted potentially contributing effects of the pilots' previous experience with the two cockpit designs "present major threats to the internal validity of these findings" [3].

Furthermore, in terms of glass-to-analog and reverse transition, not all studies have been able to identify a distinct piloting performance decrease attributed to previous operations with EFIS. Thus, a study by Embry-Riddle Aeronautical University in 2006 analyzed performance of 110 professional pilots with both varying total flight experience and specifically glass cockpit operations background [17]. The average total flight time was 5.583 hours, while pilots with EFIS experience had accumulated, on average, 5.700 hours in total and 2.034 hours in a glass cockpit. The participants were asked to manually perform an hour-long flight composed of a take-off, a complex instrument departure procedure, various maneuvers and instrument procedures followed by an instrument approach. An air-transport-grade simulator with a round-dial conventional cockpit was used within the experiment. Although glass-experienced pilots expressed slightly less confidence in their instrument scans and flight performance compared to their counterparts without considerable glass cockpit experience, no statistically significant correlation between the type of previous experience and the piloting errors was found. The study only identified an expected positive relation between the total flight experience and the piloting precision. Thus, the hypothesis of performance degradation as a result of cockpit transition was not confirmed. Interestingly, the paper has also been able to identify an additional positive correlation between the EFIS experience and instruments procedures proficiency. While particular reasons remain unknown, the authors suggest that better visualization techniques of glass cockpits might contribute to pilots' understanding of certain maneuvers (for example, holding).

While the aforementioned studies shed some light on the piloting performance directly following the transition, the issue of long-term effects of the ergonomics change is not documented to a considerable extent. The present literature review has been able to retrieve only one study explicitly investigating the topic. The research specifically focused on student pilots transitioning from the conventional instrument panel to flying the glass cockpit within their training [18]. 35 subjects were monitored for their piloting technique progress over a period of a semester (6 months) including two assessment flights (in Spring 2010 and Autumn 2010). The study came to surprising results: 18 out of 35 students (51,43%) demonstrated a decrease in their piloting abilities 6 months after switching to the glass cockpit, despite presumably having gained more flight time and experience. The maneuvers performed at both flights are very similar, and the standard progression of learning, according to the researchers, shows that student performance should have improved over time. A follow-up survey was introduced for further investigation of the issue receiving 30 usable replies. According to the obtained data, more students felt less prepared for the autumn flight than for the spring one. 70% of the student pilots felt less comfortable on the autumn check, and five subjects reported not feeling fully prepared by their instructors. Overall, 76% of students felt prepared for the autumn check while the number was 92% for the spring test. It was believed by 21 out of 30 survey participants that the autumn check had been more complicated. Only 5 pilots stated the Spring check to have been more troublesome. 13 out of 30 reportedly had more difficulties flying with the glass cockpit than with the analog one. The two most problematic areas mentioned were glass-cockpit aircraft systems and the Garmin G1000 (Garmin Ltd., Olathe, Kansas, U.S.) unit operations. The students believed that more attention should be allocated to aircraft familiarization and differences training. Thus, the study has concluded that the cockpit transition had had a generally negative impact on the students' success rate over the semester, which can be considered rather long-term when compared to other publications in the field. These unexpected findings after such a substantial period following a transition raise certain questions with regards to adaptation to the new cockpit and possibly transition training as such. Nevertheless, generalization shall not be made until more research involving larger samples over greater time periods is available.

1.1.3. Additional factors affecting cockpit transition

Aside from the instance of transition itself, there are a number of additional factors possibly affecting it to be considered. Thus, a suspected factor associated with the cockpit transition is the age of the pilot. A study in 2008 working on specific transition training recommendations observed younger pilots experience fewer issues transitioning to the glass cockpit owing to having grown up in the age of computers while older pilots had a significantly harder time throughout the process [19]. Another publication summarized the effects of aging with regards to the issue and reviewed the accident-related statistics [20]. It concluded that age-induced cognition degradation and the complexity of operating a glass-cockpit-equipped aircraft themselves may already represent an issue. The review of the NTSB accident data demonstrated an increase in accident rates for both cockpit types. It was stated that older learners require a different study program that should focus not solely on traditional maneuvering-based skills, but also on flight management and critical thinking. The publication emphasizes the importance of scenario-based training implementation for these purposes.

Another additional factor and a special case of transition to consider is the so-called "mixed-fleet flying" occurring when the pilot has to be transitioning from one cockpit to the other and vice versa on a daily basis. The review has been able to retrieve a publication concerning evidence-based decision making using a practical example of an airline experiencing the issue [21]. A company operating the ATR 72-500 aircraft had purchased the ATR 72-600 model which, unlike its predecessor, incorporated the glass cockpit design. Otherwise, aside from slightly different positions of switches in the cockpit, the two aircraft types are practically identical. Thus, the pilots had to experience interchanging forward (to the glass cockpit) and backward (to the conventional cockpit) transitions. In particular, the study observed airspeed interpretation difficulties during high workload-situations due to different indications in the two cockpit designs. For example, when required to make an immediate decision to abort or to proceed with the take-off, the crew experienced a confusion as to how fast they were moving. In addition, a number of other errors, misunderstandings, and slowdowns associated with the new cockpit were observed (mostly, automation and equipment interaction). Some issues were reported to have occurred even 12 months after the transition training. According to the research, a clear example of the mixed-fleet flying risks is the crash of Lao Air Flight QV 301 caused by inadequate monitoring of primary flight parameters. This accident will be further reviewed in chapter "Practical Implications of Cockpit Transition". Notably, the airline participating in the study decided not to proceed with its initial plans for the mixed-fleet flying due to the safety concerns uncovered.

1.2. Practical Implications of Cockpit Transition

Based on the publications considered within the literature review, it is evident that the issue of cockpit transition bears certain significance in terms of its practical implications to flying. This statement is supported by factual evidence reviewed further within this chapter.

1.2.1. Case studies

In terms of the analog-to-glass transition, according to the literature review, one of the risks is likely to be represented by a possibly impaired instrument scan, specifically reading of altitude and, most importantly, airspeed, which are critical flight parameters. An example of the issue leading to a fatal accident is a crash at Socorro, New Mexico on the 19th of September 2011 [22]. Having spent around 30 minutes of familiarization training in a newly purchased aircraft, an experienced (4000 total flight hours) commercial pilot license holder departed for a ferry flight with his son. The flight was to be performed under Visual Flight Rules (VFR). The deadly crash occurred on the approach at their destination and was attributed to the pilot's failure to maintain adequate airspeed while maneuvering, taking the lives of the two people on board. The investigators traced the cause to the pilot's lack of familiarity with the new airplane and specifically the EFIS. Their conclusions are supported by the previously mentioned short training time and the pilot's claims of the difficulty of airspeed and altitude read-outs in EFIS later recalled by the airplane seller. It is important to note that an additional factor of specific medication use possibly leading to certain sedative effects was listed as contributing, however, the particular extent of the possible impairment cannot be determined.

As the previous case study demonstrated, despite the same general idea of instrument indications in the glass and the conventional cockpits, the required scanning techniques and pilots' expectations differ substantially. However, it is not only a different instrument scan that can lead to pilot confusion but also certain display features of the glass cockpit. Thus, the following case study was mentioned in the 2010 NTSB report [2, 23]. On April 7, 2007, near Luna, New Mexico, a Cirrus SR22 (registration N953CD) piloted by a private pilot under Instrument Flight Rules (IFR) was climbing through an area with prevailing Instrument Meteorological Conditions (IMC). The airplane was in the clouds and reportedly encountered icing conditions that led to the pitot tube becoming blocked. As a result, the airspeed indication became unreliable forcing red crosses to be displayed instead of the airspeed and the altitude tapes. As the pilot reacted by immediately initiating a descent and turning the pitot tube heat on the speed reading reappeared on the display. However, the Primary Display (PFD) then "went haywire" (started displaying a red "X" as an indication of unreliable data), as described by the pilot, the terrain warning system sounded, and the pilot activated the emergency ballistic parachute system. The aircraft came to rest inverted lying on the trees with its empennage separated and the outboard portion of the right wing crushed. The subsequent NTSB investigation revealed that the error indications with red crosses were the expected behavior of the system according to its design. The EFIS automatically replaces unreliable information with X-flags. Nevertheless, instruments' response to a pitot tube blockage in a conventional cockpit is drastically different - the airspeed indicator would eventually display zero with all the remaining instruments, including the artificial horizon, functioning properly. While the pilot did cross-check the airspeed indication with the backup airspeed indicator, he failed to verify readings of the backup attitude and altitude indicators displaying critical and correct information. The situation caused him to interpret the pitot tube blockage with ice as a complete air data computer failure, as he lacked familiarity with the system, leading to an inadequate reaction. Importantly, this kind of abnormal-situation behavior can differ from one EFIS to another one as the research notes. Unfortunately, not all airplanes are equipped with an emergency ballistic parachute, and thus, for example, another airplane (Piper Meridian) mentioned in the NTSB study experienced a similar condition of pitot tube blockage and broke up mid-air in the result of all air data parameters in the PFD having been lost [2]. Similarly to the previous accident, the standby gauges must have provided sufficient information for the flight to continue in a safe and stabilized manner. Although the particular avionics systems involved are not specified, the report claims that these accidents forced the manufacturer to review the system philosophy of disabling all the air data parameters as a result of a pitot input failure. Respective changes are claimed to have been made to the avionics manual. Nevertheless, certain EFIS can exhibit a similar kind of behavior to this day. Thus, for example, a manual for one of Aspen Avionics units (Aspen Avionics Inc., Albuquerque, New Mexico, US) warns that inputs from the pitot-static system serve as a component of the eventual attitude and heading reference system solution, and therefore, pitot tube or static port blockage has a potential to lead to a complete loss of various PFD indications, including intuitively unrelated attitude and heading [24]. However, it is worth noting that a "check pitot heat" message will be displayed. Nonetheless, principally it leaves a potential for a similar situation to occur again.

While the aforementioned situations are generally related to general aviation flying (a single-engine piston airplane flown within a class rating), the hazards of cockpit transition are still relevant within a considerably wider scope involving commercial aviation. The following accident is a clear example of mixed-fleet flying threats described within the literature review. In fact, it is the case that affected the final decision of an airline to abandon the idea of simultaneous operation of ATR-72 aircraft with glass and conventional cockpits in the reviewed study [21, 25]. It is the crash of Lao Airlines Flight QV 301 that took place on October 16th, 2013. It involved a 4-month-old ATR-72-600 (an ATR-72 version equipped with a glass cockpit), an experienced captain (5.600 hours total, 3.200 hours on the type), and a relatively new first officer (around 400 flight hours in total). The crew was type-rated to operate both variations of the ATR-72 - an EFIS-equipped and modernized -600 version and the conventional -500 model. The flight was performed under IFR as the airplane entered IMC in the form of heavy rain and thunderstorm while performing a non-precision approach (without vertical guidance) at Pakse, Laos. The approach chart contained an error displaying the minimum descent altitude to be lower by around 350 feet than the required 990 feet. However, the crew set their minimum descent altitude even lower - almost 400 feet below the established minimums. In addition, the selected minimums of 600 feet was for an unknown reason also set as the selected missed approach altitude. These factors substantially reduced the obstacle clearance. The crew discontinued the approach and activated the go-around mode. In accordance with the avionics philosophy, flight director bars appeared on the PFD to guide the pilots for the maneuver, however, they immediately switched to the altitude hold mode since the airplane was approximately at the erroneously selected missed approach altitude. This led to crew confusion and further inadequate primary flight parameters monitoring as they followed the required lateral profile but not the vertical one. The crew eventually overreacted and reached a roll of 37 degrees with pitch attitudes of up to 25 degrees before the aircraft struck a riverbank taking the lives of all 44 passengers and 5 crew members on board. Unfortunately, the review has not been able to acquire the full final report for the accident since only its summary has been made publicly available. Nevertheless, from the findings and conclusions available, it is evident that among a number of other significant factors (an error in the chart, crew mis-cooperation, possible illusions) the issue crew’s transition to the new type did indeed contribute to the tragedy. One of the safety recommendations issued to the operator directly addresses the issue and emphasizes the significance of ensuring that all the crew members are competent in simultaneous operations of the conventional ATR-72-500 and the glass ATR-72-600 after appropriate training.

1.2.2. Legal provisions

Based on the studies and the case studies reviewed, it can be said that cockpit transition may indeed pose a threat to flight safety. Ergo, it comes as no surprise that this point is reflected by the current legislation. Thus, EASA (European Aviation Safety Agency) Part-FCL.710 requires the pilot to undergo familiarization or differences training for transitioning between airplanes with EFIS and analog cockpits even if the transition takes place within the same class or type or airplane [26]. In the case of a complex airplane requiring a type rating, the particular amount and type of training depends on the aircraft certification conditions. It corresponds to the previously mentioned research conclusions emphasizing the importance of transition training for switching cockpit types. Both differences and familiarization training include acquisition of new knowledge, however, differences training also implies a certain extent of practical preparation. It is required to be secured with a record in the logbook supported by the instructor's signature. Nevertheless, a detailed syllabus for these two transition training types do not exist and conditions for either are not specified.

1.3. Piloting Performance and Workload Analysis

Since pilots' performance analysis is a crucial part of this research, reviewing various approaches available in this regard is within the scope of state of the art analysis. Most studies considered within the literature review applied piloting precision (deviations from the required flight parameters) as the measure of the performance. It was noted that the choice of the specific measurement technique is generally governed by the hardware used: experiments involving real airplane flights typically incorporated an instructor manually recording maximum deviations from the predetermined parameters [12], while purely simulator-based experiments utilized mean or standard deviations of the designated flight readings [3]. The raw data obtained was not necessarily used for further statistical analysis directly and typically was processed and possibly normalized, however, the mitigation of these issues is in the scope of Chapter 3.

Nevertheless, piloting performance, despite being the main focus of this study, can further be augmented by analysis of additional factors affecting it. It can serve as a viable tool to shed light on the possible origins of piloting performance variations within the experiment. Thus, previous research in the field of mental workload determined that performance can be directly and adversely affected by demanding situations with excessive workload causing a decrease in the resulting performance [27]. This hypothesis is supported by the following empirical evidence. An experiment involved participants taking several simulated flights with increasing difficulty achieved by deteriorating atmospheric conditions and failures [28]. Their deviations from the required parameters were consistently higher in the case of the more complicated and demanding flight. Therefore, workload data, when collected along with piloting precision indicators, can serve as an additional tool for further data analysis.

Ergo, it comes as no surprise that certain cockpit transition studies within the literature review incorporated some forms of workload recording [3, 5, 12]. However, the selected methods of workload assessment vary: subjective workload questionnaires, concurrent duration production (CDP), electroencephalography (EEG), and electrocardiography (ECG) or heart rate variability (HRV) analysis, etc.

The most popular subjective (questionnaire) approach applied in the papers acquired within the literature review is NASA TLX (Task Load Index) developed by the agency in the late 1980s [29]. It offers the participants to rate their experience according to 6 scales: mental demand, physical demand, temporal demand, performance, effort, and frustration level. Despite the advantage of its relative simplicity and surprisingly high precision as for a questionnaire, NASA TLX developers recognize certain limitations resulting in undesirable index variability. They include but are not restricted to, experimental variation in the magnitude of some factors, differences in the rules by which individuals combine information about the task, their own behavior, and psychological responses to the task into subjective workload experiences. While these measures are relatively easy to collect and are accepted by the participants, all types of subjective workload assessment do not represent a continuous form of workload monitoring [30]. If performed during a simulator session, NASA TLX can pose an intrusion interfering with the flight task itself, while delays of over 15 minutes in data collection after the task have a potential to compromise data quality, as the critical rating information might be lost [31].

Concurrent duration production (CDP) is applied as a workload measure based on the time perception of the participants. It is believed that time estimation is directly proportional to the workload imposed, while time production is affected oppositely. Nevertheless, this method itself (since it basically involves counting) might interfere with the primary task, according to the researchers [32].

Approaches involving electroencephalography (EEG) analyze the electrical activity of the brain. A paper retrieved within the literature review focused on the event-related brain potential as the measure of workload and proved it to be a feasible option for aviation applications [33], however, the list of available and feasible indicators includes a number of other possible criteria [34].

Measures utilizing electrocardiography (ECG) typically focus on assessing heart rate variability (HRV). It has been observed that physiological arrhythmia (slight variations in the heart rhythm) is diminished under conditions of a higher workload [35]. Ergo, continuous monitoring of the heart rate and its variability (usually in the form of the variability of R-R intervals of the QRS complex) can be incorporated for mental workload determination. An example of the QRS complex with its respective parts marked is provided in Figure 2.

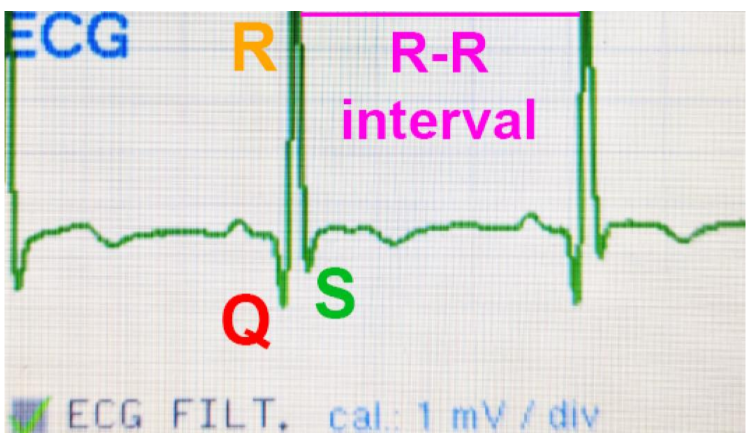

Figure 2. An example QRS complex recorded during the present study

In terms of these methods' performance, the use of heart rate monitoring is believed to be one of the most precise methods for physiological workload assessment. Thus, a paper presented in 2017 specifically investigated various approaches in the branch of aviation [36]. It compared myopotential tracking, respiratory monitoring, and heart rate analysis in terms of their potential for pilot's psychophysiological condition evaluation. It experimentally proved the latter to be a substantially more significant indicator of psychophysiological state than the others. The article attributes its efficacy to the heart rate's direct connection with the parasympathetic activity of the autonomic nervous system. Further general research of the field supports these findings. Thus, a review paper in 2019 compared 91 studies and physiological workload studies used [34]. It was determined that approaches incorporating cardiovascular workload indicators were the most representative, demonstrating a correlation with the actual workload in 76% of the cases. A study in 2020 compared EEG recording, task-performance-based workload assessment, eye movement tracking, and ECG monitoring for the purposes of determining the mental workload within the same experiment [37]. According to their conclusions, the ECG-based method involving HRV was found to have the smallest error, while EEG analysis was associated with the lowest accuracy. In addition, HRV measurements have been said to be one of the least intrusive and operationally acceptable in the realm of aviation [38].

1.4. Limitations of the Current State of the Art

The review of the relevant literature has uncovered substantial limitations within the current state of the art. Most importantly, the field of cockpit transition vastly remains understudied, especially in terms of empirical evidence, despite the proven significance. The data available does not provide an integral picture for any given focus group - for instance, certain issues remain unclear for the field of general aviation flying, while commercial flying offers other unknowns, thus forcing the following research to consciously take some assumptions in between the groups. Practically, the literature review part mentions the majority of available credible and relevant papers retrieved through an extensive search. Unfortunately, their results cannot be taken deterministically as they practically always recommend further investigation of the topic.

With respect to the reviewed articles, only one study investigating both glass-to-analog and analog-to-glass transition side-by-side with actual pilots has been found [16], and it was widely criticized by some authors [16]. The only other research involving both transition types studied the issue on participants with no previous experience [3]. Furthermore, pilot workload analysis supplementation for piloting performance was utilized in a limited number of experiments. In terms of workload assessment, physiological measures were taken only in one research [12], while the others incorporated workload questionnaires or CDP (one more publication [13] claims to have collected physiological measures, however, no respective results are provided). Based on the aforementioned papers comparing different workload assessment techniques, it can be considered as another limitation for the state of the art. In addition, there is little information available as to which specific components of the system or instruments can be causing issues following a transition. These issues can be considered fundamental and are still pending their respective answers.

Other limitations of the state of the art include a generally small size of the investigated groups that are not always found to be uniform. The studies lack a definitive description of pilots' experience on cockpit types. Only several studies investigate the relation between transition effects and the pilot's age (there are other publications on the same topic by the same author that are not included in the literature review) [19, 20]. Further, public research and statistics specifically on transition has been performed mostly within general aviation and less complex airplanes while commercial aviation and advanced avionics are out of focus. Long-term effects of cockpit transition remain a vastly understudied topic with only one research paper explicitly focusing on it [18]. Generally, a considerable amount of the available information belongs to a timeframe around 10-30 years old and has not been publicly updated to this date. Nevertheless, investigation of these issues requires considerable resources, a substantial material base, and a significant amount of time to complete, thus, remaining a viable subject for further research in the long term.

Chapter 2 – Goals and Hypotheses

A comprehensive investigation of the available materials, as it is evident from the section above, has revealed numerous limitations in the state of the art. While piloting performance is of paramount importance in aviation and any factors affecting it represent safety-critical issues, a number of basic questions with regards to the cockpit transition process occasionally faced by pilots within different fields of the industry remain unanswered. It is crucial that the particular mechanisms and factors of transition have not been completely determined yet. Furthermore, little is known about its related physiological manifestations and their background. In addition, as it has been mentioned, transition can take place in either way, and glass-to-analog ergonomics change has even more unknowns into it. These limitations represent the state of the art with regards to an issue that is known to have caused accidents with loss of human life. Thus, the particular points listed above, along with the cockpit transition generally being an under-investigated topic, create the motivation for the present thesis.

2.1. Goal and Partial Goals

Therefore, the primary goal pursued by the present thesis is to investigate the issue of cockpit transition in either direction and to assess its effects on the piloting performance. Achieving the set goal is facilitated by several consecutive partial goals.

The first partial goal is to comprehensively review the materials available for the issue and to indicate particular points of interest, which has been fulfilled by the state of the art review. The second partial goal is to, using the accumulated knowledge, develop and to experimentally verify appropriate methodology for the piloting performance assessment in the realm of cockpit transition. The third partial goal is to apply the said methodology for a controlled measurement of comparable groups of participants in order to assess the effects of the transition on the piloting performance. The fourth partial goal is to apply adequate statistical methods to evaluate the findings and to suggest an explanation for the changes observed.

2.2. Research Questions

Thus, based on the goals set, the present thesis aims to answer the following research questions:

1. What are the effects of cockpit transition on piloting performance?
2. Is there any difference in the response to cockpit transition depending on the initial experience of the pilot?
3. Can the cockpit transition effects be attributed to an increased workload?
4. Which particular elements of the two cockpit designs contribute to the effects of cockpit transition?

2.3. Hypotheses

The present research was initiated with an assumption of the following hypothesis:

1. Cockpit transition has a negative effect on piloting performance.
2. There is a difference in pilots' response to transition depending on the type of their initial experience.
3. Cockpit transition does not induce a greater-than-normal mental workload.
4. The cockpit elements switching from round dials to vertical tapes and vice versa during the transition make a negative contribution to the final outcome.

Chapter 3 – Materials and Methods

The following experiment was planned and arranged in order to assess effects of cockpit transition on the piloting precision, to compare its effects depending on the pilot's familiarity with the cockpit, and to possibly identify the cockpit elements that might cause them. The overall approach and the selection of methods were governed by the respective results of the state of the art review, along with the goals set in the previous chapter.

3.1. Participants

This thesis has investigated the issue of cockpit transition among 20 subjects on a volunteering basis, all of whom were full-time undergraduate bachelor students of the professional pilot program. All the participants had already accumulated varying levels of actual flying experience within their studies before the data collection was commenced. While just a few participants had obtained their pilot licenses, it is important to note that all the subjects had been endorsed to perform solo flights (without an instructor on board). Based on their familiarity with the two cockpit types, they were assigned into one of the two following groups: Group A (Gr. A) and Group B (Gr. B).

Gr. A contained 15 student pilots who had experience exclusively with the analog cockpit. Except for 1 participant who flew Tecnam P92, the volunteers in Gr. A performed the majority of their time building in Cessna aircraft (C150, C152, and C172). All the pilots within Gr. A were at the VFR phase of flight training, with the mean experience being around 70 flight hours. The average age of the subjects within the group was 21 ± 1 years.

Gr. B contained 5 student pilots who had flown exclusively in airplanes fitted with the glass cockpit. Participants in this group were experienced in various Tecnam aircraft types (P2002, P2006, and P2008). Similarly to Gr. A, except 1 flight student in the IFR training phase, Gr. B pilots were proficient in VFR flying, having accumulated approximately 90 flight hours on average. The mean age within the cohort was 23 ± 4 years.

Although the average experience of the participants is comparable, a certain level of inter-individual and inter-group variability can be expected, especially given their background of coming from two different flight schools with different airplane types flown. This factor is taken into account within further investigation. The particular decisions made in this regard are described in the "Statistical Analysis" section. While the initial aim was to involve an equal number of people for the two groups, finding participants, especially for Gr. B, has proven to be difficult. All the subjects tested were males. Physical and psychological fitness of every participant was backed up by a class 1 medical certificate issued in accordance with Commission Regulation (EU) No 1178/2011, Annex IV (Part-MED), as amended.

Before the experiment, the subjects were briefed about general terms and the procedure of the research, along with conditions of data collection and anonymization in accordance with the ethical principles for medical research involving human subjects [39]. The participants' consent was secured by signing a data collection and processing agreement. Every experiment was preceded by a basic explanation of the cockpit features (indicators) to ensure the subjects' ability to correctly interpret the flight parameters required. However, no other additional training, specifically transition training, was provided.

3.2. Experimental Setup

To a considerable extent, the present experiment followed the setup of a similar study published in 2020 [12]. Not only it offers proof-tested methods and a refined research framework but also enables a possibility to further cross-compare the data obtained with the previous results. Thus, the general idea was to conduct two short flights. Due to the nature of the bachelor thesis study, the flights were simulated, however, to achieve a higher level of immersion and awareness, a virtual reality (VR) kit was used. The airplane utilized within the research was Cessna 172 available in two versions: a classic variation with analog gauges and a variant fitted with Garmin G1000 (Garmin Ltd., Olathe, Kansas, U.S.) EFIS. The two cockpit layouts are depicted side by side in Figure 3. Since they possess practically identical handling characteristics and other experimental conditions described further remained unchanged, it can be expected that the cockpit type and familiarity with it will be the only factors affecting the discrepancies in piloting performance and workload after a change of the instrument panel between the two flights. The first flight was to be conducted with the cockpit type the subject is experienced with. It also included some free maneuvering time for the subject to get used to the simulator and the airplane. The second flight followed straight after and was to be performed in the cockpit unfamiliar to the participant, thus, introducing a cockpit transition.

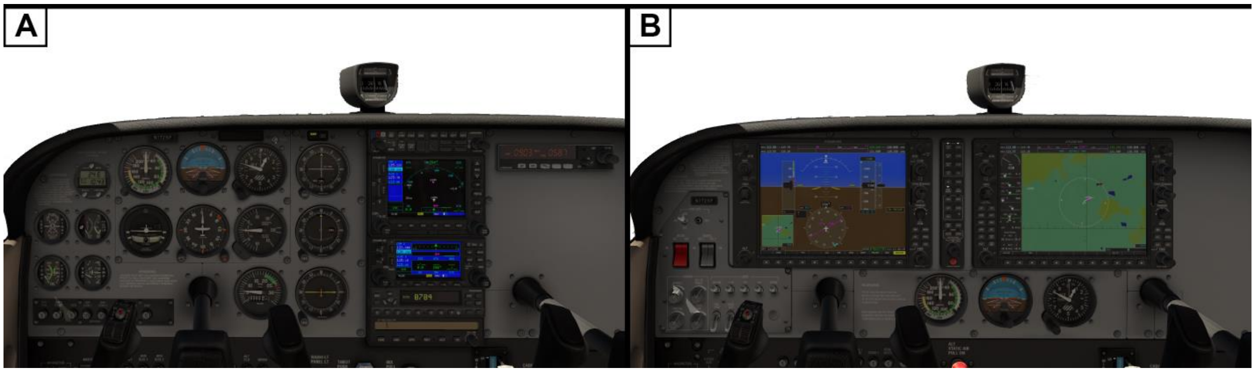

Figure 3. Simulated Cessna 172 analog (A) and G1000 (B) cockpits

In order to keep the task complexity consistent among the participants and between the two measurements, the simulated flights were performed from the airport of Mnichovo Hradiště in the Czech Republic (ICAO code: LKMH) under daylight conditions (around 12:00 local time). Although it is reasonable to suggest that an absence of external visual cues might be preferred for the instruments' performance to be tested more thoroughly, as it has been mentioned previously just 1 pilot from the two groups had actual experience with instrument flights in IMC. Thus, the weather throughout the experimental process was set to VMC (Visual Meteorological Conditions) with a visibility of more than 10 km with no clouds, wind, or turbulence. The settings of weight and balance remained unchanged to preserve the handling characteristics of the airplanes.

In terms of the contents, every flight represented the same sequence of 6 maneuvers. The first 4 activities largely followed the example of the aforementioned 2020 research for the purposes of data compatibility [12]: straight and level flight, level turn at a given bank angle, climbing 180° turn at given rate, and descending 180° turn at given rate. Such an arrangement makes the pilot utilize the artificial horizon, altimeter, variometer, and heading indicator. However, it does not involve the airspeed indicator and turn-slip readings. Therefore, the present experimental setup incorporated 2 additional maneuvers: a rate-one (at a rate of 3° per second) climbing turn at given speed, along with a straight descent at given speed and vertical rate. The maneuvers, parameters required, and the indicators involved are summarized in Table 1. A dash ("-") indicates that the given parameter was not subjected to monitoring and further analysis within the given maneuver. For the sake of brevity, henceforth designations of the maneuvers will be abbreviated to M1-6. The indicator names are shortened as follows: Airspeed Indicator (ASI), Altimeter (ALTM), Attitude Indicator (AI), Heading Indicator (HI), Turn and Slip Indicator (TSI), Vertical Speed Indicator (VSI).

Table 1. Predetermined maneuvering parameters

	M1 (Straight and level flight)	**M2** (Level turn at given bank)	**M3** (Climbing turn at given bank and rate)
Heading [°]	360	-	-
Bank angle [°]	0	30	15
Turn rate [°/s]	-	-	-
Altitude [ft]	2000	2000	-
Vertical speed [ft/min]	-	-	500
Airspeed [kt]	-	-	-
Instruments required	AI, ALTM, HI	AI, ALTM	AI, VSI
	M4 (Descending turn at given bank and rate)	**M5** (Climbing rate-one turn at given speed)	**M6** (Straight descend at given speed and rate)
Heading [°]	-	-	360
Bank angle [°]	15	-	0
Turn rate [°/s]	-	3	-
Altitude [ft]	-	-	-
Vertical speed [ft/min]	-500	-	-500
Airspeed [kt]	-	80	90
Instruments required	AI, VSI	ASI, TSI	AI, ASI, HI, VSI

A watch item universal to all the maneuvers was the sideslip indication: the whole controlled (maneuvering) portion of the flight is expected to be flown in a coordinated way (at a zero sideslip angle). Whenever possible, parameter selection bugs available in the cockpit were used. It involved the heading bug in the analog cockpit, along with altitude and heading bugs in the G1000 cockpit. While it is practically possible to also display vertical speed and airspeed selection bugs, they were not used during the experiment, as their activation inevitably leads to flight directors engagement in G1000, which, in turn, can compromise manual flying results by posing a distraction [40]. In addition, the participants were specifically instructed not to use standby gauges in the G1000-fitted cockpit. The maneuvers were executed in the persistent sequence from 1 to 6 during every flight to keep the task consistent for all the subjects. Every flight additionally involved take-off and landing portions flown by the subjects, however, they were not used for the purposes of data collection.

3.3. Equipment

As previously mentioned, the experiment involved simulated flights utilizing VR. Therefore, a basic physical cockpit framework was incorporated, consisting of a pilot's seat, primary flight controls (a yoke and rudder pedals), and a throttle quadrant. It is depicted in Figure 4. Such a setup enabled basic flight control inputs by the participant, which was sufficient for the maneuvers to be executed. If needed, more advanced interactions within the cockpit (for example, heading bug adjustments) were performed by a separate human operator.

The software used for flight simulation was X-Plane 11 (Laminar Research Ltd., Columbia, South Carolina, USA). Models of the airplanes flown are available by default with the simulator. The VR environment was supported by a FOVE0 VR headset (FOVE Inc., Tokyo, Japan).

Heart rate of the participants was continuously monitored throughout the flight by means of the FlexiGuard mobile telemetry system (Czech Technical University in Prague, Prague, Czech Republic) [41, 42]. However, due to operational reasons and equipment availability, two different approaches for heart rate recording were incorporated. 10 participants utilized a heart rate sensor, while the other 10 subjects had their heart activity monitored by means of ECG. The application of these monitoring methods on the participants is depicted in Figure 5.

Figure 4. A participant at the VR cockpit setup

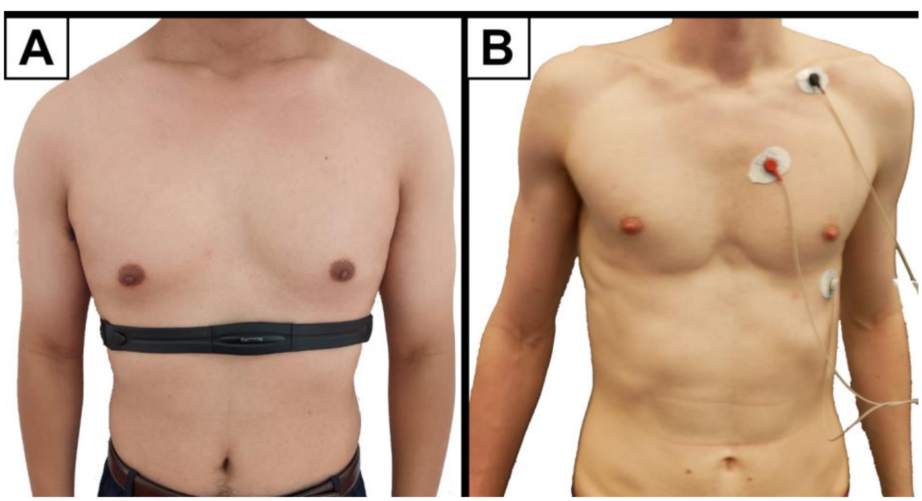

Figure 5. Illustration of FlexiGuard sensors placement for heart rate detection (A) and ECG (B)

3.4. Data Collection and Processing

As it has been previously mentioned, the process of data collection was performed in two ways. On the one hand, for the purposes of piloting performance evaluation, piloting precision data was recorded. On the other hand, heart rate data was collected for further physiological condition assessment by means of HRV.

3.4.1. Flight data collection and processing

The piloting performance data was derived from a recording of various flight parameters (as per Table 1) within the simulator. This process was facilitated by inbuilt software capabilities. The monitored flight parameters were collected continuously throughout the flights at a sampling frequency of 5 Hz. The maneuvers were framed by starting and ending times, which required a human operator's supervision to be manually recorded. Efforts were made to keep the data representative and its quality consistent. Therefore, the participants were given time to achieve a stabilized condition according to the parameters required before the data collection for the given maneuver was initiated. In order to ensure data quality and a sufficiently large sample size of the parameter values, the target maneuver timeframe length was set to 60 seconds.

The final selection of the flight parameters assessed for every maneuver was governed by the expected instruments to be used, even though certain conditions allowed for more data to be considered. Thus, turning rate deviations were not taken into account for M1 and M6, despite a possibility to use them as an assist for maintaining the prescribed heading and wings level. This assumption was made based on a practical approach to execution of the maneuvers, as no substitution for the AI was required. Similarly, although zero vertical speed would correspond to a constant level flown, it is more of a tool to facilitate altitude maintenance than a goal to achieve. Therefore, VSI readout analysis for M1 and M2 was found redundant, along with being non-representative under certain circumstances due to aggressive corrections performed by some of the participants. In addition, sideslip indication was considered secondary, and therefore, it was not assessed per maneuver but rather for the whole maneuvering portion of the flight.

The flight data initial processing, similarly to all calculations performed further, was done in the MATLAB environment (MATLAB R2021a, MathWorks, Inc., Natick, MA, USA). Continuous flight data monitoring enabled piloting performance to be assessed with the help of several indicators - something no studies acquired within the literature review have applied. A basic script was created to compute the following three metrics for every monitored parameter per each maneuver: root mean square piloting error, standard deviation, and maximum absolute piloting error (the highest recorded deviation from the required value). These three measures are essentially proposed as indicators of piloting performance within this research. Root mean square piloting error (spread of the parameters around the required value) serves as the primary indicator for piloting performance assessment and corresponds to the accuracy of pilotage since it is the main task for the subject to perform the flight according to the prescribed parameters. Standard deviation of the sample was selected as a measure of piloting precision (overall dispersion of the parameter values maintained). Maximum absolute piloting error was assumed to be an indicator of the greatest deviation that went unnoticed and uncorrected by the subject in a given cockpit. Thus, data pre-processing resulted in 51 usable values per participant per flight. Nevertheless, within Gr. A, one participant was found to have incomplete data for one flight (3 parameters missing), while one of the maneuvers for a different subject turned out to be corrupted, - these factors were accounted for in further statistical analysis.

The only instrument read-out that was not recorded directly was the turn rate indication from the TSI. It is caused by a limitation in the flight recorder used. Thus, the assessment of the three aforementioned piloting performance metrics for it was derived from the angular velocity recorded. However, it was found that rate-one turn indication in the two cockpit layouts resulted in different values of radial velocity (exactly 3°/s in the glass cockpit and approximately 4°/s in the analog cockpit), which is probably connected to instrument simulation. Therefore, different target reference values were used, depending on the cockpit type.

3.4.2. Heart rate data collection and processing

Heart rate data was recorded continuously during the maneuvering portion of the flights. However, the means of recording differed, depending on the equipment in use. Thus, in the case of participants wearing the heart rate sensor, only timestamps of R-peaks of the QRS complex were recorded (see Fig. 1). The subjects monitored with the ECG kit had the whole electric potential curve recorded at a sampling frequency of 500 Hz. Since the reference timer used within the experiment was that of the simulator, for synchronization purposes, the timestamp of the heart rate data recording starting point was manually marked by a human operator. When the heart rate sensor was in use, the data was additionally substituted by markers indicating starting and ending points of each maneuver. Although per-maneuver heart rate analysis is not within the scope of the present thesis, partly due to certain limitations specified further in this chapter, it still leaves a potential for the data collected to be possibly processed for other applications, including ultra-short-term analysis in case a larger sample size is investigated within the same experimental setup in the future.

With regards to further heart rate assessment, the HRV approach was selected. This decision was governed by the conclusions made in the state of the art review - it is sensitive to variations in mental workload and has been proof-tested in the branch of aviation. In terms of the HRV analysis, a number of indicators can be used for the physiological state assessment. The majority of them involve investigation of intervals between heart beats (i.e. R-R intervals) [43]. Ergo, heart rate data pre-processing was concerned with their computation. Recordings made with a heart rate sensor were processed by means of calculating the differences between successive heartbeat timestamps. Data involving the ECG curve required a higher level of processing, which was facilitated by the Pan-Tompkins algorithm [44]. It represents a complex proof-tested sequence of filters and analysis to extract various metrics from an ECG recording, including detection of QRS complexes. Its adaptation for the MATLAB environment was incorporated for the purposes of the present thesis [45].

After the raw heart rate data had been pre-processed into a sequence of successive R-R intervals lengths, it underwent further analysis utilizing the specialized HRVAS (Heart Rate Variability Analysis Software) program [46]. Although a considerable number of parameters can be computed with the help of this tool, selection of particular metrics and assessment methods to use is to be done carefully since not all of them might be representative given the time frames involved. These issues within an experimental setup similar to the present have been reviewed by the researchers [12]. As the authors note, in terms of short-term recordings, a 5-minute-long signal is considered to be a “gold standard” for HRV analysis [47, 48, 49]. As the aforementioned publication worked with considerably shorter recordings, the issue was dealt with by expanding the monitored time frame to include the time period before and after maneuver execution. It is also important to note that reliable and reproducible results for a limited group of indicators were experimentally achieved for substantially shorter-than-standard signal lengths. Nevertheless, since practically all

HRV indices are sensitive to the duration of the ECG segment of interest, since the maneuvers' target length was set to 60 seconds within the present research, and because such time frame extensions would often "step onto" certain other measured intervals, a decision was made not to perform any correlation analysis with respect to the particular maneuver being executed. Ergo, the whole ECG recording per the maneuvering portion of the flight was used for further derivation of various HRV indicators, and thus, the actual signal duration easily exceeded the 300-second standard (as the flight is composed of 6 maneuvers each 60 seconds long, the duration of at least 360 seconds is assured). Compared to otherwise ultra-short-term recordings, the obtained domain of short-term recordings offers a greater number of usable measures.

Therefore, the following 6 HRV indices were selected for further data processing: mean of R-R intervals (mRR), standard deviation of normal-to-normal intervals (SDNN), root mean square of successive R-R interval differences (RMSSD), frequency-domain analysis in low frequency power (LF) and high frequency (HF) power bands, and the LF/HF ratio. mRR indicates the average interval between two successive heart beats and therefore inversely correlates with the mean heart rate, which is one of the most robust measures in this regard reproducible even for very-short-term recordings [47]. While serving as a general indicator of the autonomic nervous system activity, studies suggest a correlation between its decrease (and a respective increase in the heart rate) and stress, along with workload [50]. SDNN is another widely accepted measure of HRV [51]. In the realm of short-term recordings, it primarily serves as an indicator of the parasympathetically mediated arrhythmia. Normal-to-normal intervals are practically synonymous to R-R intervals with the exception being the former not containing any abnormal beats are removed. RMSSD is another robust index recommended for HRV evaluation in terms of its short-term components [47]. Studies have demonstrated that RMSSD tends to decrease during stress [52]. In the realm of frequency HRV assessment, two metrics were found usable for the given experimental setup: LF and HF bands with minimum recording durations of 2 and 1 minutes respectively, which were met [51]. The LF frequency band is generally affected by the sympathetic nervous system, while the HF shows correlations with RMSSD and indicates the activity of the parasympathetic nervous system. HF would generally display a lower value in case the subject is experiencing stress or anxiety. Thus, one would expect to use another metric: the ratio of LF/HF indicating a parasympathetic balance. It is believed that a high LF/HF ratio corresponds to a sympathetic dominance and thus indicates the “fight-or-flight” reaction, while low LF/HF ratio indicates a parasympathetic domination and corresponds to the “tend-or-befriend” behavior [47, 51]. Nevertheless, this approach has been challenged by some of the authors in the field [52]. Thus, they claim that a relation between the two nervous systems’ activities is vastly more complex. In addition, it is worth noting that both bands can be affected by breathing at different frequencies.

3.4.3. Other forms of data collection

Along with the data processing agreement before the experiment, the participants were offered a basic questionnaire for personal data collection to record their age and flying experience, along with contact information. These data underwent basic statistical processing to describe the samples involved and was presented in the “Participants” section.

The flight and heart rate data recording process was followed by an optional general feedback collection. This information was further used for experimental setup assessment and adjustments. Some of the noteworthy remarks made by the test subjects will be further discussed in the following chapters.

3.5. Statistical Analysis

Due to the nature of the experimental setup and the different measurements involved, several analysis approaches were incorporated, depending on the investigated issue. Thus, the present statistical assessment is split into 3 main branches according to the following objectives: general comparative analysis of the piloting performance between the two groups, research of the specific transition effects on piloting performance within the groups, and evaluation of the workload by means of the HRV indices obtained earlier.

3.5.1. Comparative analysis of piloting performance between the groups

Since Gr. A and Gr. B were tested in an identical way under the common experimental setup, a general comparative analysis of the piloting performance between the two investigated groups can be used to determine if there are any significant differences. It primarily purports to ascertain whether the cockpit transition in general had an effect on the performance and if the type of initial experience of the pilot had any influence on its consequences.

As the two groups can be expected to have a certain degree of variability in between, along with the aforementioned inter-individual variability, the particular magnitude of the flight parameter values observed, along with their absolute differences, will again not be assessed in terms of their significance. To a more considerable degree, this analysis is concerned with the general progression and trends of piloting performance through the measured flights.

To further facilitate this process, a single piloting performance metric derived from standardization of the values. In order to support data normalization across various parameters in different scales and units, the normal score (or Z score) method was used [53], transforming the values into dimensionless indicators with respect to their mathematical expectation and standard deviation. The following formula was used:

$$Z_p = \frac{x_p - \mu_p}{\sigma_p},$$

where Z_p is the resulting Z score for parameter p, x_p is the particular value of the parameter observed, μ_p is the average (or the mathematical expectation) for the parameter, and σ_p is the standard deviation for the sample. Next, these normal scores were summed and averaged per maneuver per participant separately in the three domains of piloting precision, piloting accuracy, and the maximum piloting error. Thus, total composite maneuvering errors were generated for every pilot. The sideslip indication was not considered as a substantial factor within this process, and therefore, was not included in the final z-scores. After the process of data normalization, normality of the values distribution within the newly obtained data set was confirmed by means of the Shapiro–Wilk test [54], therefore, enabling parametric statistical tools to be used for further analysis. Thus, a repeated-measures three-way ANOVA (Analysis of Variance) test was applied to the reformatted data with the dependent variable being the subject’s performance and independent variables of the group, cockpit familiarity, and the maneuver identifier [55]. Thus, the model used for repeated-measures ANOVA can be described as following, using Wilkinson’s notation:

$$M1 - M6 \sim Group + Cockpit\ Familiarity + Group\ x\ Cockpit\ Familiarity$$

The procedure was repeated 3 times according to the aforementioned categories of the piloting performance assessment. Data sphericity, which is one of the assumptions for ANOVA, was checked and not confirmed by Mauchly's test [56], and therefore, Greenhouse–Geisser correction was applied to determine the particular p-values [57]. Further post-hoc analysis of the obtained results was facilitated by means of the Tukey's test [58].

3.5.2. Assessment of effects on within-group piloting performance

The goal pursued by the assessment of cockpit transition effects is, most importantly, to determine what particular changes in piloting performance have occurred within the given experimental setup for Gr. A and Gr. B. Owing to a continuous monitoring of flight parameters resulting in the precise and comprehensive data obtained, it appears possible to assess this factor separately for each flight parameter involved. Thus, certain conclusions can be made further with regards to possible flight instruments or indications potentially contributing to any such effects.

Due to a certain anticipated level of inter-individual variability involved, straightforward assessment of the absolute values involved was assumed to be unrepresentative. Neither their magnitude nor the particular differences observed will be given an evaluation but rather a general trend and its statistical significance. Thus, this part of the statistical analysis deals with a set of paired data from repeated measurements per flight parameter per maneuver (firstly, in the cockpit a subject is familiar with and, secondly, in the other cockpit type) with the objective being determining any statistical significance in between. Normality of the data sets was assessed by means of the aforementioned Shapiro–Wilk test and was not confirmed universally, thus restricting the use of parametric tests. Therefore, a decision to resort to non-parametric tests for the present part of statistical analysis was made. These took the form of the Wilcoxon signed-rank test [53]. Piloting precision, piloting accuracy, and the maximum piloting error were assessed independently.

3.5.3. Evaluation of HRV

Taking into account the aforementioned subject variability factors, the following assessment of HRV will evaluate the general workload trend as a result of the transition in its primary focus. Thus, the aim is to determine whether the workload has increased, decreased, or stayed unchanged as a result of the variation in ergonomics.

Therefore, since one heart rate recording per flight was used for HRV indices computation, the current analysis will deal with sets of paired values. Since the data did not belong to a normal distribution, use of parametric tests was rendered impossible. Thus, the process of determining whether a statistically significant difference is present, accounting for the relatively small number of data sets involved, was facilitated by means of the Wilcoxon signed-rank test described earlier in the case of within-group analysis and the Mann–Whitney U test (essentially an adaptation of the former for two independent samples) in the case of inter-group comparison [53]. This approach was repeated with Gr. A and Gr. B per every index investigated.

Chapter 4 – Results

Results obtained during the process of statistical analysis are presented in this chapter. They are categorized into four following groups: generalized comparison of the two groups' results, analog-to-glass transition, glass-to-analog transition, and HRV assessment. Box plots are widely used within this chapter for data presentation, therefore, their legend, henceforth, is as follows: the red line indicates the median, the blue rectangle marks the first and the third quartiles below and above it respectively, the black whiskers correspond to 1,5 times interquartile range, and any red crosses indicate outliers. In case any statistically significant differences between a pair of indicators are present, they are indicated with a magenta-colored asterisk ("*").

4.1. Generalized Comparison of Gr. A and Gr. B Results

The following results detail the findings obtained after a single-score per-maneuver comparison of the two experiment groups.

4.1.1. ANOVA results

Repeated-measures ANOVA returned mixed results for a generalized comparison of the two groups. Thus, firstly, the subjects' performance through the progression of the flight showed a statistically significant difference depending on the maneuver in terms of accuracy ($F[5, 180] = 3.9$, $p \approx 0.007$), precision ($F[5, 180] = 4.7$, $p \approx 0.001$), and maximum deviation ($F[5, 180] = 4.8$, $p \approx 0.002$). Furthermore, it is also important to note that the correlation analysis between the groups and their performance led to somewhat contradicting results: a statistically significant difference was observed between the two groups' accuracy per maneuvers flown ($F[5, 180] = 2.7$, $p \approx 0.042$), however, the null hypothesis was far from rejection for the other two metrics of precision ($F[5, 180] = 1$, $p \approx 0.41$) and maximum deviation ($F[5, 180] = 1.2$, $p \approx 0.29$).

With regards to the effects of the transition, a statistically significant difference was observed per maneuver before and after the transition for the two groups combined in the realm accuracy ($F[5, 180] = 3.7$, $p \approx 0.01$), precision ($F[5, 180] = 2.5$, $p \approx 0.045$), and maximum deviations ($F[5, 180] = 2.9$, $p \approx 0.032$). Meanwhile, no statistically significant variations for any of the three indices were identified in the relation of the group and the factor of transition ($F[5, 180] = 2.1$, $p \approx 0.066$;

F[5, 180] = 1.9, p ≈ 0.096; F[5, 180] = 1.4, p ≈ 0.23 for accuracy, precision, and maximum deviations respectively). Practically identical results were obtained from another ANOVA test where composite scores from the three metrics were summed and averaged per participant. A box plot summarizing the composite score for groups before and after the flight is depicted in Figures 6, 7, and 8 for accuracy, precision, and maximum deviations respectively.

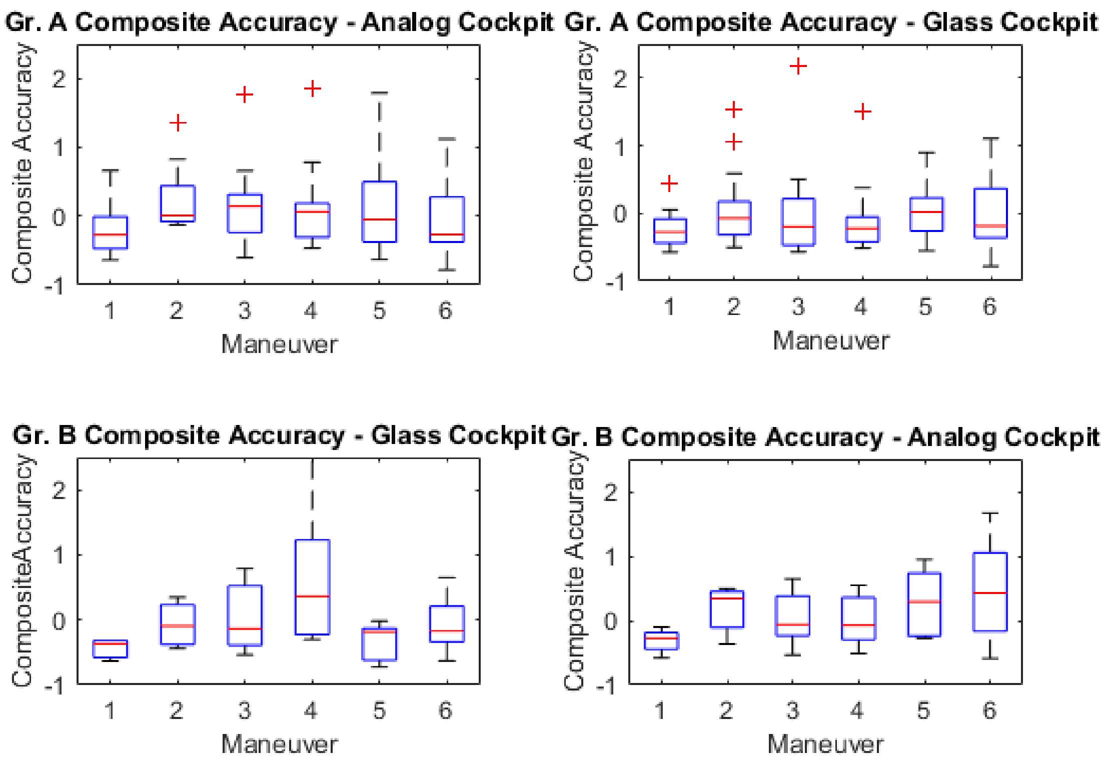

Figure 6. Composite accuracy for the two groups before and after the transition

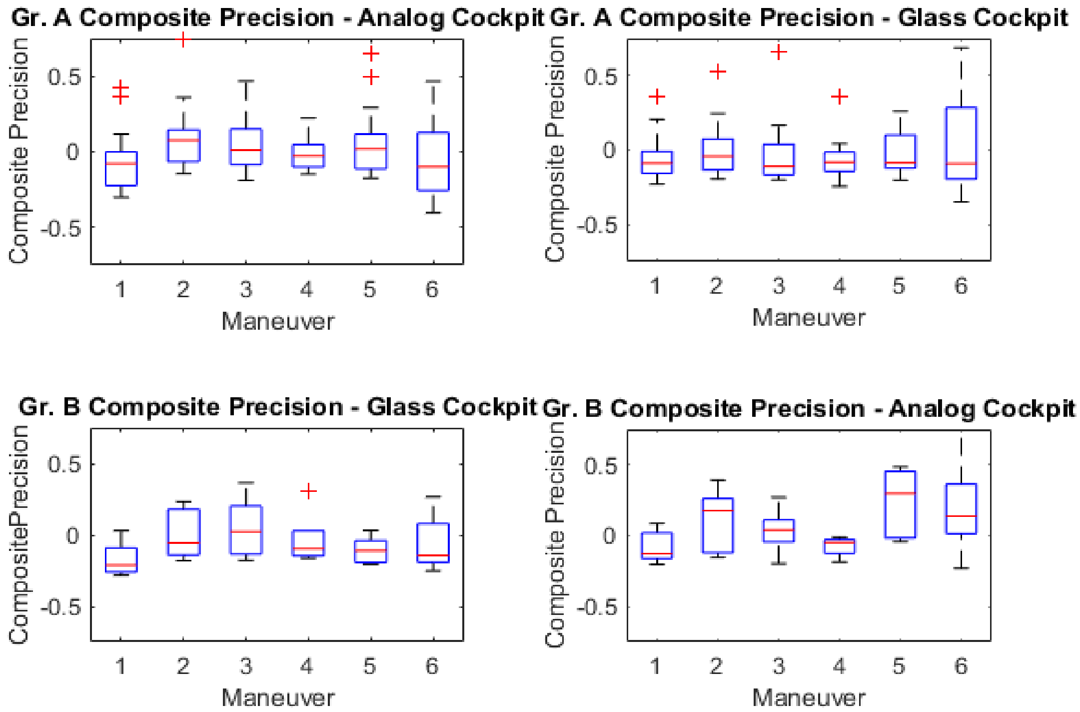

Figure 7. Composite precision for the two groups before and after the transition

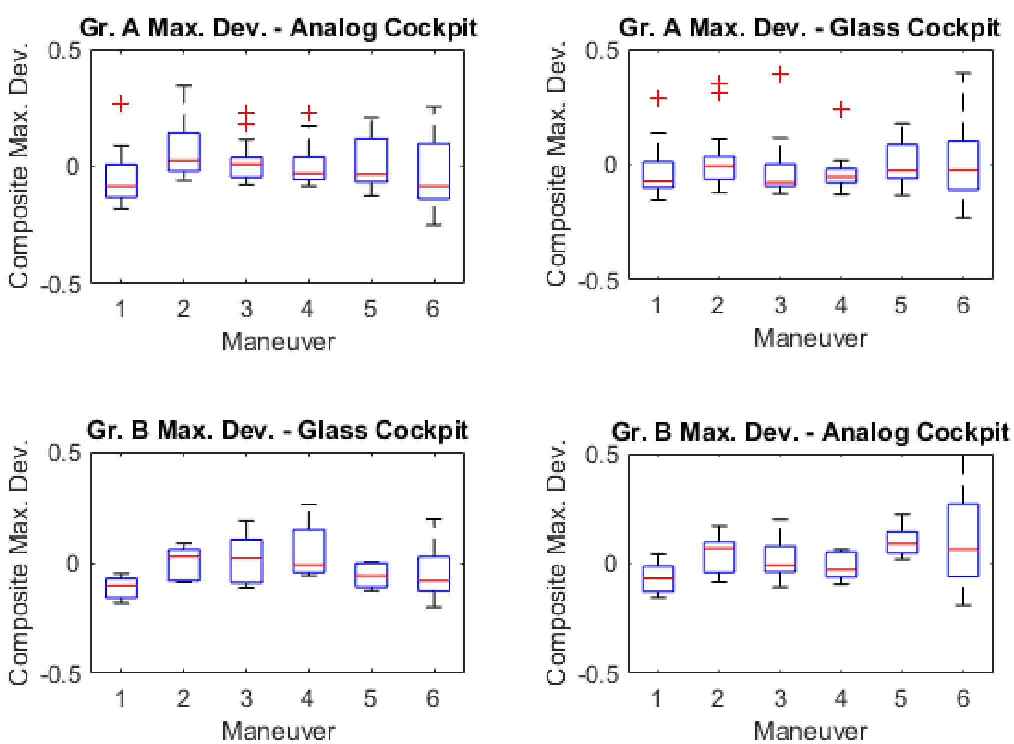

Figure 8. Composite maximum deviations for the two groups before and after the transition

4.1.2. Post hoc analysis

Post hoc analysis in the form of the Tukey's test used to further process the ANOVA data returned the following results. In terms of maneuvers, Gr. A and Gr. B showed a statistically significant decrease in their accuracy and maximum deviation performance between M1 and M2 on the first flight ($p = 0.013$; $p \approx 0.001$ for Gr. A and $p = 0.033$; $p \approx 0.043$ for Gr. B respectively). Unlike Gr. A, Gr. B demonstrated the same tendency in terms of accuracy also on the cockpit transition flight ($p \approx 0.007$) for M1-M2, along with exhibiting a statistically significant deterioration in accuracy, precision, and maximum deviations performance between M1 and M5 ($p \approx 0.045$, $p \approx 0.003$, and $p \approx 0.008$ respectively), which was not present before the change in ergonomics.

Further pairwise comparison of composite scores before and after transition for the groups found no statistically significant differences in the values for Gr. A. Nonetheless, a statistically significant decrease in precision and maximum deviations performance was identified for Gr. B during M5 ($p \approx 0.02$ and $p \approx 0.008$ respectively) between the two flights. Pairwise comparison of Gr. A and Gr. B performance for each of the maneuvers showed no statistically significant discrepancies in all three metrics.

4.2. Gr. A Results – Analog-to-Glass Transition

Specific results retrieved for Gr. A are further categorized by the particular parameter investigated.

4.2.1. Heading

Repeated application of Wilcoxon test to examine the heading behavior within M1 and M6 demonstrated no statistically significant difference at the significance level of $\alpha = 0.05$ when comparing the performance before and after the transition. The deviation values observed are displayed with a box plot in Figure 9.

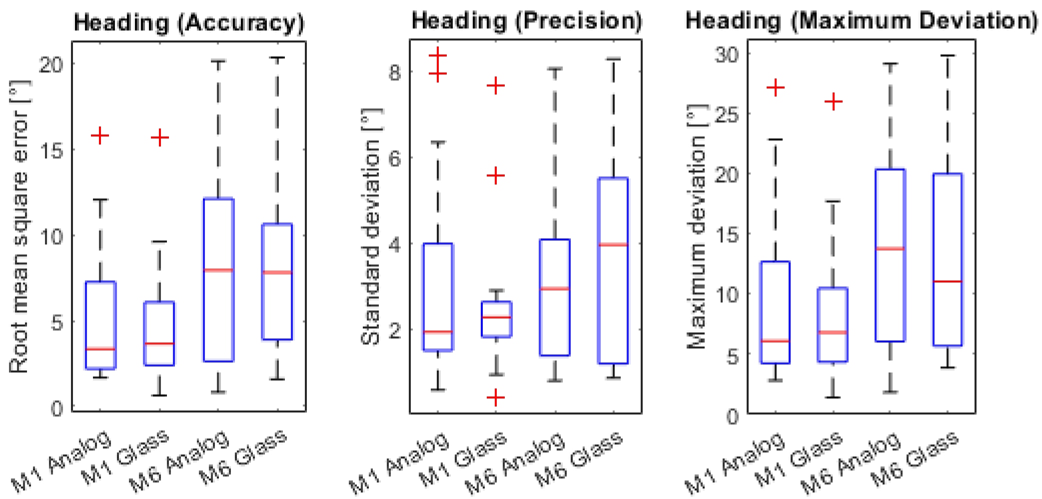

Figure 9. Comparison of heading deviations for Gr. A per maneuver and cockpit

4.2.2. Bank angle

Assessment of bank angle deviations returned interesting results demonstrating an increase of piloting performance to an extent for certain parameters. Probably, the findings in terms of M3 were the most notable: it showed a clear and statistically significant improvement for accuracy ($p \approx 0.0002$), precision ($p \approx 0.0001$), and maximum deviation ($p \approx 0.0006$). Practically every pilot experienced an increase in performance with very few exceptions of insignificant degradation that can be attributed to variations in the subjects' capacity through the flight. Similar tendency is visible for M4: not as uniformly, but the subjects' performance had an increasing trend for accuracy ($p \approx 0.0017$), precision ($p \approx 0.0067$), and maximum deviation ($p \approx 0.0023$). Furthermore, M2 resulted in a statistically significant improvement in the realm of maximum deviation ($p \approx 0.0494$). Nevertheless, a remarkably opposite tendency was identified for the last maneuver: both accuracy ($p \approx 0.0327$) and precision ($p \approx 0.0398$) showed a statistically significant degradation. These findings are prominent in Figures 10 and 11.

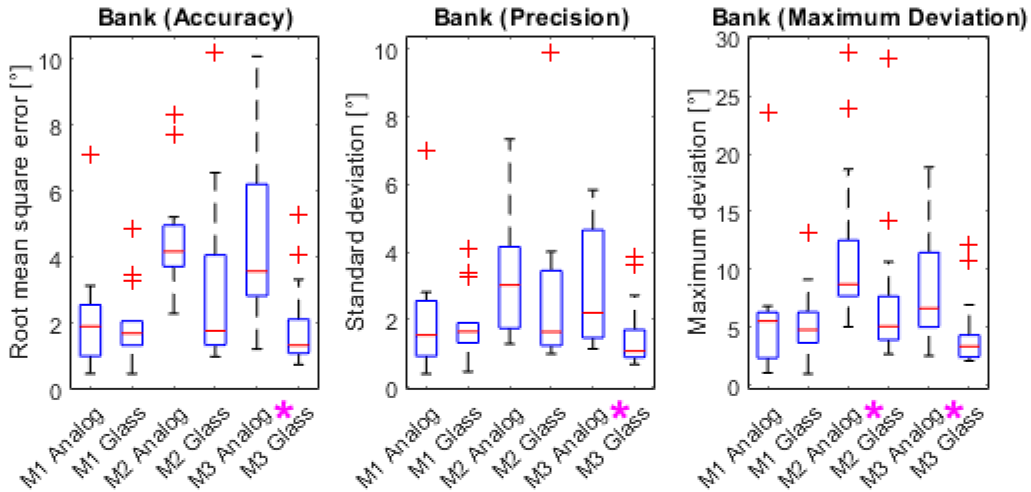

Figure 10. Comparison of bank deviations for Gr. A per maneuvers 1 through 3 and cockpit

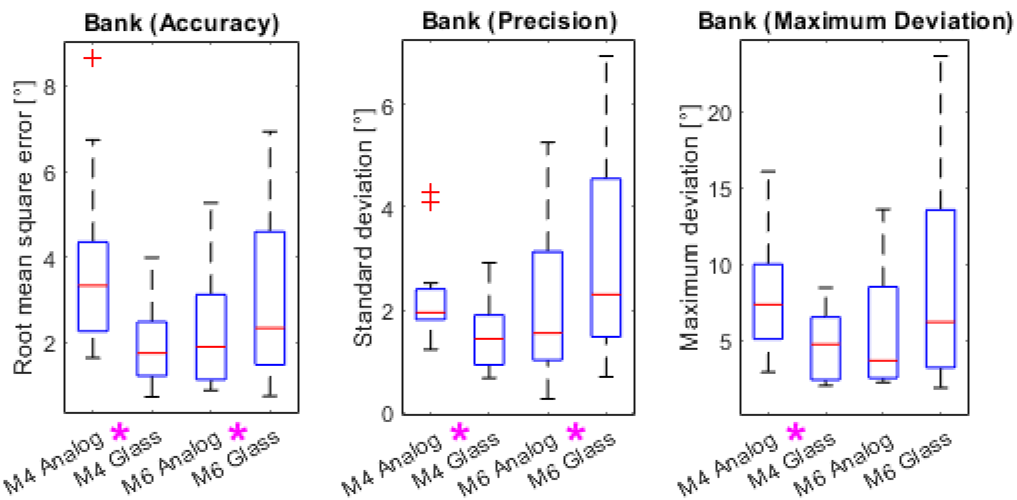

Figure 11. Comparison of bank deviations for Gr. A per maneuvers 4 and 6 and cockpit

4.2.3. Altitude

The results of altitude deviations assessment are presented in Figure 12. One participant was found to be an extreme outlier following the transition (the accuracy value exceeded 360 ft for the first maneuver in the glass cockpit), but otherwise this parameter for Gr. A was unremarkable: no statistically significant differences in the altitude holding performance of the participants were observed.

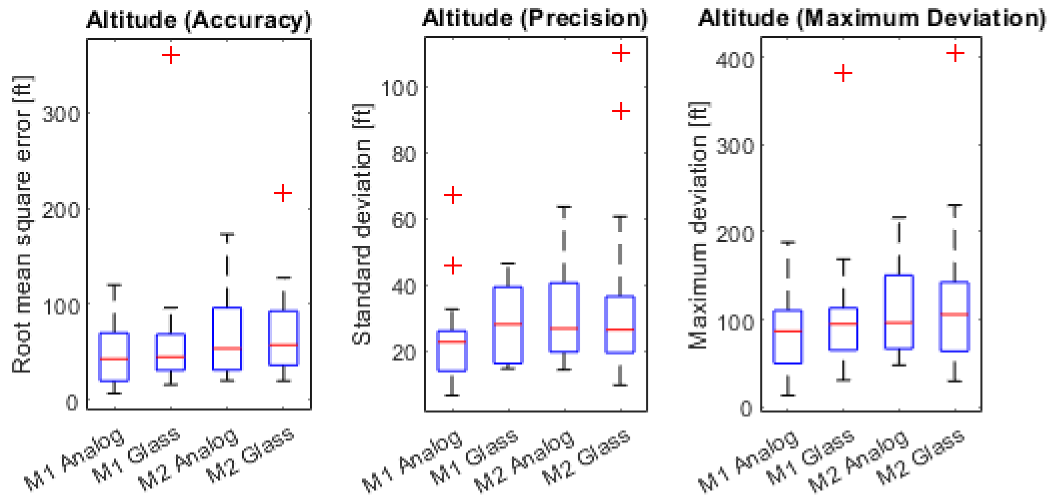

Figure 12. Comparison of altitude deviations for Gr. A per maneuver and cockpit

4.2.4. Vertical speed

Since a certain level of correlation between the vertical speed performance and altitude holding can be expected, results for Gr. A come as no surprise: no statistically significant trend for this parameter before and after the transition was identified for any of the involved maneuvers. However, similarly to the previous section, the same participant was observed to struggle with transition, demonstrating extreme outlying values for every maneuver in the glass cockpit. The results are displayed in Figure 13.

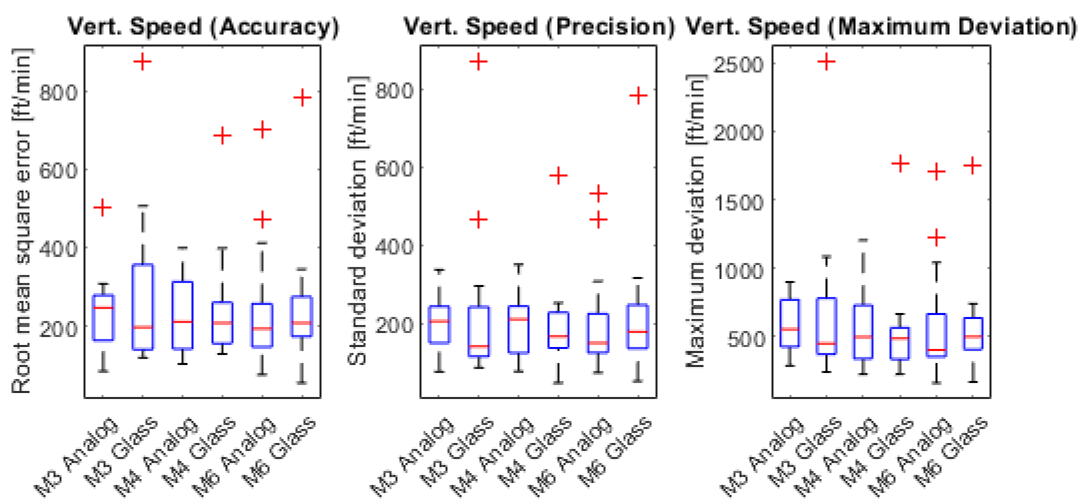

Figure 13. Comparison of vertical speed deviations for Gr. A per maneuver and cockpit

4.2.5. Airspeed

Comparison of the paired airspeed values for M5 and M6 before and after the transition was not able to identify and statistically significant differences or distinct trends in the subjects' performance. These findings are prominent in Figure 14.

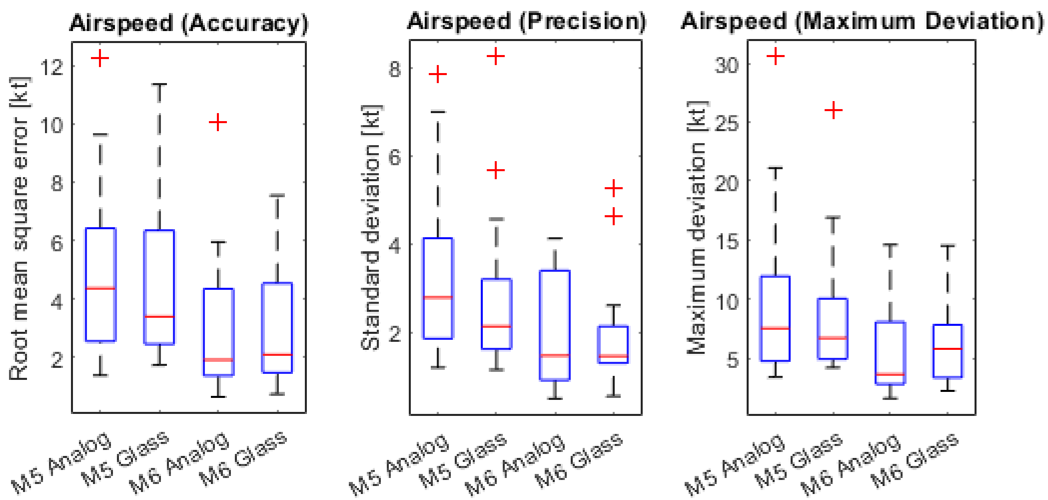

Figure 14. Comparison of airspeed deviations for Gr. A per maneuver and cockpit

4.2.6. Turn rate and slip angle

Evaluation of the turn and slip data for Gr. A did not indicate any statistically significant differences or distinct trends in the monitored parameters following the transition. These results are plotted in Figure 15.

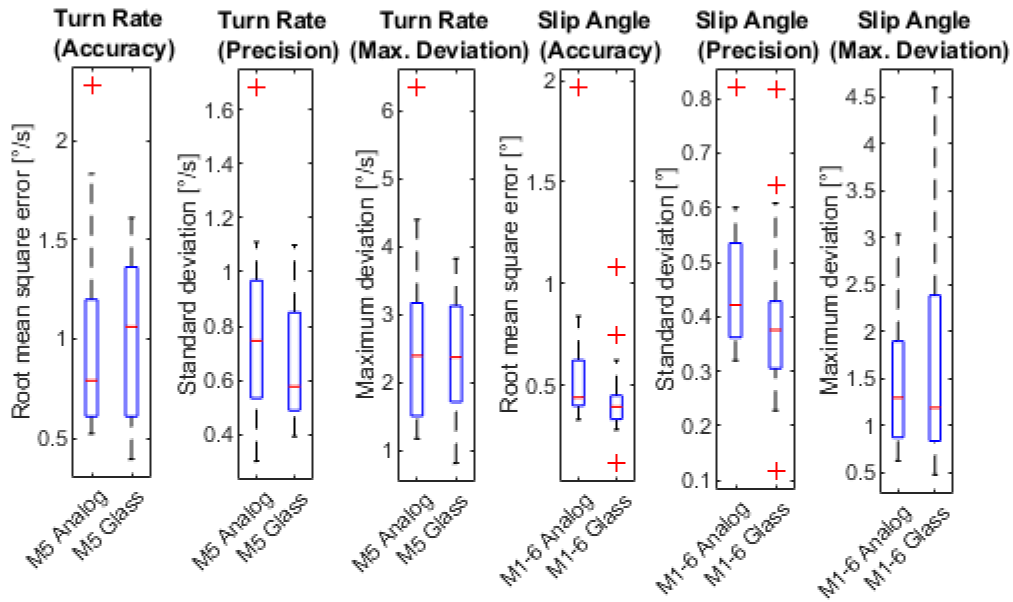

Figure 15. Comparison of turn-slip deviations for Gr. A per maneuver and cockpit

4.2.7. Summary for Gr. A

The results of this parameter-specific review for Gr. B are provided in Table 2. Empty cells indicate that the parameter was not monitored for the given maneuver. The three signs from left to right correspond to accuracy, precision, and maximum deviations respectively, with an arrow up ("↑") indicating a statistically significant increase in deviations, an arrow down ("↓") showing a statistically significant decrease in deviations, and a dash ("-") indicating no significant change.

Table 2. Summary of flight parameter variations for Gr. A following the transition

Parameter	M1	M2	M3	M4	M5	M6
Heading	---					---
Bank angle	---	--↓	↓↓↓	↓↓↓		↑↑-
Altitude	---	---				
Vertical speed			---	---		---
Airspeed					---	---
Turn rate					---	

4.3. Gr. B Results – Glass-to-Analog Transition

It is important to note that a relatively sample size of Gr. B poses a significant limitation with regards to the test applied. Thus, due to the computation procedure, the lowest p-value that can be obtained for a sample of 5 is 0.0625 [53], which is greater than the universally accepted significance level of $\alpha = 0.05$. Therefore, while recognizing it as a potential threat to the validity of the findings, a decision was made to apply the alpha-value of 0.0625 for interpretation of results within the Gr. B section. Similarly to the Gr. A description, piloting performance assessment results for Gr. B are further categorized by the parameters as follows.

4.3.1. Heading

In the realm of M1, no statistically significant differences were observed for either of the three metrics of piloting performance. Nevertheless, the comparison for M6 resulted in statistically significant differences for every indicator involved ($p = 0.0625$ for all three cases). These findings are clearly reflected in Figure 16. According to the particular pairs of values investigated, every single participant from Gr. B showed lower performance in terms of lower accuracy, precision, and a higher maximum deviation in heading the last maneuver following the transition.

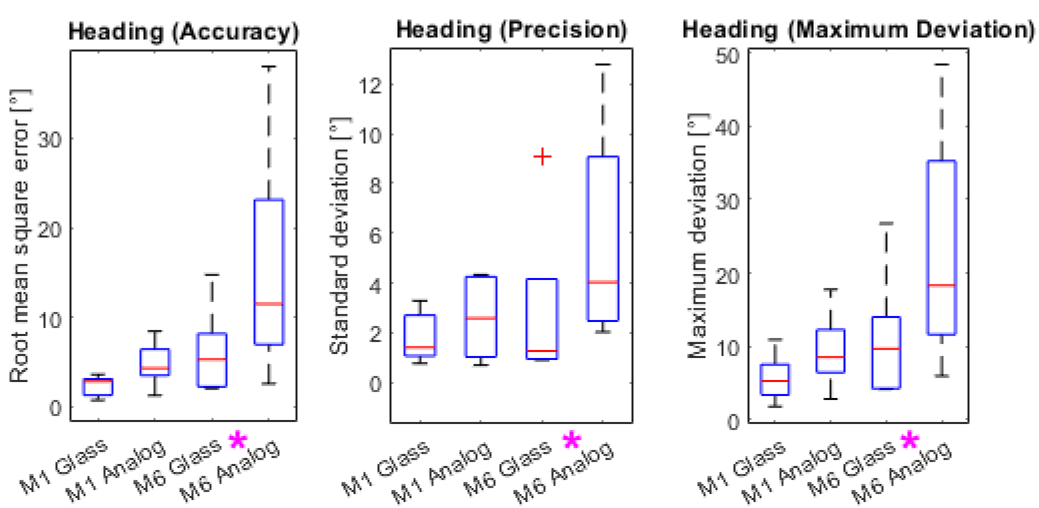

Figure 16. Comparison of heading deviations for Gr. B per maneuver and cockpit

4.3.2. Bank angle

Compared to those within Gr. A, no drastic differences in the Gr. B bank performance after the transition, were observed. A statistically significant decrease in piloting performance occurred for M1 in terms of accuracy and precision (p = 0.0625 in both cases). Otherwise, a generally negative trend can be noticed in the other remaining maneuvers and parameters, but there is not enough statistical evidence to assume it significant (see Fig. 17 and Fig. 18).

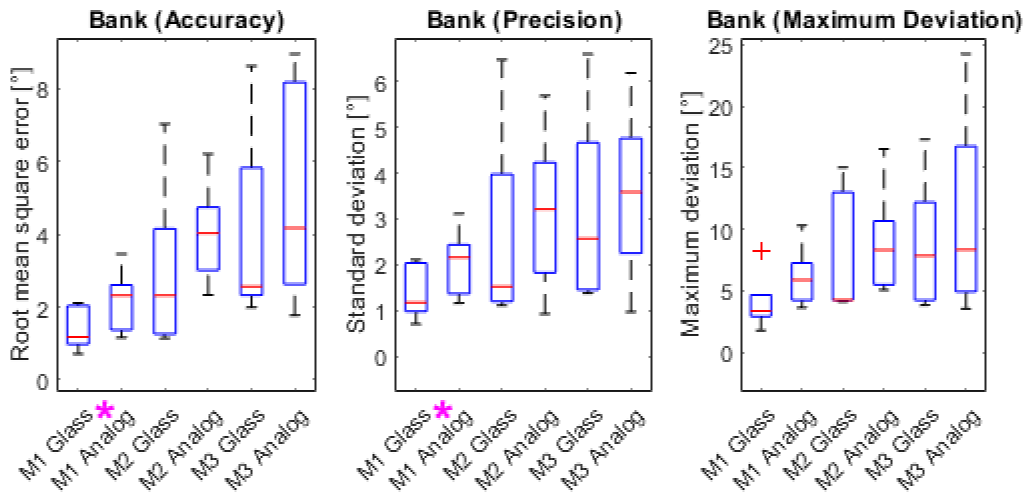

Figure 17. Comparison of bank deviations for Gr. B per maneuvers 1 through 3 and cockpit

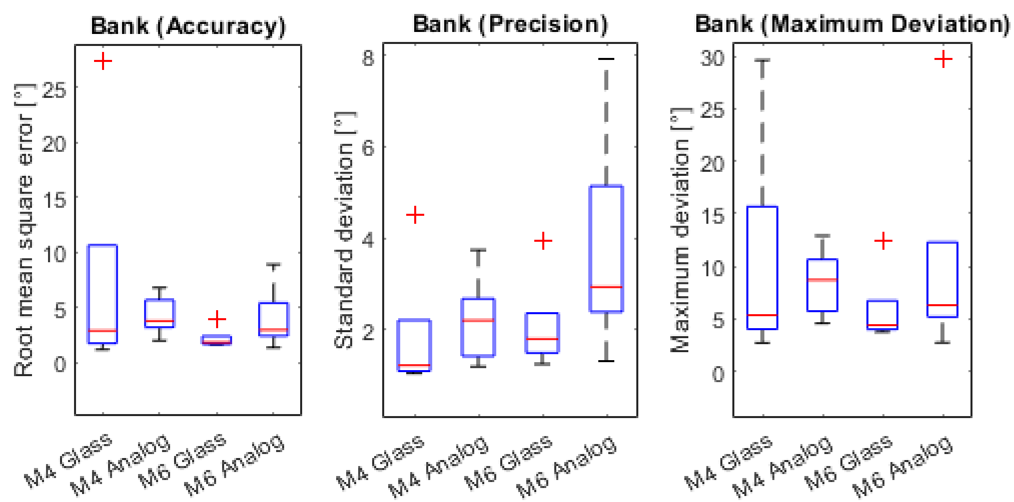

Figure 18. Comparison of bank deviations for Gr. B per maneuvers 4 and 6 and cockpit

4.3.3. Altitude

Testing the pairs of values in terms of altitude showed no statistically significant changes for Gr. B. Nevertheless, it is still important to note that for some of the parameters, there was just a single participant experiencing an increase in their performance. Thus, yet again, the results are to be taken with caution because of the small sample size involved. The results are depicted in Figure 19.

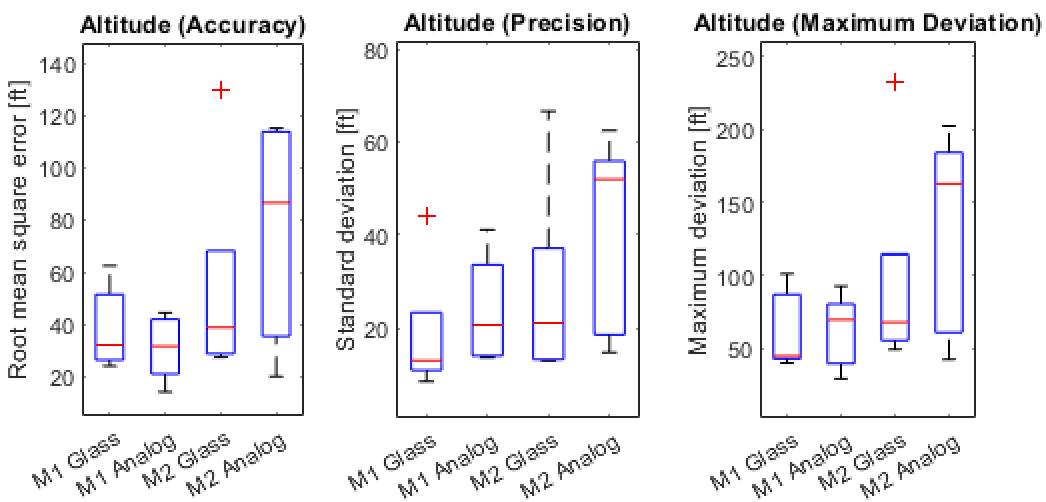

Figure 19. Comparison of altitude deviations for Gr. B per maneuver and cockpit

4.3.4. Vertical speed

In terms of vertical speed, Gr. B showed a statistically significant decrease in piloting performance for M6 both for precision and maximum deviation ($p = 0.0625$ in both cases). After the transition, every participant achieved lower values in this regard compared to the cockpit type they are familiar with. Apart from that, 4 out of 5 participants exhibited an increase in their performance for M4, but the result cannot be taken with statistical significance (see Fig. 20).

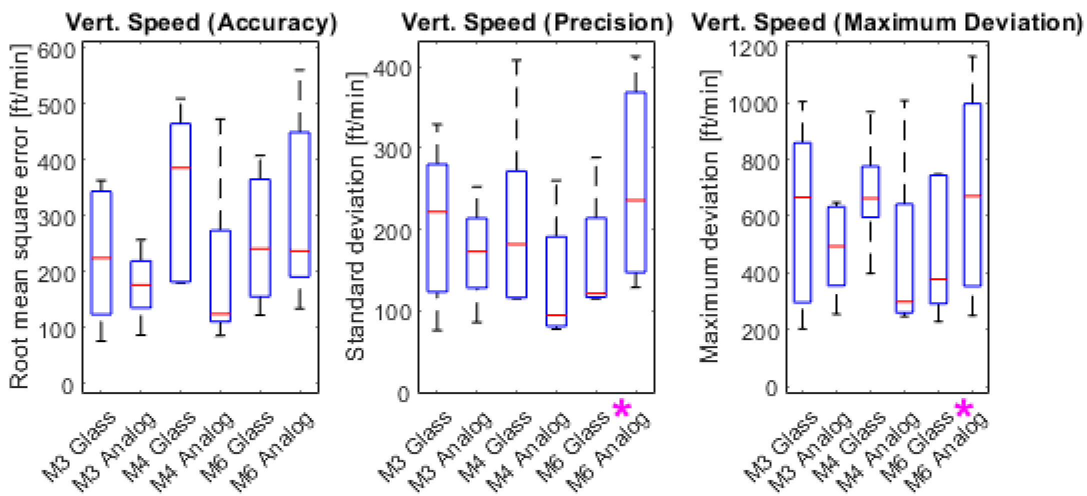

Figure 20. Comparison of vertical speed deviations for Gr. B per maneuver and cockpit

4.3.5. Airspeed

In the realm of airspeed performance of Gr. B, a statistically significant difference was identified for the maximum deviations observed during M5 before and after the transition ($p = 0.0625$). Except 1 participant, the group demonstrated a generally negative tendency in accuracy and precision as well for this maneuver. No statistically significant variations were found for M6 (see Fig. 21).

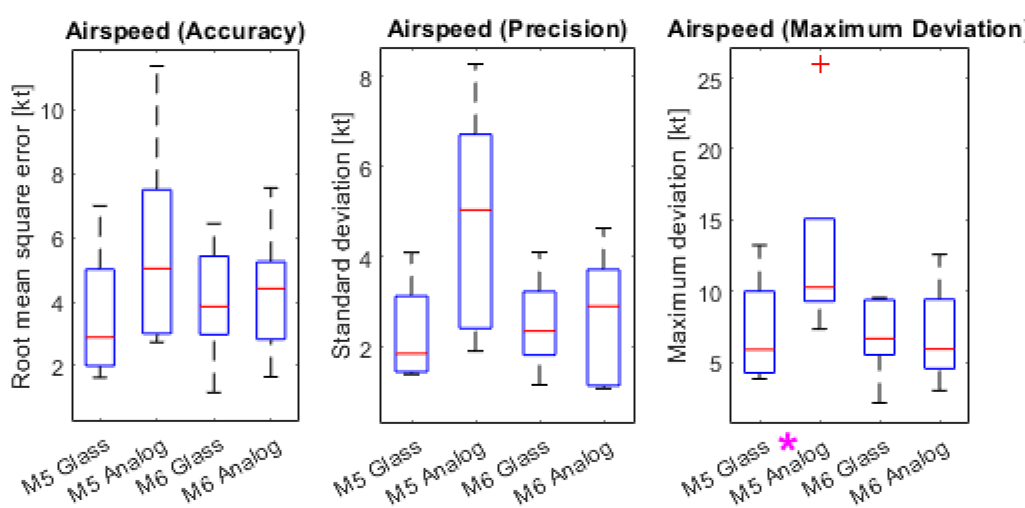

Figure 21. Comparison of airspeed deviations for Gr. B per maneuver and cockpit

4.3.6. Turning rate and slip angle

Unlike Gr. A, the comparison of turn rate and slip angle indications for Gr. B identified statistically significant differences in terms of turning rate accuracy, precision and maximum deviation ($p = 0.0625$ in all cases), indicating that practically all participants showed lower performance in this regard. In addition, a statistically significant difference was found for the precision in terms of slip angle ($p = 0.0625$), indicating a greater dispersion of the values (see Fig. 22).

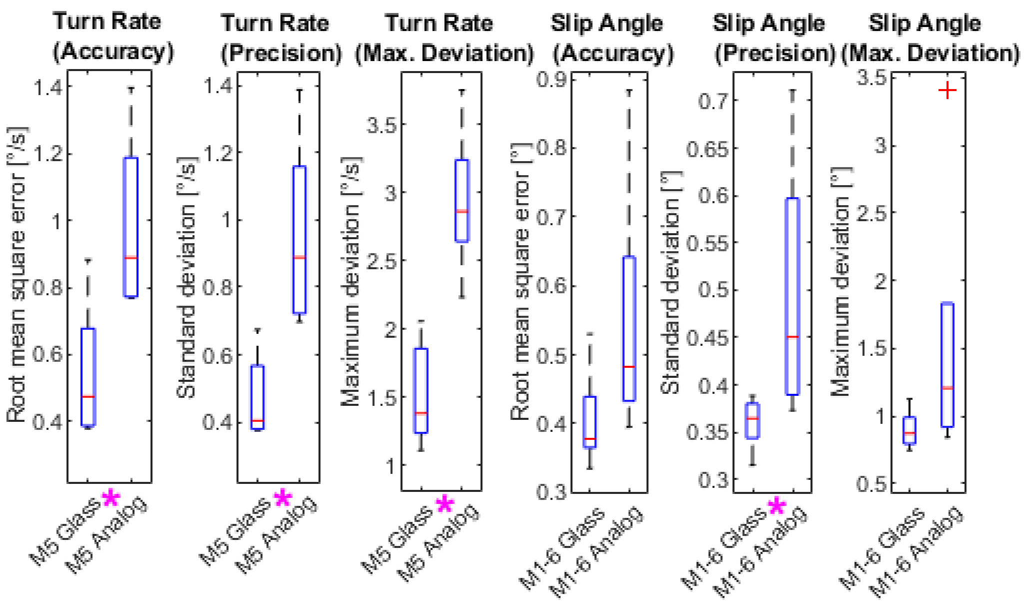

Figure 22. Comparison of turn-slip deviations for Gr. B per maneuver and cockpit

4.3.7. Summary for Gr. B

The results of this parameter-specific review for Gr. B are provided in Table 3. The table interpretation is as per 4.2.7.

Table 3. Summary of flight parameter variations for Gr. B following the transition

Parameter	**M1**	**M2**	**M3**	**M4**	**M5**	**M6**
Heading	---					↑↑↑
Bank angle	↑↑-	---	---	---		---
Altitude	---	---				
Vertical speed			---	---		-↑↑
Airspeed					--↑	---
Turn rate					↑↑↑	

4.4. HRV Assessment

Pairwise comparison of the HRV indices obtained returned the following results. No statistically significant differences were identified for both analysis within groups and between groups for all 6 indices involved, except the LF/HF ratio for Gr. A before and after the transition, where a statistically significant reduction occurred ($p \approx 0.0034$) with the median dropping from 1.97 to 1.16. The p-values obtained are provided in Table 4. These results are evident in Figure 23.

Table 4. Summary of p-values obtained for HRV indices

p-value Category	**mRR**	**SDNN**	**RMSSD**	**Area of LF**	**Area of HF**	**LF/HF**
Gr. A x Gr. B before transition	0.57	0.25	0.17	0.14	0.34	0.77
Gr. A x Gr. B after transition	0.85	0.12	0.09	0.24	0.20	0.38
Gr. A before and after transition	0.14	0.63	0.16	0.54	0.15	0.003
Gr. B before and after transition	0.81	0.62	0.81	0.31	0.44	0.31

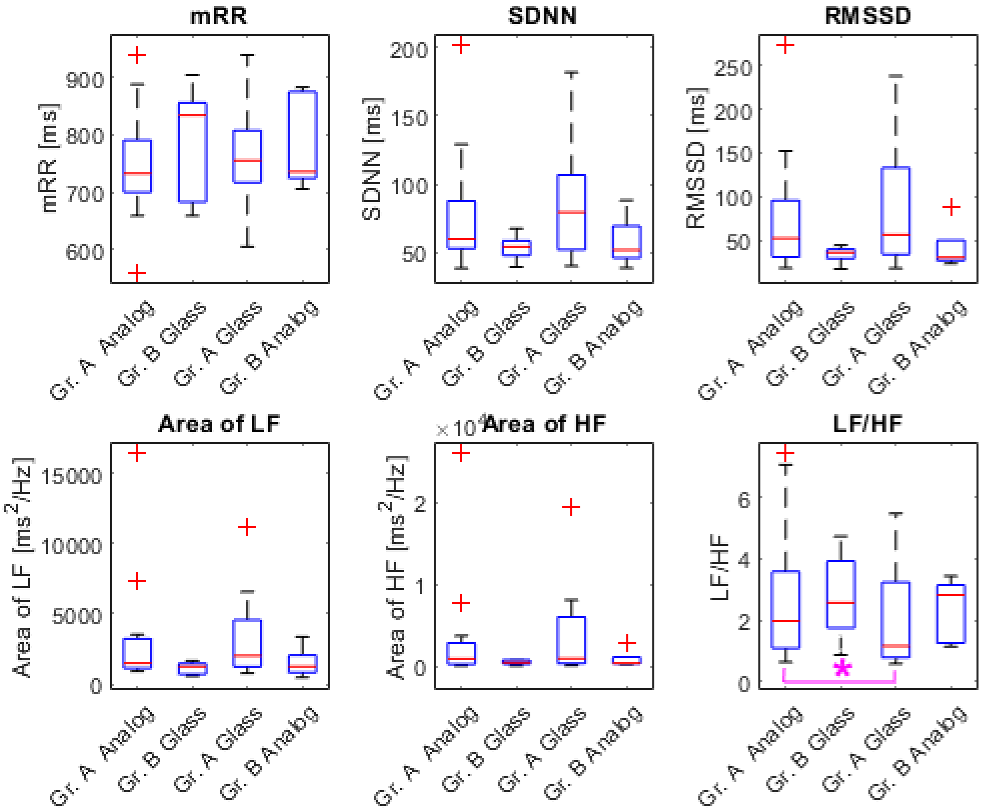

Figure 23. Comparison of HRV indices per group and cockpit type flown

Chapter 5 – Discussion

In the first place, it is important to note that the implemented experimental setup appears to be feasible and reasonable for the purposes and the background of the present research. It has enabled the participants to perform experimental flights to full extent according to a varying flight profile with the necessary data being retrieved. The maneuvers flown addressed different regimes of the flight and allowed for the cockpit designs to be comprehensively tested in terms of various instruments and their changing combinations. Their complexity appears to vary depending on the particular maneuver flown, which is reflected in the statistically significant difference among them. The participants involved and the consecutive groups formed, despite originating from two different flight schools, having experience predominantly with two separate airplane manufacturers, and possessing varying levels of flight experience, appear to share a considerable degree of commonality in terms of their abilities and, therefore, are comparable to a substantial extent, especially given the pathfinding nature of the present study. In addition, it is worth noting that, given the young age of the participants, their results should not have been unequally affected by any age-induced cognitive degradations mentioned in the state of the art review. These statements are supported by the results of the repeated-measures ANOVA, where no significant difference was found for the piloting precision and maximum deviations, assessing the group factor. It is further backed up by the post hoc tests not identifying any statistically significant differences for the pairwise comparison of the groups' performance per the maneuvers.

The same appears to hold true for the proposed methodology. The three assessed metrics of piloting accuracy, precision, and maximum deviation as measures of piloting performance demonstrated a certain degree of correlation among them and are definitely not opposed to each other. It is evident from the results, where statistically significant changes for a given value typically occurred within all three metrics or at least two of them. Therefore, on the one hand, it enables the collected data to thoroughly be utilized to a substantial extent, while, on the other hand, it demonstrates that the data collected shares a considerable degree of commonality, compatibility and applicability with respect to other studies which implemented different methodologies (for example, to studies utilizing maximum deviations from predetermined parameters as the sole measure of piloting performance). At the same time, it appears possible to utilize them both as a single measure of piloting performance (when averaged in terms of their Z scores) as well as to use them as standalone indicators for the purposes required.

A detailed examination of the results obtained revealed certain changes and variations in the performance. However, before assessing and interpreting them, certain additional factors shall be considered with respect to the possible sources of any such performance variations. Thus, the literature review has been able to identify the two suspected generalized reasons. On the one hand, it is the anticipated adaptation process when the pilots have to readjust their instrument scan and mental model of information collection to better suit the updated environment, - something that was theorized by the majority of the studies in the field. On the other hand, it is a possibility of one cockpit being capable of delivering superior performance compared to the other design. Therefore, for instance, when transitioning to a cockpit with a less ergonomic airspeed display, the pilots can be reasonably expected to perform worse in terms of maintaining the required speed, - it is not an adaptation implication but more of a layout limitation. Unfortunately, this factor so far has been considered to a rather limited extent by other studies. Finally, specifically within the experimental setup implemented for the purposes of the present thesis, it is reasonable to distinguish yet another factor - adaptation to the simulator itself. In fact, the majority of the volunteers who expressed their optional feedback at the end noted that they did not perceive the transition to be a substantial performance-inducing factor. However, the VR environment used was subjected to certain criticism as a factor increasing the complexity since some adaptation was required. It comes as no surprise, since none of the participants reported any previous experience with VR flight simulators.

Therefore, with regards to the key focus of the present thesis, – cockpit transition, – according to the general anticipation on the grounds of the state of the art review, it appears to have an effect on piloting performance. Nevertheless, the particular expectations were not exactly met. Thus, it can be concluded that in most cases the performance appears to be affected to a mild extent. For example, it is prominent from the comparison of composite scores for the study groups: neither Gr. A nor for Gr. B individually exhibited any statistically significant differences in terms of their total performance per maneuver flown before and after the transition. However, an important factor for interpretation of these findings is the aforementioned VR setup. Thus, while the first flight was anticipated to be generally simpler than the second one from the standpoint of any cockpit-transition-induced complications, the opposite can be said about the simulator adaptation. Ergo, any simulator-induced deviations must have been greater during the first flight compared to the second one. It effectively puts the two opposing factors causing deviations against each other, which has a potential to diminish the absolute difference that would have otherwise been observed as a result of the cockpit transition. The data contains certain indicators suggesting this hypothesis to be correct. One of the probable examples of this phenomenon is the statistically significant performance degradation exhibited by the groups between M1 and M2 on the first flight for the cockpits they are familiar with. Thus, Gr. A experienced it with the analog cockpit, while Gr. B encountered this deterioration in the glass cockpit, however, after the transition, Gr. A no longer displayed it in the glass cockpit during the second flight, evidently indicating that they had adapted to the simulator. Therefore, with regards to the summarized transition effects observed, there is still a potential for them to be greater under real conditions.

In terms of the role of the pilots' initial experience for the transition, it appears not to be significant with regards to their total performance. As it has been stated in the results, ANOVA did not confirm statistical significance in the relation of group and transition factor. Nevertheless, owing to the post hoc analysis and further deeper examination of the monitored flight parameters, it is quite prominent that the two groups had considerable discrepancies in the general pattern of their response to the cockpit transition, and their previous experience appears to have played a significant role in it. The groups' parameter performance differences were not mirrored in any way: neither both groups had deterioration in the same areas nor had a group the identical extent of degradation or improvement in the area where the other group experienced the opposite. In other words, neither both groups did exhibit the same degradations nor did one group experience a performance improvement in an area where the other group performed identically worse. Yet again it serves as a proof that there are several factors involved, including the aforementioned limitations of the cockpit layout, along with any possible implications of adaptation. Essentially, Gr. B appears to have been affected negatively and to a greater extent than their counterparts. It is signified by them still exhibiting the aforementioned drop in performance between M1 and M2 even after the transition. Yet another factor supporting this statement is a statistically significant negative difference emerging between M5 flown before and after the transition.

Focusing on the specific parameters observed, there was an expectation to observe discrepancies in terms of the airspeed and altitude performance, since concerns with regards to the round dials and vertical tapes were regularly prominent through the literature review. Therefore, the results of practically no statistically significant differences for either of the two parameters for both groups are rather surprising. The only statistically significant difference was observed for M5 in Gr. B and only in terms of maximum altitude deviations. While a generally negative tendency was visible for the other metrics, a larger sample size is required to claim anything with certainty in this regard. Quite interestingly, with regards to the instruments that were actually observed to make a difference, none of the reviewed studies indicated them as a risk or an issue. Thus, for Gr. A, the cockpit element of interest is the AI and its respective bank indications. The fact that the analog group demonstrated a statistically significant improvement in all three metrics of piloting precision for maintaining the required bank after the transition suggests the superiority of the glass cockpit design in these terms. Indeed, a large attitude indicator covering the whole PFD appears to be more easily recognizable in terms of any attitude changes since its read-out can be more readily caught with peripheral vision when compared to a considerably smaller analog artificial horizon in the middle on the 6-pack layout. It is also the size that is probably enabling a more precise read-out of the particular bank angle value that contributed to the improved participants' performance, even despite the fact that they possibly had to adapt for a new scanning model. However, while this tendency is valid for generally more simple maneuvers with just 2 parameters to hold (i.e. bank and altitude or bank and vertical speed for M2 and M3-4 respectively), the transition appears to have affected the participants bank performance negatively for the last maneuver (M6) which required a considerably broader instrument scan (the required parameters were heading, bank, airspeed, and vertical speed) and was generally more complex (unlike M1-5, the participants were required to actively adjust the power setting). It can suggest the adaptation effects might start to prevail under greater pilots' workload conditions. This trend will be further visible for Gr. B as well.

Variations in bank angle for Gr. B before and after the transition were observed, however, statistically significant ones occurred only for M1, possibly indicating some form of initial exposure to the new cockpit and adaptation. With regards to the other maneuvers, the absence of a statistically significant negative trend opposite to what was observed in Gr. A can be explained in two different ways. On the one hand, a generally negative trend was observed, however, verifying its statistical significance is problematic due to the small group size. On the other hand, a different possibility is that pilots flying the glass cockpit, owing to a precise value read-out, might tend to put more effort in maintaining the flight according to the value required, whereas analog cockpit flyers would probably stay with an approximation of what is “good enough”. In either case, further studies with regards to the artificial horizon would be of great scientific value.

The cockpit elements of interest for Gr. B are VSI and TSI since a statistically significant increase in their respective indications was observed. Following the transition, the participants performed considerably worse in terms of maintaining a rate-one turn during M5 and the required vertical speed for M6 (while no issues with vertical speed had been exhibited in M3-4). A greater value spread was also identified for the sideslip angle. One of the possible explanations lies in the comparison of the cockpits’ layout. The glass cockpit appears to be optimized for a T-shaped scan as any instrument read-out can be obtained by looking directly to the right, to the left, or down. The analog cockpit has a T-shaped scan employed for the crucial flight instruments (ASI, AI, ALTM, and HI), but TSI and VSI fall outside of its scope. Therefore, the fact that Gr. B performed worse in utilizing these instruments when compared to Gr. A may suggest that adapting the glass-cockpit instrument scan for the purposes of the analog cockpit might be more troublesome. In the case of VSI deviations in M6, they also appear to correlate with HI inaccuracies, therefore, indicating that a higher workload situation has a potential to make the effects of transition more pronounced. However, with regards to the heading deviations, their causes remain unclear since the instrument design is very similar between the two designs and the heading bug was used during both flights. Therefore, these indicators would be a valuable addition to the list of watch items for future research.

Yet another possible explanation for the discrepancies observed in the transition behavior is the fact that the participants belong to a relatively young group in terms of their age, and thus, are used to modern technology in their day-by-day lives. Therefore, transitioning towards the more technologically sophisticated glass cockpit might be accomplished more intuitively than a backwards transition from electronic displays to “steam gauges”. In addition, another factor worth noting is that the discussion above followed the assumption that the instruments during transition affect mostly their respective flight parameters. However, based on the information obtained, it is impossible to exclude a possibility that some of the effects observed might have originated not exclusively from the instruments corresponding to the flight parameters showing significant performance differences but also from interferences with other instruments. For example, if an airspeed indicator in the new cockpit requires longer fixation time to be interpreted, it is reasonable to expect the remaining part of the panel to receive less attention. However, this phenomenon would have likely been accompanied by an increase in mental workload, which is not prominent in the examined HRV indices. Nonetheless, further investigation involving eye tracking with instrument scanning pattern recognition would be required to fully rule out such a possibility.

In terms of the HRV evaluation, the majority of the indices are unremarkable in the sense of indicating results similar to those of previous studies - no significant workload discrepancies identified. However, the interesting and unexpected significant difference was that for the LF/HF ratio for Gr. A before and after the transition. What makes it even more surprising is that it actually decreased, indicating that the sympathetic nervous system dominance was weakened during the transition. In essence, such results would correspond to a lower level of stress and anxiety in the participants. Although such results fit the overall picture with Gr. A having a much less troublesome transition and even exhibiting some positive effects, this metric is highly affected by breathing [51]. Thus, a similar decrease could theoretically be achieved also in case the participants started breathing more frequently, which, in turn, would oppositely indicate a greater level of stress [59]. While it is remarkable that this metric decreased significantly for the dominating majority of the subjects in Gr. A, since the breathing rate was not recorded and since other indexes showed no significant variations, the LF/HF findings are deemed inconclusive. It emphasizes the importance for further scientific activities in this field to utilize comprehensive physiological measures for assessment of the pilots’ state.

Chapter 6 - Conclusion

The present thesis has dealt with the issue analog to glass and opposite cockpit transition and their respective effects on the piloting performance. This issue was subjected to a comprehensive review under the state of the art analysis resulting in numerous critical limitations being revealed. Thus, the topic was determined to be understudied, significant, and safety-critical, especially, given the known associated cases involving loss of life. Appropriate experimental methodology and setup were developed and then applied to 20 student pilots split into comparable groups of 15 and 5 representing pilots having experience exclusively with analog and glass cockpits respectively. The experiment aimed to subject the participants to two flights each consisting of a set sequence of maneuvers with a switch of the cockpit in between in order to detect any possible changes in their performance as a result of the aforementioned factor. Deviations from the required parameters were collected and processed as a measure of piloting performance, while heart rate measurements were used to assess the subjects' psychophysiological state and mental workload. On the grounds of the statistical analysis, sufficient information was accumulated to fully answer the set research questions. Thus, with regards to the first question, "what are the effects of cockpit transition on piloting performance?", it was determined that pilots exhibit a decrease in piloting performance with occasionally possible increases in particular parameter performance depending on the transition environment, but the observed effects are generally mild. Therefore, the first hypothesis of the cockpit transition being a purely negative factor had to be dismissed. The second research question, "is there any difference in the response to cockpit transition depending on the initial experience of the pilot?", received a positive response. The present observations determined that there is a significant difference in the pilots' response to the transition depending on their initial experience, with glass-to-analog transition appearing to be more troublesome. Ergo, a respective hypothesis of the initial experience being a factor was confirmed. The third question, "can the cockpit transition effects be attributed to an increased workload?", received a negative response: no statistically significant indicators suggest any levels of increased mental workload. It confirms the respective hypothesis of increased workload not being a factor in the issue of cockpit transition. Finally, the last research question, "which particular elements of the two cockpit designs contribute to the effects of cockpit transition?", was answered as follows. The cockpit layout elements suspected to play a role in the transition are the AI, VSI, TSI, and HI. Thus, the hypothesis of ASI and ALTM being involved was dismissed. Hence, the primary research goal, along with partial goals, were successfully fulfilled.

Nevertheless, the present thesis had to deal with certain limitations. The issue considered primary in this regard is the small sample size for Gr. B. It made determining statistical significance of their respective findings problematic and required an increase in α-value to 0.0625. It reflects the importance of involving more participants for this kind of research. Furthermore, the VR setup (specifically, its novelty to the participants) represents another limitation since the subjects had to adapt to it, thus possibly interfering with the results. It emphasizes that the participants must be completely familiar with the hardware used for cockpit transition, whether it is a real airplane or a simulator. Furthermore, with regards to certain HRV metrics, the experimental setup lacked breathing control to distinguish the sources of any observed variability. Finally, the findings of this work can be directly applied only to the general aviation environment as any other branches of aviation involve different aircraft in terms of their performance and equipment, along with a higher qualification of the pilots involved.

Notwithstanding the aforementioned limitations, the present thesis retains its scientific value. Now that the issue of transition has not yet attracted a major researchers' attention, this study practically remains one of its kind: it is the only publication comparing the two transition types for actual pilots while utilizing monitoring of the subjects' psychophysiological state. Furthermore, it provides the deepest analysis of the flight parameters and instruments involved when compared to the other studies in the field. Even though its findings cannot be generalized given the total sample size, the present thesis still serves as a pathfinder for further research in this field that can take advantage of the experience accumulated here.

Although this chapter brings to end to this year-long process of literature review, methodology development, experimentation, and data analysis, the case for cockpit transition is not closed and the general research in the field is far from being over. This topic still possesses a number of unknowns to be addressed. Thus, there is a great potential for a similar experimental setup to be utilized under a larger sample size. The maneuvering portion can be further developed to include dynamic flying such as approach. The experiment can validate the hypothesis under various sets of conditions (IMC, VMC). Furthermore, eye tracking information would be of great scientific value so that light can be shed on the instrument scanning patterns and their variations during the cockpit transition. All in all, this vastly understudied issue should finally get the attention it deserves for the benefit of aviation safety overall and especially pilots who trust their lives to these cockpits.

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