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Research report

Reducing flight upset risk and startle response: A study of the wake vortex alert with licensed commercial pilots

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ABSTRACT

The study aimed at investigating the impact of an innovative *Wake Vortex Alert* (WVA) avionics on pilots' operation and mental states, intending to improve aviation safety by mitigating the risks associated with wake vortex encounters (WVEs). Wake vortices, generated by jet aircraft, pose a significant hazard to trailing or crossing aircrafts. Despite existing separation rules, incidents involving WVEs continue to occur, especially affecting smaller aircrafts like business jets, resulting in aircraft upsets and occasional cabin injuries. To address these challenges, the study focused on developing and validating an alert system that can be presented to air traffic controllers, enabling them to warn flight crews. This empowers the flight crews to either avoid the wake vortex or secure the cabin to prevent injuries. The research employed a multidimensional approach including an analysis of human performance and human factors (HF) issues to determine the potential impact of the alert on pilots' roles, tasks, and mental states. It also utilizes Human Assurance Levels (HALs) to evaluate the necessary human factors support based on the safety criticality of the new system. Realistic flight simulations were conducted to collect data of pilots' behavioural, subjective and neurophysiological responses during WVEs. The data allowed for an objective evaluation of the WVA impact on pilots' operation, behaviour and mental states (mental workload, stress levels and arousal). In particular, the results highlighted the effectiveness of the alert system in facilitating pilots' preparation, awareness and crew resource management (CRM). The results also highlighted the importance of avionics able to enhance aviation safety and reducing risks associated with wake vortex encounters. In particular, we demonstrated how providing timely information and improving situational awareness, the WVA will minimize the occurrence of WVEs and contribute to safer aviation operations.

1. Introduction

Wake vortices are swirling air masses generated by the wings of an aircraft as it flies. These vortices create rotating columns of air that can persist for several minutes and travel considerable distances. The intensity and persistence of a wake vortex depend on factors such as the weight, speed, and configuration of the generating aircraft, as well as atmospheric conditions. Wake vortex encounters (WVE) present therefore significant threats to aircrafts, especially smaller aircrafts, primarily due to the turbulent air generated by preceding aircraft. These vortices

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can cause severe disturbances in the flight path of trailing aircraft, potentially leading to loss of control, structural damage, and in extreme cases, accidents and incidents. When an aircraft encounters a wake vortex, it can experience sudden and severe rolling moments. This is particularly dangerous during takeoff and landing when the aircraft is close to the ground and has limited room for recovery. Uncommanded roll rates induced by wake vortices can exceed the aircraft's control authority, making recovery challenging, especially for smaller aircrafts with limited roll control capabilities. At the moment, there are separation rules concerning how close aircrafts can be, which affects when they might encounter a wake from a leading or crossing aircraft. Despite the correct traffic separation according to the applicable minima, some of these events have resulted in significant upsets (reaching far in excess of 60 degrees bank angle) and loss of controlled flight, in particular for small aircrafts. These separation criteria are based on our understanding of wake phenomena: their intensity, their impact on the stability of the following or crossing-behind aircraft, their movement and decay rate according to a range of factors such as the prevailing atmospheric conditions at the flight level of the aircraft generating the wake. Generally, the separation criteria work well. However, from 1983 to 1993, the National Transportation Safety Board (NTSB) documented at least 51 wake vortex-related accidents and incidents in the United States alone. These incidents resulted in 27 fatalities, 8 serious injuries, and substantial damage or destruction to 40 airplanes (NATIONAL TRANSPORTATION SAFETY BOARD (NTSB), 1994). In the upper European airspace from 2009 to 2012, 26 wake turbulence incidents were reported during the *en-route* ('cruise') flight phase sometimes resulting in significant destabilisation of the aircraft encountering a wake, and occasionally resulting in injuries in the cabin (Aviation Week Network, 2017; Bobylev et al., 2010; EUROCONTROL, 2020; Gerz et al., 2002; Schwarz et al., 2019). This highlights the ongoing risk of wake vortex encounters even at higher altitudes. At the moment, these wake vortex (WV) events are not predicted by Air Traffic Control (ATC), nor they are foreseeable by pilots unless the wake or contrail of the aircraft ahead is visible. For such reasons, WV events are primarily of concern to airlines, flight and cabin crews, and passengers. Consequently, continuous improvements in operational procedures, pilot training, and technological advancements are essential to mitigate these risks and enhance flight safety. In this regard, the present study aimed at providing an innovative solution in terms of technological advancements to predict and mitigate the impact of WVE on pilots, cabin crew, passengers and the overall flights safety.

1.1. Flight upsets and future Aviation

As confirmed by the analysis of wake turbulence encounter reports, in almost all the cases the flight crews did not anticipate the events, creating a risk of cabin crew or passenger injuries, due to the sudden unannounced turbulence effects, and in the extreme case, aircraft loss of control (i.e flight upset or unusual attitude) due to the startle effect of the wake turbulences on the flight crew. As reported by ICAO (ICAO, 2014), the term "flight upset" is defined in the glossary as an in-flight condition by which unintentionally an aeroplane exceeds the parameters normally experienced in normal line operations or training. An upset is generally recognized as a condition of flight during which the pitch angle of the airplane unintentionally exceeds either 25 degrees nose up or 10 degrees nose down; or a bank angle exceeding 45 degrees; or flight within the aforementioned parameters but at inappropriate airspeeds. Experience has demonstrated that if the pilot reacts at the first roll motion influenced by the startle effect when in the core of the vortex, the overall roll motion could be potentially amplified by startle reactions. In other words, in case of a wake turbulence encounter, the crew's rapid reaction in roll may amplify the roll motion with rapid roll control reversals carried out by the crew in an "out of phase" manner. Some in-flight incidents have also demonstrated that in case of engaged autopilot, intentional disconnection can complicate the scenario. In fact, wake vortex encounters (WVE) can affect many important flight parameters related to aircraft control For example, during a WVE, deviations in flight altitude (ΔH), true airspeed (ΔV), angle of attack ($\Delta \alpha$), bank angle ($\Delta \phi$) and load factors (Δn_x, Δn_y, Δn_z) can be substantially high and even critical (Bieniek et al., 2016; Gerz et al., 2002; Vechtel, 2016). The control applied by the pilot can either minimize the impact of the WVE on the aircraft, or, conversely, enhance the WVE effect. It depends on the pilots' competencies and preparation for WWE events. In this regard, the risk of exposure to WVs is likely to increase in the future because of the traffic growth and the mix of traffic type involving larger and smaller aircraft across upper airspace. Appropriate and specific countermeasures must be therefore designed and evaluated (Yang et al., 2023; Zachariah et al., 2023). In addition, according to the world statistics of the last 40 years, most of the accidents/incidents in aviation (from 50 – 55 % up to 70 – 75 %), are associated to human involvement or "pilot errors" (Khan et al., 2022; Mathavara et al., 2022).

In this perspective, the present study aimed at developing and validating an innovative alert solution that would be presented on air traffic controllers' radar screen to warn the relevant flight crews ahead of time, thus allowing them to either avoid the wake, or at least, secure the cabin to avoid injuries (Rooseleer et al., 2022). Three approaches have been used in the study. The first approach employed the SESAR-Human Performance Human Factor Issues Analysis (SESAR-HP HFIA) by which questions about the potential impact and benefits of the alert solution were asked to the flight crews. Their responses provided useful information about potential changes of current standard operating procedures (SOPs). The second approach aimed to determine the required Human Factors (HF) support based on the Human Assurance Levels (FAA/EUROCONTROL, 2004). The Human Assurance Levels (HALs) consider vital the aspect "safety" when designing and developing new solutions, e.g., insufficient situation awareness or fatigue can increase the risk of air accidents and incidents. A review on accidents and incidents revealed that a crash arising from a wake vortex encounter (WVE) is very rare amongst commercial air traffic. Nevertheless injuries among cabin crews and passengers can and do occur (Federal Aviation Administration (FDA), 2007), and total loss of an aircraft remains a credible (albeit remote) risk. The third approach consisted in collecting different kinds of data while the pilots were dealing with flight simulations and WVEs. In particular, behavioural (reaction time), flight simulator log - file (roll angle, speed, altitude, etc.), subjective (self - reports) and neurophysiological (brain activity and skin conductance) data were acquired. In particular, the neurophysiological signals were employed to validate the impact of the WV in terms of pilots' mental workload, stress and arousal by comparing the experimental conditions with (WV) or without (NO VW) the WV alert. The capability and advantages of using neurophysiological – based measures to assess human performance have been demonstrated by the authors in many different contexts, like aviation (Aricò, Borghini, Di Flumeri, Colosimo, Bonelli, et al., 2016; Aricò, Borghini, Di Flumeri, Colosimo, Pozzi, et al., 2016a; Borghini, Di Flumeri, et al., 2020; Borghini et al., 2014, 2022a; Di Flumeri et al., 2019; Gomez et al., 2024; Hamann and Carstengerdes, 2023; Hight et al., 2024; Masi et al., 2023; Mumtazi et al., 2024; Sebastiani et al., 2020; Toppi et al., 2016), automotive (Di Flumeri et al., 2022; Kong et al., 2015, 2017; Maglione et al., 2014; Sciaraffa et al., 2022a; Zeng et al., 2021), healthcare (Borghini Gianluca et al., 2023), industry (Giorgi, Ronca, Vozzi, Sciaraffa, Di Florio, et al., 2021; Ronca, Di Flumeri, et al., 2021; Ronca, Giorgi, et al., 2021; Ronca, Rossi, et al., 2020; Song et al., 2023; Ronca et al., 2021), virtual reality (Marucci et al., 2021; Reynal et al., 2019, 2020) and training (Borghini, Aricò, Di Flumeri, Sciaraffa, et al., 2017; Borghini et al., 2016, 2022c; Taya et al., 2015).

The overall assumption of the study was that the WV alert would facilitate the preparation of the crew to WV encounters and the securing of cabin with proper time before the WVEs. We were therefore expecting to observe an increase in the pilots' mental states right after the alert (i.e. the WV alert requires to process more information), and a decrease during the following phases (i.e. the WV alert would make the preparation to deal with and WV recovery easier) compared to the condition without the WV alert (NO WV) condition. These assumptions were based on the fact that the alert provides information about the WVEs, so that the pilots are able to promptly analyse the situation, take a decision, secure the cabin and plan the procedure to adopt. For example, the pilots would employ a Threat Error Mitigation (TEM) approach to the alert: *Threat* = wake upset, *Error* = inappropriate rudder inputs, *Mitigation* = avoid rudder and focus on pitch/roll. These activities would likely have an impact on the pilots' mental workload (information processing, decision making), stress (unexpected event, unusual upset) and arousal (enhance awareness and clearer expectation of what is going to happen).

1.2. *Wake alert concept*

From a pilot perspective, the availability of information about a potential en-route WVE would be useful and beneficial. The effects of WVEs can be significantly minimised if crews have sufficient time in advance to secure the cabin and prepare to take over manual control in case needed, without being startled. The wake alert delivered by controllers and the response by the pilots were defined in a two-step process, as follows:

Step 1 - Alerting of Encounter Risk. In order to prepare the flight crew for a wake turbulence encounter, simulated ATC provided the crew with an alert i.e., "caution wake turbulence". The phraseology of the alert included a 'time to contact' with the wake turbulence, according to Table 1.

Step 2 - Prepare for Wake Encounter according to upset management training and procedures. In this study the flight crew were instructed not to request clearance to adjust trajectory or make an avoidance manoeuvre, thus the pilots were expected to fly through the wake vortex. The wake-specific aircraft upset preparation consisted in the following actions:

❖ Secure the cabin:

- Put seatbelt sign on.
- Passenger announcement (if time allows).
- Cabin Crew instruction – stop service / get seated.

❖ Prepare for aircraft upset management according to SOPs. SOP example:

➢ *Before the encounter*

- CPT takes control at his/her discretion.
- Do not voluntarily disengage the Autopilot.
- Cover the controls.

➢ *During the encounter*

- Do not impose large rudder deflection.
- Wait for a reasonable stabilisation of the aircraft, before controlling the aircraft with manual inputs.
- Roll wing level, return to cruise level and re-engage the Autopilot as necessary.

Table 1
ATC phraseology to announce wake turbulence cautions.

Alert Phraseology	Pilot understanding
"…, caution wake turbulence imminent"	Time to WT encounter $< \sim 30$ s
"…, caution wake turbulence within 1 minutes"	~ 30 s < Time to WT encounter < 1 min
"…, caution wake turbulence within 2 minutes"	1 min < Time to WT encounter < 2 min
"…, caution wake turbulence within 3 minutes"	2 min < Time to WT encounter < 3 min

Fig. 1 shows a schematic view of potential WVEs, functionality of the WV alert and interaction between Air Traffic Controllers and Pilots.

1.3. *Wake vortex alert function*

The short-term automated wake alerting function is based on a ground-based prediction of the imminent risk of significant wake turbulence encounters. The prediction is built from wake predictor module and encounter conflict logic which is fed by flight data, traffic trajectory profiles and prevailing altitude winds for determining the wake decay and transport evolution. The time horizon of the alert prediction used in the flight simulations was set to 30 seconds (WV0), 1 minute (WV1), 2 minutes (WV2) and 3 minutes (WV3). The real achieved time horizon will be depending on the minimum level of prediction accuracy and confidence, which itself depends on the type and quality of the available input data and prediction algorithm. Today, ATC primary role and responsibility is to ensure collision prevention and provide a service supporting an efficient and orderly flow of traffic. In case of traffic crossing in relatively close proximity (while above the surveillance minima of 5 NM longitudinal), some Air Navigation Service Provider (ANSP) provides traffic information on a systematic basis, e.g., within 7.5 NM. This includes the ICAO wake turbulence category for large lead aircraft ('Heavy' or 'Super'). Area Control Centre (ACC) ATC has no specific means to detect wake encounter risk. The wake turbulence category is not part of the core flight label information (unlike for the Approach or Departure phases of flight where specific separation minima are applicable). Although some arguments against superimposing meteor data on the main ATM radar display exist, as a parallel with metrological information, some ANSPs already operate an ATC system with capabilities to superimpose the weather information visualization onto the surveillance air traffic picture (e.g., thunderstorms area/CBs) enhancing the Controllers situation awareness and context of pilot route deviation / requests.

During the flight simulations, the IOS acted as an ATC and provided caution wake turbulence information to the crews. The 'caution' information was accompanied by traffic information about the crossing configuration in line with current ICAO provisions set in Document 4444 PANS-ATM (ICAO, 2001) for traffic information provision related to collision prevention, including:

- Direction of the wake-generating flight;
- Position;
- Relative altitude difference (if any);
- Generating aircraft type.

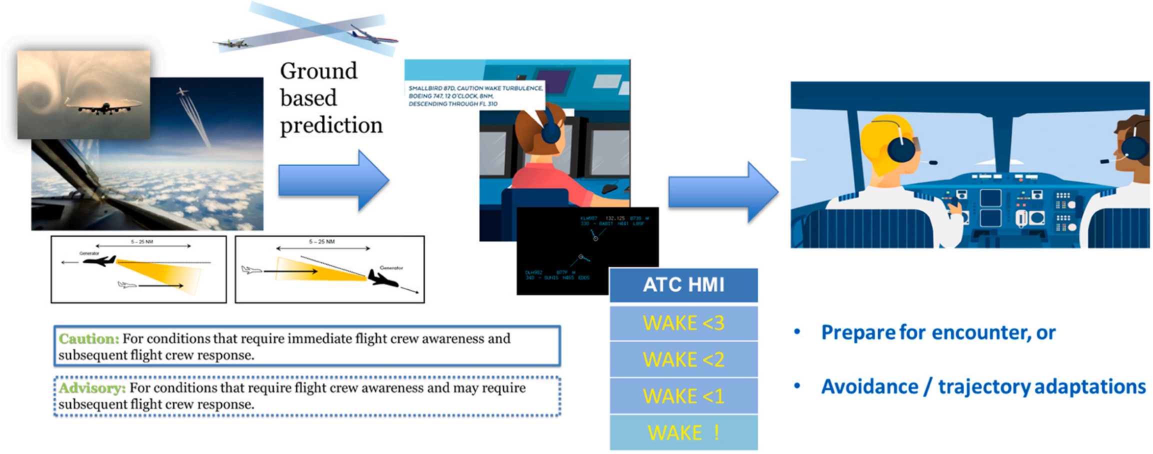
The wake caution and traffic information were intended to be transmitted to the pilots of the exposed traffic via standard radiotelephony (R/T) voice communication.

The overall goal of the study was therefore to assess the impact of the WV alert combining pilots' operational (behavioural), subjective (questionnaire) and neurophysiological (mental states) data.

2. Material and methods

2.1. *Participants*

In the context of the EU project "SAFEMODE" (https://www.safemodeproject.eu/), we aimed at evaluating the potential benefits and impact of an innovative technology (Wake Vortex Alert – WVA) by involving professional pilots, therefore we sought professional flight crews among the airlines in the consortium. In particular, we needed licensed pilots (with at least 1000 flight hours) and who had experienced WV encounters (WVE). In this regard, since WVEs are not so common,



Caution: For conditions that require immediate flight crew awareness and subsequent flight crew response.

Advisory: For conditions that require flight crew awareness and may require subsequent flight crew response.

- **Prepare for encounter, or**
- **Avoidance / trajectory adaptations**

Fig. 1. Schematic functionality of the WVA and interactions between Pilots and Air Traffic Controllers.

only ten pilots (40.6 ± 9.8 years old, 1471.4 ± 161.4 flight hours) were found among the airlines: 8 pilots from TUI Airways and 2 pilots from Ryan Air Group The experiments were conducted following the principles outlined in the Declaration of Helsinki of 1975, as revised in 2008. The experiments have been approved by the Institutional Review Board (or Ethics Committee) of the SAFEMODE project (protocol code 2022/04.7 on the 12/04/2022) for studies involving humans. Informed consent was obtained from each pilot on paper, after the study explanation, as well as the consent for recording and employing videographical material. All the data collected during the flight simulations were (pseudo)anonymized and processed according to the current EU GDPR regulations to prevent any association with the participants' identities.

2.2. Full – motion and high - fidelity flight simulator

The flight simulations have been performed using the AIRFOX UPRT flight simulator at the AMST-Systemtechnik GmbH (Ranshofen, Austria). The flight simulator was configured with the B737–800 cockpit layout as the pilots involved in the study were licensed to fly such an aircraft. The Captain (CPT) sat to the left, the First Officer (FO) to the right, and the Instructor Operator Station (IOS) seat was behind the crew. The IOS also acted as an ATC and cabin staff for simulating the communications to and from the pilots. Two additional floor positions behind the crew were used by the Observers (OBS1 and OBS2) which collected neurophysiological and eye tracking data (Fig. 2). In this regard, the eye tracking data has not been used for this study, therefore they will not be discussed.

The AIRFOX UPRT flight simulator can replicate the extended flight envelope covering the stall and post-stall flight regimes (Pugh et al., 2023) and it is generally employed for Upset Prevention and Recovery Training and simulation studies of Loss-Of-Control In-flight (LOC-I) events (Abramov et al., 2019; Nguyen et al., 2022). The implemented class-specific out-of-the-envelope flight simulation model was based on the compliance with the aircraft flight performance, stability and controllability and it was validated by several experienced test pilots (Frederic et al., 2023). In addition, Airbus provided the most common wake disturbances geometries of aircrafts crossing in the form of aerodynamic forces and moments acting on the aircraft (Table 5). The profile of the flight simulation was set for all runs as reported in Table 2.

2.3. Experimental protocol and hypothesis

The flight simulations were held at the AMST - Systemtechnik GmbH (Ranshofen, Austria). The validation objective of the protocol was focussed on the performance of the pilots in managing the aircraft upset, firstly in terms of flight control inputs to stabilise the aircraft (according

Fig. 2. The full motion B737–800 flight simulator provided by AMST – Systemtechnik (GmbH (Ranshofen, Austria).

Table 2
General details of the flight simulation scenario.

Parameter	Value
Time of day	Daytime
Weather conditions	Smooth weather (no atmospheric turbulence)
Traffic	Traffic will not be on TCAS No visual clue of generating aircraft (other traffic, contrail)
Phase of flight	Cruise
Aircraft status	Cruise speed / wings level / at various flight levels above FL285 / all system functions normally / no planned change of flight level
Autopilot status	Engaged

to the success criteria in Table 3), management of the aircraft upset from the subjective perception of the pilot, and finally in terms of mental states variations *before*, *during* and *after* the WVEs with (WV) or without (NO WV) the WV alert.

In order to maximise data collection and control for flight crew experience and seniority, each flight crew (CPT and FO) performed four runs where they swapped position from 'pilot flying' (PF) and 'pilot monitoring' (PM) after each run. Moreover, the strength of the encounter was varied to deter learning effects and maintain operational validity. Concerning the familiarisation with the flight simulator and WVA, before the experimental days at the AMST facilities, the pilots were briefed about the WVA concept and functionality to make sure they were familiar with it. In addition, a period of training with the flight simulator, its commands and interfaces, and WVA phraseology was conducted before starting the experiments to avoid confounds due to familiarisation aspects. This training phase, lasting between 3 and 5 minutes as the pilots were licensed to flight with the B737–800 aircraft, was conducted with each crew whilst the aircraft was in the cruise phase. This provided familiarisation with the simulator and use of WVA information, as well as a period of adjustment to the instrumentation and neurophysiological sensors. Each flight simulation run lasted 45 minutes and included three WVEs. The WVEs were classified according to the 'time to contact' (in minutes) or absence of the alert, labelled respectively as *WV1* (1 min caution), *WV2* (2 mins caution), *WV3* (3 mins caution), *WV0* (Imminent – less than 30 sec) or *NO WV* (No alert). The presentation of these events was randomised to avoid any expectation and habituation effects. Each wake encounter lasted about 15 minutes from start to finish and consisted in the following phases: stable flight (cruise), wake alert/no wake alert, time to prepare, wake onset and recovery. WVEs strength (high, low, positive and negative) was varied across the runs. Subjective, flight simulator log – file, behavioural and neurophysiological measurements were acquired and a final debrief was made with each crew after their four runs (Fig. 3).

Table 3
Success criteria for pilots' operational, behavioural and mental states assessment.

Success Criteria	Related Experimental Hypothesis
The secondary maximum roll angle when the flight crew is alerted by ATC ahead of the wake encounter shall be reduced compared to the situation without pre-encounter alerting. The maximum number of secondary upsets when the flight crew is using the wake alert, shall be reduced compared to the situation without. The maximum time to level flight and aircraft stabilisation when the flight crew is using the wake alert, shall be reduced compared to the situation without. The ability to control the aircraft upset is judged by pilots as improved when using the wake alert, compared to the situation without. The capability of receiving the alert will make the pilots less mentally loaded and stressed, and more aroused during the encounter compared to the situation without.	If the ATC wake alert is used, then there will be an improvement in flight crew wake-upset management. The greater improvement in flight crew wake-upset management will be observed when the ATC alert is given at 3 minutes out, rather than when the wake-vortex is imminent. If the ATC wake alert is used, the pilot's arousal will most likely increase immediately after the caution has been received, and thus aircraft piloting will be better (quicker time to respond, less standard deviation in roll, bank angle correction) when responding to the onset of wake turbulence, than without the alert. If the ATC wake alert is used, the amplitude of the stress level will be lower and the time to recover the baseline value (transient over time) will be quicker than without the alert. If the ATC wake alert is used, the pilots' mental workload and stress will be higher right after the alert and lower during the recovery, while their arousal will increase right after the alert and will stay high overtime.

2.4. Flight simulator data collection and analysis

In order to assess the impact of the wake alert on the pilots' ability to manage the wake upset on the aircraft, the flight simulator kept recording several aircraft parameters. In particular, we considered the deviations in flight altitude (ΔH), true airspeed (ΔV), angle of attack ($\Delta\alpha$), bank angle ($\Delta\phi$), pitch angle ($\Delta\theta$), control inputs in the pitch and roll channels, X_{LON} and X_{LAT}, Mach number in roll, pitch and yaw (ΔL_{WV}, ΔM_{WV}, ΔN_{WV}), and load factors (Δn_x, Δn_y, Δn_z) to compare the recovery with (WV) and without (NO WV) the WVA.

2.5. Self-reports

A feasibility questionnaire was administered during crews debriefing. It queried how the presence of the WVA impacted on aspects of flight management, including decision-making, communications, mental workload and flight inputs. The pilots were required to rate, on a seven-point Likert scale, how the presence of the alert improved or hindered their performance. The results were then amalgamated to give a frequency distribution of responses. In addition to the feasibility questionnaire, the Situational Awareness Rating Technique (SART) was administered after each run on both PF and PM. SART (Taylor, 2017)is a multidimensional scaling technique that consists of a series of questions that have bipolar responses. There are ten dimensions which involve participants subjectively rate on a seven-point rating scale (1 = Low, 7 = High) based on their performance. The ratings are then combined to calculate a measure of participant's SA.

The ten dimensions were partitioned into three categories as follows:

I.Demands on attentional resources: complexity, variability, and instability of the situation.

II.Supply of attentional resources: division of attention, arousal, concentration, and spare mental capacity.

III.Understanding of the situation: Information quantity and information quality.

A composite SART score was finally calculated using the following formula:

$$SA = Understanding - (Demands - Supply) \tag{1}$$

Therefore, if a pilot had low attentional demands, a high supply of attentional resources and a high level of understanding, then they will have a high SART score, and vice - versa.

2.6. Neurophysiological data

The pilots' brain activity (electroencephalogram - EEG) and skin conductance (electrodermal activity - EDA) were recorded during the flight simulations. In particular, the signals were collected continuously for the entire flight simulations. Although the raw EEG and EDA signals were acquired with different sampling rates, we aligned the Neurometrics by estimating the corresponding parameters with the same time resolution, that is one minute. The details are reported in the following sections.

Fig. 3. Pilots' behavioural, subjective and neurophysiological data were acquired together with the simulator log - files during the entire flight simulation and WVEs.

2.7. EEG data collection and analysis

The pilots' EEG signals were recorded by the digital monitoring system Mindtooth Touch (Brain Products GmbH, Gilching, Germany - BrainSigns srl, Rome, Italy, www.mindtooth-eeg.com) with a sampling frequency of 125 Hz. The eight water-based recording electrodes were properly placed over the frontal and parietal brain areas commonly considered for mental states assessment (Borghini et al., 2022b; Ronca et al., 2022; Sciaraffa et al., 2022b). In particular, the EEG channels were the following ones: AFz, AF3, AF4, AF7, AF8, Pz, P3, P4, all referenced to the left mastoid and grounded to the right mastoid. Once the electrodes' impedances (kept below 50 kΩ) and the quality of the EEG signals were checked, the experimental protocol started. The EEG signal was first band - pass filtered with a 5th-order Butterworth filter in the interval 2 – 30 Hz. The eyeblink artifacts were detected and corrected online by a modified implementation of the Multi-Channel Wiener (Somers et al., 2018) filtering through the Reblinca method (Di Flumeri et al., 2016). For further sources of artefacts, specific algorithms of the EEGLAB toolbox (Delorme and Makeig, 2004) were applied. Specifically, the preprocessed EEG signal has been divided into 1-sec epochs. Three criteria have been applied to recognize artifactual data automatically. Firstly, EEG epochs with the signal amplitude exceeding ±80 μV (*threshold criterion*) were marked as "artifacts''. Then, each EEG epoch was interpolated to check the trend's slope within the considered epoch (*trend estimation*). If such a slope is higher than 20 μV/s, the considered epoch is marked as "artifact." Finally, the signal sample-to-sample difference (*sample-to-sample criterion*) was analysed: if such a difference, in terms of absolute amplitude, was higher than 25 μV, i.e., an abrupt variation (no-physiological) happened, the EEG epoch was marked as "artifact". In the end, the EEG epochs marked as "artifacts'' were removed from the EEG dataset with the aim of having a clean EEG signal to perform the analyses. Table 4 reports the percentages of artifacts identified for each EEG channel.

Table 4
Percentage of artifacts for each EEG channel.

EEG channel	Percentage of artifacts (%)
AF3	6.33
AF4	6.83
AF7	7.11
AF8	6.81
AFz	7.09
P3	6.27
P4	5.41
Pz	5.07

From the *artifact-free* EEG, the Global Field Power (GFP) was calculated for the EEG frequency band of interest for the mental states evaluation, which was the Theta, Alpha, and Beta. The GFP was chosen as the parameter of interest describing brain EEG activity since it has the advantage of representing, in the time domain, the degree of synchronization or a specific cortical region of interest in a specific frequency band (Cartocci et al., 2018; Flumeri et al., 2016; Skrandies, 1990). More specifically, the GFP was calculated over all the considered EEG channels for each epoch using a Hanning window of the same length of the considered epoch (1 s length, which means 1 Hz of frequency resolution), as it follows:

$$GFP_{band,region} = \frac{1}{N}\sum_{i=1}^{N} x^{2}_{i,band}(t) \tag{2}$$

where N corresponds to the number of the considered EEG channels and $x^{2}_{i,band}$ is the i_{th} EEG channel filtered within the selected EEG frequency band. The different EEG frequency bands were defined according to the Individual Alpha Frequency (IAF) value (Klimesch, 1999) computed for each pilot. Since the Alpha peak is mainly prominent during rest conditions, the pilots were asked to keep their eyes closed for a minute before starting the experiments. After the EEG data preprocessing, the GFP - derived features were computed to objectively characterize the pilots' mental states. In particular, the mental workload and stress indexes were computed as reported in the following equations:

$$Mental\ workload = \frac{Frontal\ Theta_{GFP}}{Parietal\ Alpha_{GFP}} \tag{3}$$

$$Stress = Parietal\ Beta\ High_{GFP} \tag{4}$$

In this regard, it has to be noted that computation of the mental workload and stress indexes were defined according to different previous work in which such mental states were deeply investigated as EEG-derived features (Aricò, Borghini, Di Flumeri, Colosimo, Pozzi, et al., 2016b; Borghini, Aricò, Di Flumeri, and Babiloni, 2017; Borghini, Ronca, et al., 2020; Sciaraffa et al., 2022a).

2.8. *EDA data collection and analysis*

The pilots' EDA was collected by the Shimmer3 GSR3+ Unit (Shimmer sensing, Ireland) with a sample rate of 64 Hz. The device was fixed on the hand managing the aircraft engines, thus the right one for the CPT and the left for the FO. In particular, the EDA electrodes were placed around the index and middle fingers. The EDA was first low-pass-filtered with a cut-off frequency of 1 Hz, and then an artifact correction Matlab tool was applied to remove discontinuities and spurious peaks from the signals. Lastly, the signals were processed by using the Ledalab suite (Bach, 2014). A continuous decomposition analysis (Cohen, 2013) was applied in order to estimate the tonic (SCL) and phasic (SCR) components. The SCL is the slow-changing component of the EDA signal, mostly related to the global arousal of the participant. On the contrary, the SCR is the fast-changing component of the EDA signal, usually related to single stimuli reactions (Borghini, Di Flumeri, et al., 2020). The pilots' arousal level has been hence estimated through the SCL as demonstrated in previous studies (Giorgi, Ronca, Vozzi, Sciaraffa, Florio, et al., 2021; Ronca, Martinez-Levy, et al., 2023; Ronca, Uflaz, et al., 2023; Ronca, Vozzi, et al., 2020):

$$\mathit{Arousal} = \text{Skin Conductance Level} \tag{5}$$

2.9. *Data normalization and statistics*

The neurophysiological indexes, i.e., the mental workload, stress and arousal were normalized through the z - *score* technique according to the following formula:

$$X_{z-scored} = \frac{X_i - median(X)}{mad(X)} \tag{6}$$

where X_i corresponds to the neurometrics value at the i-th time interval, *median(X)* is the median value of the entire distribution of the neurometric X considered (e.g. X = Mental Workload, Stress or Arousal) and *mad* corresponds to the median absolute deviation of the entire distribution of the neurometric X considered (Arachchige and Prendergast, 2019; Pham-Gia, 2001; Pinsky and Klawansky, 2023). Such a normalization procedure was selected for obtaining comparable distributions among the different participants and, at the same time, preserving such distributions from outliers. Subsequently, the Shapiro–Wilk test was used to assess the normality of the distribution related to each of the considered parameters.

2.10. *Wake turbulence characteristics and geometry*

During the cruise phase, wake vortex intensity and time to dissipate depend not only upon the weight, size and speed of the aircraft, but also on atmospheric conditions. Wake vortices (WVs) may persist for 2–3 minutes and can descend more than 1000 ft with a typical sink rate of 400 ft/min. When flying below the tropopause, there is an increased likelihood of encountering wake turbulence as the decay is slower (Bobylev et al., 2010; Gerz et al., 2002; Schwarz et al., 2019). Large aeroplanes generate stronger wake vortices, mostly affecting the following smaller aircrafts. In this condition, (en-route) wakes can be encountered even up to 25 NM behind the generating aeroplane, while the most significant wakes are reported within 15 NM of the generating aircraft. The wake generated by crossing traffic climbing or descending in the vicinity might cross the follower's trajectory before it fully decayed. The basic effects of WVE are inducing roll, vertical acceleration (which can be negative) and variation in altitude (Aviation Week Network, 2017; Bieniek et al., 2016; Bobylev et al., 2010; EUROCONTROL, 2020; Gerz et al., 2002; Schwarz et al., 2019; Vechtel, 2016). This can lead to loss of control or possible injuries to cabin crew and passengers as VWs are sudden and unexpected events. Beyond the cruise phase, some air traffic will be climbing to or descending from cruising levels or changing cruising levels. These additional situations create different traffic crossings geometries and proximities, which can each lead to potential wake turbulence encounters in case of unfavourable prevailing atmospheric and wind conditions. Most of the reported wake encounter cases involved a large aircraft (generators) and smaller aircraft (following) types. The majority of the significant upsets resulting from wake encounters generally occur when the leader or following aircraft is in a climbing or descending flight profile (Rooseleer et al., 2022). Table 5 lists the typical wake encounter configurations based on the possible en-route traffic crossing geometries which can induce a wake encounter (EASA, 2017).

Based on the EUROCONTROL voluntary ATM incidents reporting (EVAIR - https://www.eurocontrol.int/service/eurocontrol-voluntary-atm-incident-reporting), the most frequent and typical wake turbulence encounter geometries are depicted in Fig. 4 and Fig. 5, where the leader (wake-generating aircraft) is descending, or in case of opposite crossing with minimum vertical separation (1000 ft in Reduced Vertical Separation Minima - RVSM - airspace).

2.11. *Selection of wake vortex encounters geometry*

Analysis of all configurations listed in Table 5 shows that flight parameters (motion cues values and frequency) differ depending on wake turbulence encounter geometry. Thus, their effect on flight crew and passengers differs as well. To compare the configurations in terms of motion cues effect, the International Standard 2631 (ISO 2631) has been used (ISO/TC 108/SC 4, 1997). The ISO 2631 defines methods for the measurement of vibrations and explain how to process measured data, standardize quantified performance measures concerning health, perception, comfort and motion sickness. The quantified discomfort (J) is based on frequency-weighted root mean square (RMS) computations of the sum of lateral (y) and vertical (z) accelerations (a_{w_i}) data as Eqs. (7) and (8) show:

$$J = a_{w_y} + a_{w_z} \tag{7}$$

with

$$a_{w_i} = \left(\frac{1}{T_e}\int_0^{T_e}(a_i(t), w_i)^2 dt\right)^{1/2} \tag{8}$$

and where $(a_i(t), w_i)$ is the acceleration in the i-th axis weighted with filter w_i in m/s^2 and T_e denotes the is wake exposure time in seconds (Asua et al., 2022). Analysis of discomfort calculations allowed us to conclude that the hazardous wake encounters, in terms of discomfort and autopilot disengaging, are those with angles $160^\circ \le \psi \le 180^\circ$ (head-on encounter) and $0^\circ \le \psi \le 40^\circ$ (in-trail encounter). These

Table 5
En-route traffic crossing geometries can typically lead to a potential wake turbulence encounter.

Geometry	Leader aircraft (Wake generator)	Following aircraft (Wake-Encountering)
In-trail	Climb in front	Level
Opposite direction	Level above	Level
In-trail	Level above	Level
Side crossing	Level above	Level
In-trail	Descending in front	Level
In-trail	Climb in front	Climbing behind
In-trail	Level	Climbing behind
In-trail	Descending in front	Climbing behind
In-trail	Climb in front	Descending behind
In-trail	Level	Descending behind
In-trail	Descending in front	Descending behind

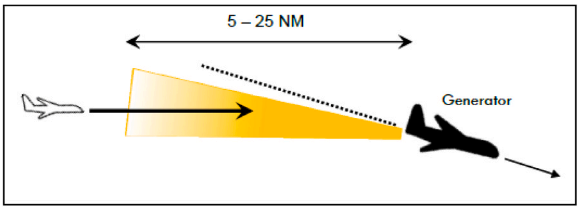


Fig. 4. En-route wake turbulence encounter risk configuration with wake-generating traffic descending in front and crossing the following traffic flight level.

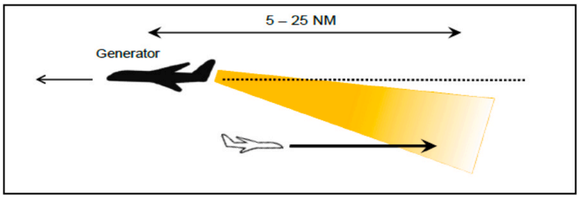


Fig. 5. En-route wake turbulence encounter risk configuration with wake-generating traffic crossing 1000 ft (10 Flight Levels) above the wave-exposed traffic in the opposite direction.

scenarios are the most unpleasant for the crew and passengers and can result in upset and Loss of Consciousness (LOC). Consequently, these scenarios were used in the flight simulations. The Dangerousness of the scenarios is also supported by the fact that the frequencies of the flight parameters are within the range of manual control frequencies ($f < 1.0$ Hz). They can also provoke Pilot Induced Oscillation (PIO) tendency (Andrievsky et al., 2020; McRuer, 1995) while upset recovering and result in LOC (Tripp et al., 2006; Whinnery and Whinnery, 1990). Together with Airbus, we finally identified 9 scenarios aiming at modelling flight upsets resulting from typical wake turbulence encounters.

3. Results

3.1. Flight simulation data analysis

Fig. 6 shows the changes in normal and lateral g-loads (n_z, n_y) and Mach number induced by WVE in the aerodynamic moments $(\Delta L_{WV}, \Delta M_{WV}, \Delta N_{WV})$ while flying through disturbed atmosphere for approximately $\Delta t \approx 10s$. Deviations of the normal load factors are very large $(\Delta n_z \approx \pm 1)$ which can affect the crews' reaction when compensating for aircraft disturbed motion caused by WVEs.

3.2. Behavioural data: aircraft stabilisation

The two experimental conditions (*NO WV* vs. *WV*) were compared by considering different parameters related to *aircraft stabilisation.* Aircraft stabilisation was defined as the point at which the aircraft stops rolling after the wake encounter. In order to ease the stabilisation detection, smoothed roll angle and roll rate signals were built by calculating the sliding averages of the absolute value of the signals with an average window of 4 s. The flight was then considered to be stabilised when the average roll over the last 4 s was below 3 degrees with an average roll rate below 1 degree per second, or if the average roll angle was below 1 degree with an average roll rate below 2 degrees per second.

In this regard, Fig. 7 shows the pilot's control inputs in the pitch and roll channels (X_{LON} and X_{LAT}) during the WVEs, as well as deviations in the pitch and roll angles (θ and ϕ). During WVEs, pilot control is quite intense $X_{LON} = (-0.45 \div 0.2)$, $X_{LAT} = (-0.35 \div 0.5)$ and it is accompanied by significant deviations in pitch and roll angles, respectively, $\theta = (-3^o \div 4^o)$, $\phi = (-48^o \div 12^o)$. After returning to level flight conditions (i.e. cruise phase), the pilot's control remains very agitated for a time interval longer than 40 s. This may be due to the pilot's compensatory control, which is a typical cause of PIO.

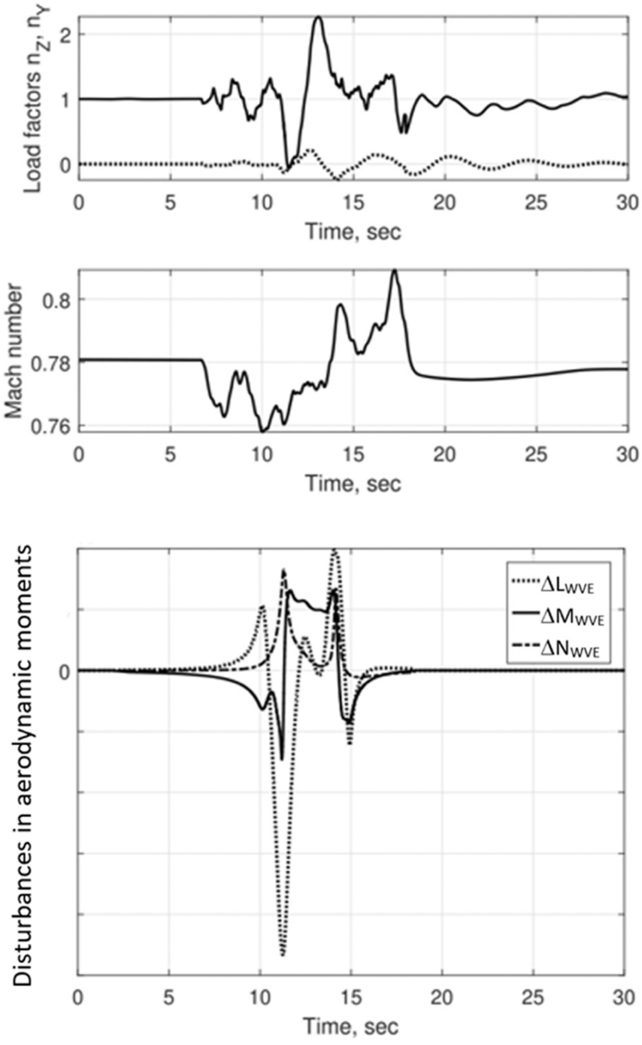


Fig. 6. Typical changes in time of normal and lateral g-loads (n_z, n_y), and Mach number caused by WVE aerodynamic moments in roll, pitch and yaw $(\Delta L_{WV}, \Delta M_{WV}, \Delta N_{WV})$.

Among the parameters considered, only the angle of attack α ($p = 0.01$) and longitudinal loads factor n_x ($p = 0.022$) reported statistical changes. The box plots in Fig. 8 correspond to simulation runs *without* WVA (green colour) and *with* the WVA (orange colour). For all crews the average maximum deviation of the angle of attack (α) was almost one degree smaller when the crew was given the WVA. This difference $(\Delta\alpha \approx 0.8^o - 1.0^o)$ was significant compared to the level flight value $\alpha_{LF} = 2.3^o$ showing that with the WVA the normal load factor was less of approximately $\Delta n_z \approx 0.3 - 0.4$ allowing better safety margin for the onset of stick shaker and stall. The deviation of the longitudinal load factor (n_x) associated with the deviation in true airspeed deviation (TAS) was also statistically meaningful ($p = 0.022$). The other parameters, maximum deviation in altitude (H), TAS and roll angle (ϕ), did not report any statistical difference between the two experimental conditions (all $p > 0.05$).

3.3. Feasibility questionnaires

The results from the feasibility questionnaires are presented in Fig. 9. According to the results, 90 % of the pilots reported an improvement

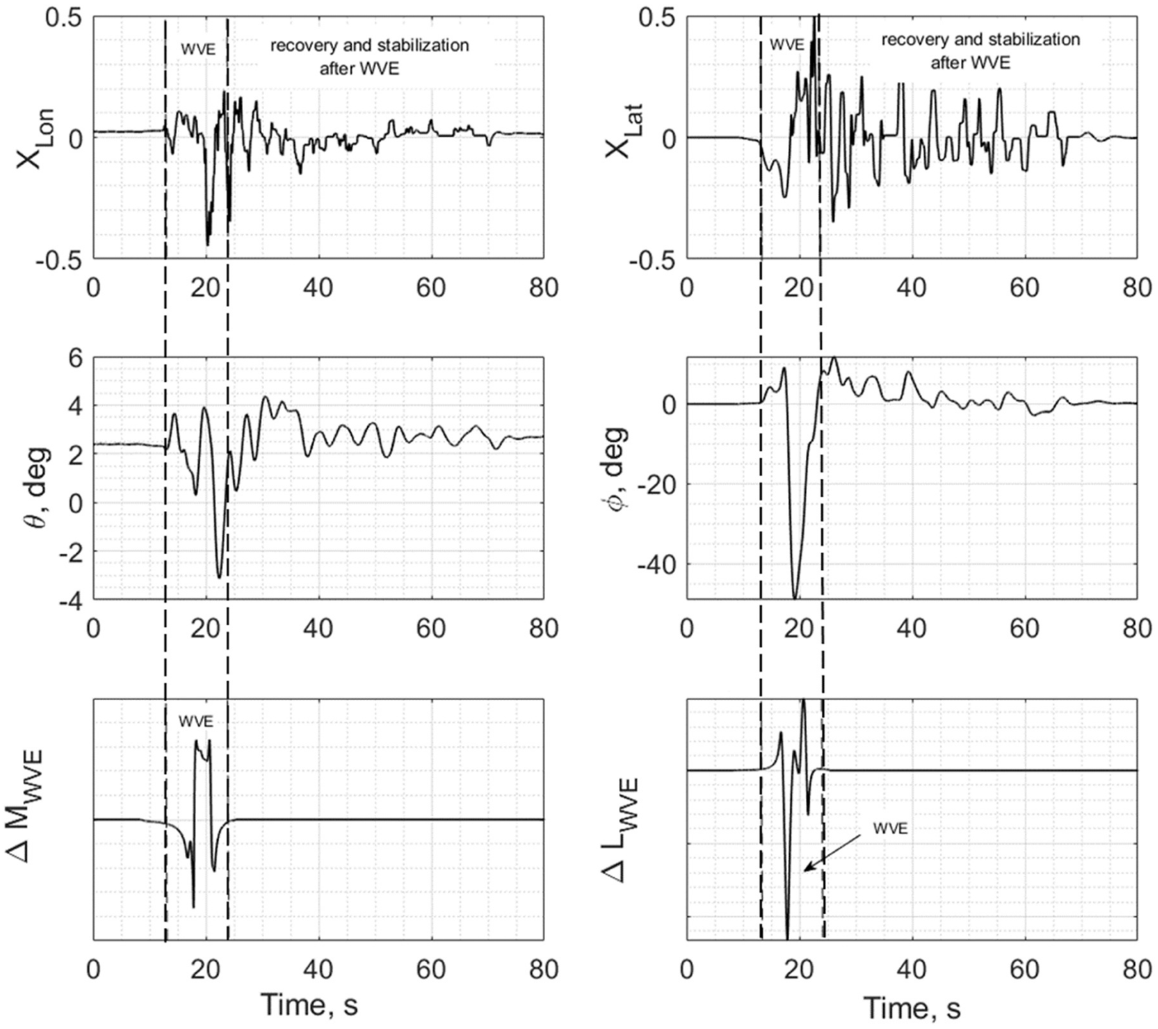


Fig. 7. Control inputs of the pilot X_{Lon}, X_{Lat}, changes in the pitch and roll angles of the aircraft θ, ϕ, disturbances of aerodynamic moments in pitch and roll ΔM_{WVE}, ΔL_{WVE} caused by wake vortices.

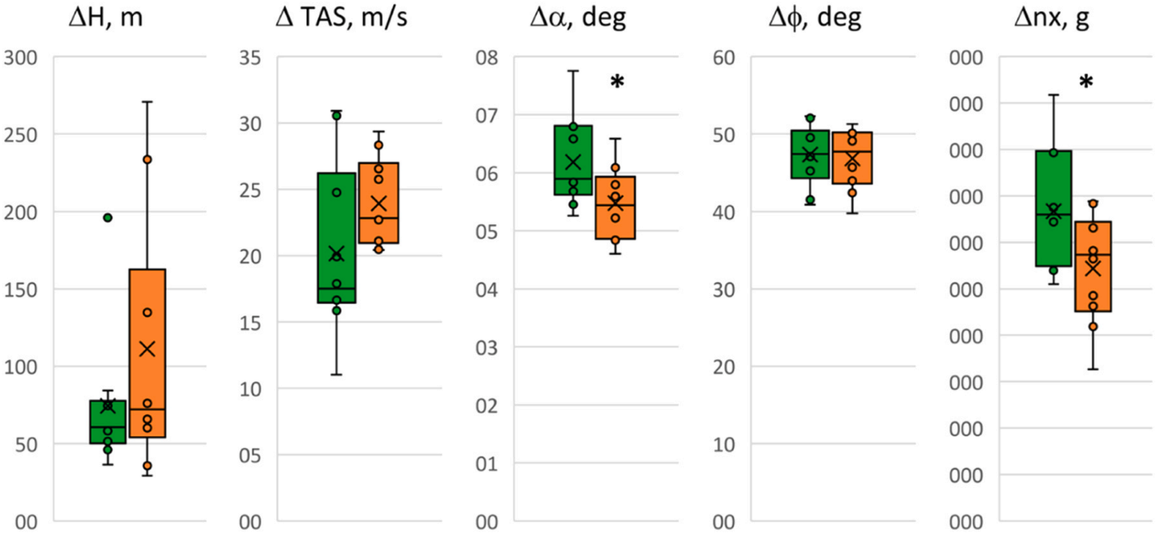


Fig. 8. Parameters for the evaluation of aircraft stabilisation without (green colour) and with (orange colour) the WVA. In particular, we considered variations of the altitude (H), true airspeed (TAS), angle of attack (α), roll angle (ϕ) and longitudinal load factor (n_x).

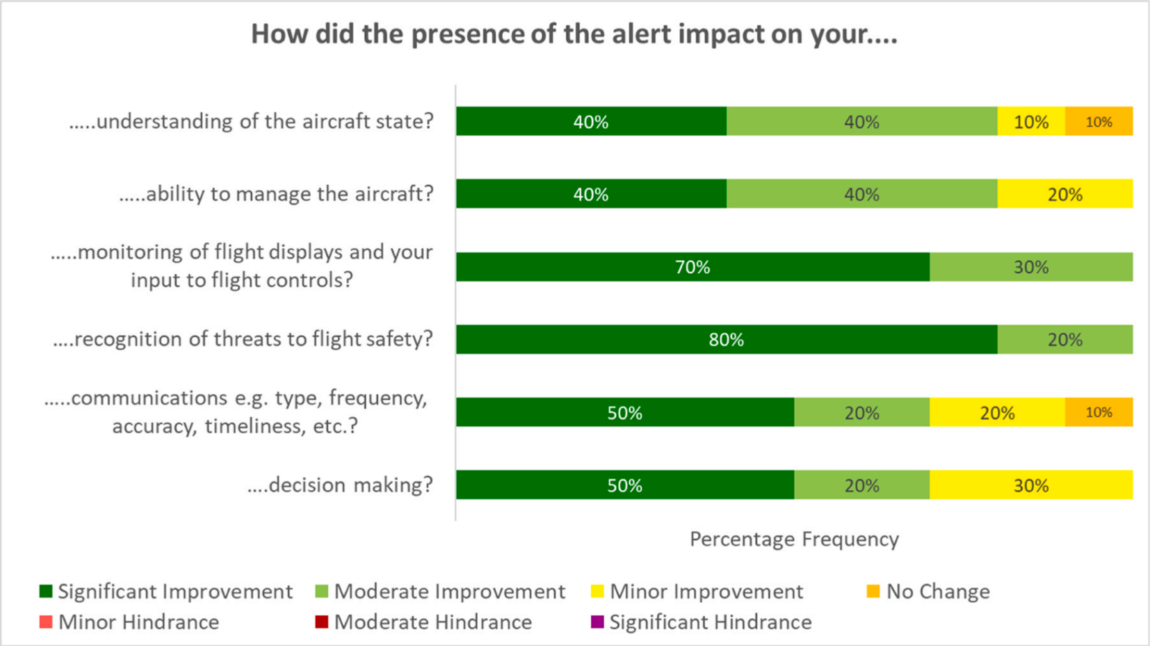


Fig. 9. Percentage frequency count, of responses on a 7-point Likert scale debrief questionnaire, on the improvement vs. hindrance of the presence of the alert (all pilots/all positions).

when using the WV alert on all six aspects related to flight management and control. In particular, all the pilots reported an improvement in the following aspects: *decision making, recognition of threats, monitoring or flight displays/ flight control inputs, and ability to manage aircraft*. Only 10 % of pilots reported ‘no change’ in terms of *communications* and *understanding the aircraft state*, in the presence of the WV alert.

The pilots were also asked “How did the presence of the alert impact on your workload?”. According to Fig. 10, 40 % of respondents stated that the alert made a significant improvement to their workload, 30 % stated that it made a moderate improvement, 20 % stated that it made a minor improvement and 10 % stated that it acted as a minor hindrance to their levels of workload. This was for all pilots, regardless of crew role (PF vs. PM), and for all runs. Therefore, although 90 % of pilots suggested that there was an improvement in their workload, 10 % said there was a worsening of workload with the alert.

3.4. *Subjective situation awareness evaluation*

According to the SART analysis, we found a significant ($p < 0.001$) SA increment when the WVA was employed during the flights (Fig. 11). In particular, PF and PM both reported higher SA with the alert (orange box) compared to without the alert (green box). This result suggested that the pilots felt more aware about potential WV encounters when the WV alert was enabled, and this capability helped them to get ready in advance for dealing with WVs.

3.5. *Neurophysiological results*

The statistics on the pilots’ mental states between the NO WV and WV conditions was performed considering two time periods:

i)From the alert caution to the wake onset (WC - WO) and,

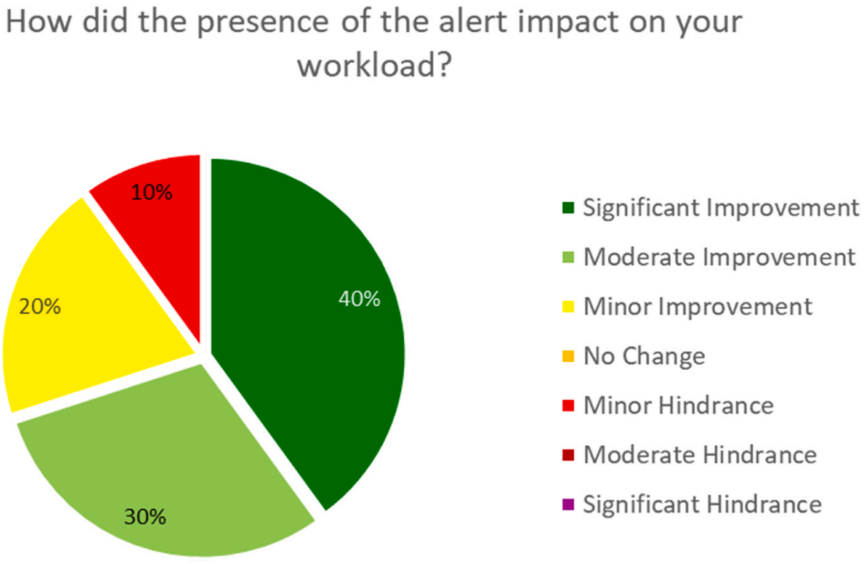


Fig. 10. Pilot responses (percentage) to the debrief questionnaire on mental workload.

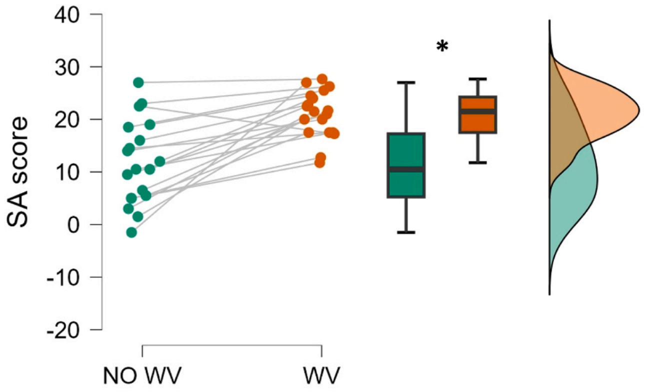


Fig. 11. SA scores analysis without (NO WV) and with (WV) the WV alert. The statistics reported significant ($p < 0.001$) SA increment when the WVA was employed.

ii)from the wake onset to the aircraft recovery (WO - W*R*).

3.6. Mental workload assessment

The pilots' mental workload did not show any significant difference (all $p > 0.05$) between the NO WV and WV conditions. However, the trend of the pilots' mental workload was slightly higher after the wake caution until the occurrence (WC - WO) than in the NO WV scenario. The pilots' mental workload over the time was therefore investigated to assess what happened after the WVEs caution. Fig. 12 exhibits the changes in the five flight crews' mental workload (calculated by averaging the PF's and PM's mental workload) from 5 seconds before the caution (vertical line) to the end of the recovery. In particular, the crews' mental workload is reported as a dashed line for WV, and as a solid line for NO WV under the different caution conditions (WV0, WV1, WV2 and WV3). The different graphs confirmed the previous results. In other words, it can be observed that independently from the caution timing the pilots' mental workload increased right after the caution (red areas) was provided as a result of pilots' preparation activities towards the vortex encounter. On the other hand, the crews' mental workload decreased when the wake vortex occurred and during the recovery (green areas) with respect to when the crews did not receive any cautions. The benefit of the alert was therefore of providing enough time for having secured the aircraft and passengers with no workload demand increase.

3.7. Stress assessment

The statistics on the pilots' stress (Fig. 13) showed a significant increase ($p = 0.03$) immediately after and while waiting for the wake occurrence (WC-WO) with respect to the no alert situation (NO WV). Successively, when the wake occurred and during the recovery (WO - W*R*), the pilots' stress became even lower (not significantly) than NO WV (green box). Similarly, to what was described for the mental workload, these findings suggest that as the pilots received the wake cautions, their stress increased (orange box) as a result of the planning and preparation required for approaching the wake turbulence. However, the pilots were subsequently more prepared and less stressed during the occurrence and recovery from the wake vortex encounter (purple box).

The analysis of the crews' stress changes over the time under the different timing conditions is shown in Fig. 14. The five crews' stress is reported from 5 seconds before the caution (vertical line) to the end of the recovery. In particular, the crews' stress is reported in the dashed line for WV, and in the solid line for NO WV under the different caution conditions. Despite the different timing cautions, the crews exhibited the same profile in terms of stress responses. After they received the information about the wake occurrence (red areas), the crews reacted promptly to secure the cabin and flight. The drop of the pilots' stress during the wake encounters and recoveries (green areas) confirmed the positive impact of the WVA: when the pilots received the cautions, they were less stressed whilst dealing with the wake encounters.

3.8. Arousal assessment

Fig. 15 shows the analysis of the pilots' arousal estimated for the NO WV and WV conditions. The results illustrate that the pilots' arousal was significantly higher (all $p < 0.02$) during all the phases of WV (orange and purple box) compared with the NO WV (green box). In other words,

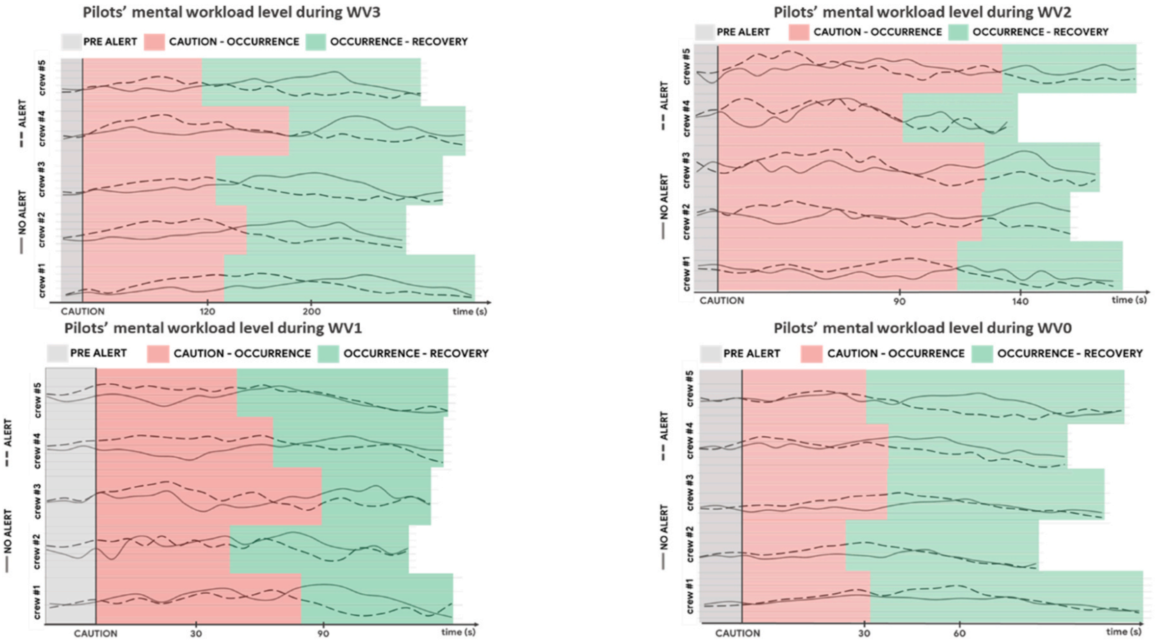


Fig. 12. Crews' mental workload over the time from 5 seconds before the caution (vertical line) to the end of the recovery. The crews' mental workload is reported in dashed line for WV, and in solid line for NO WV under the different caution conditions (imminent -W0, 1 minute - WV1, 2 minutes - WVs and 3 minutes - WV3).

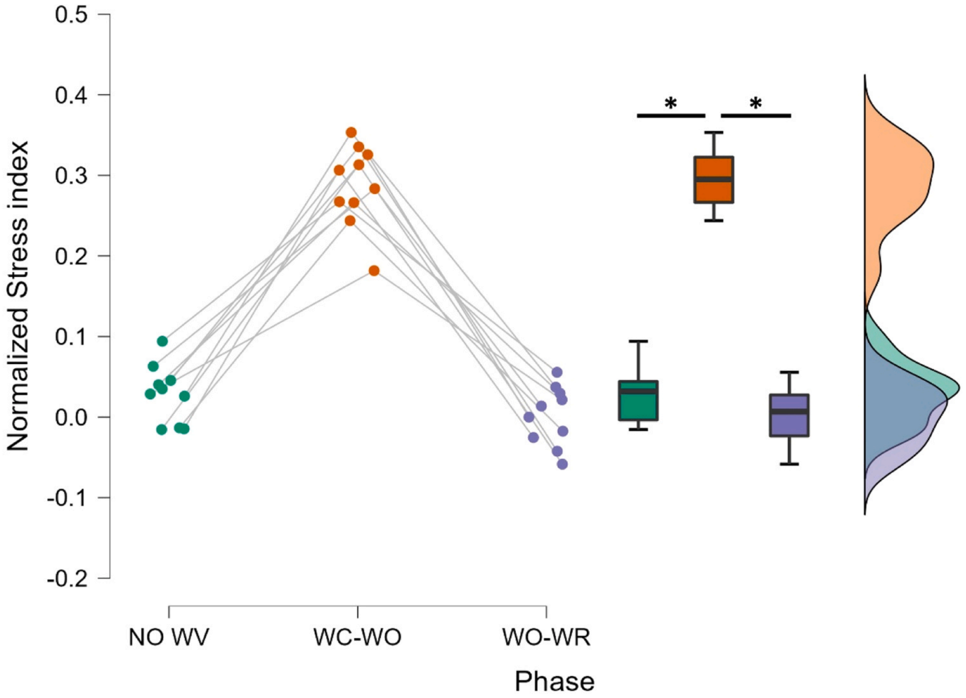


Fig. 13. Averaged pilots' stress evaluated during the NO WV (green values) and WV during the time segment between the wake caution and occurrence (WC -WO, orange values) and between the wake occurrence and recovery (WO – *WR*, purple values). Significant stress increment (p = 0.03) was found within WC – WO, but lower stress was exhibited within WO – *WR*.

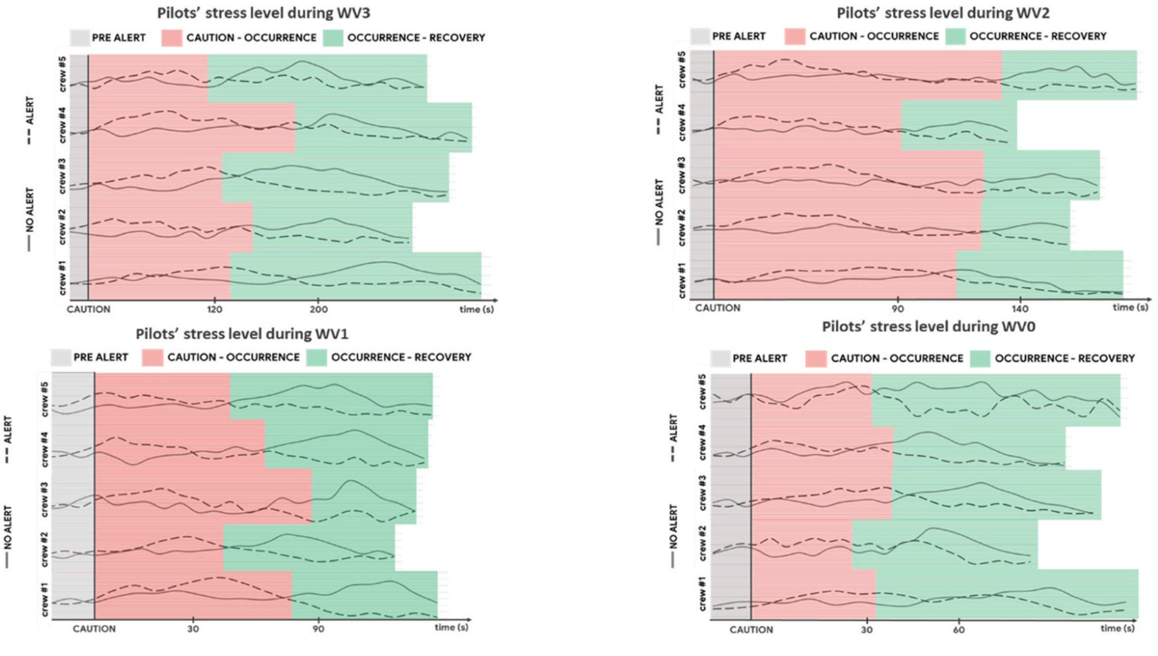


Fig. 14. Crews' stress over the time from 5 seconds before the caution (vertical line) to the end of the recovery. The crews' stress is reported in dashed line for WV, and in solid line for NO WV under the different caution conditions (imminent -W0, 1 minute - WV1, 2 minutes - WVs and 3 minutes - WV3).

the pilots started being significantly more prepared after they received the caution to face the wake encounters along with the timeline of the entire event (caution – wake occurrence – recovery) compared to the conditions in which they did not receive it.

Fig. 16 exhibits the variation of the crews' arousal over the time revealing the impact of the alert on the pilots in terms of arousal. The five crews' arousal is reported from 5 seconds before the caution (vertical line) to the end of the recovery, and it is reported in dashed line for WV, and in solid line for NO WV under the different caution conditions. For all the timing horizons, the crew's arousal started increasing right after the caution (red areas), and it kept higher values than the NO WVs until the full recovery of the aircraft (green areas).

4. Discussion

4.1. Alignment with existing research and interpretation of findings

The study investigated the impact of an innovative Wake Vortex

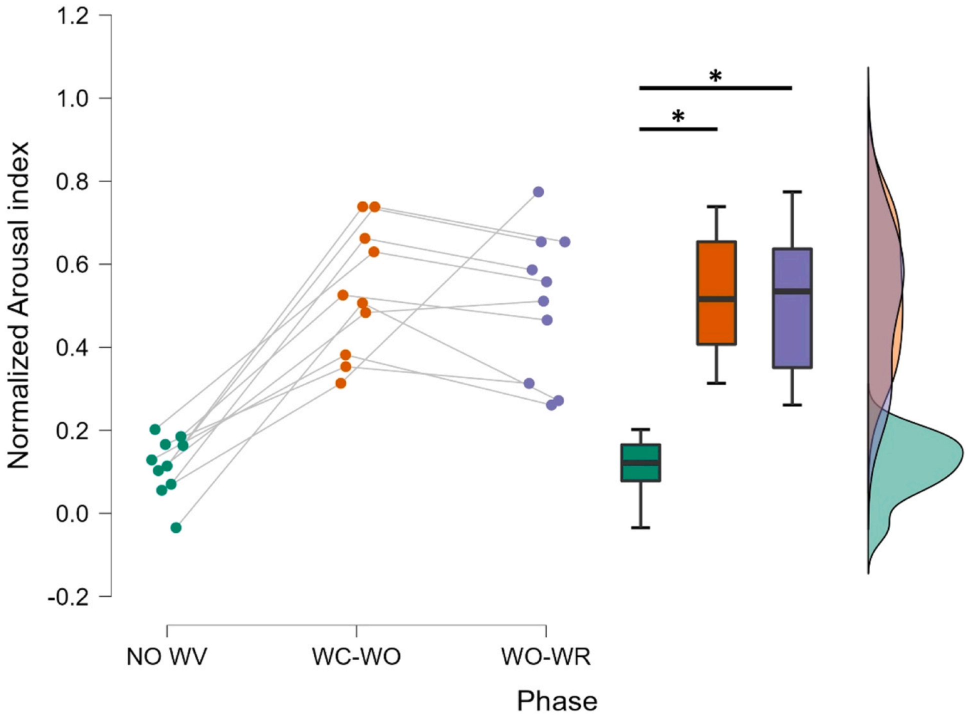


Fig. 15. Averaged pilots' arousal evaluated during the NO WV (green values) and WV during the time segment between the wake caution and occurrence (WC -WO, orange values) and between the wake occurrence and recovery (WO – *WR*, purple values). Significant (all $p < 0.02$) arousal increment was found when the WV alert was used than when no cautions were provided (NO WV).

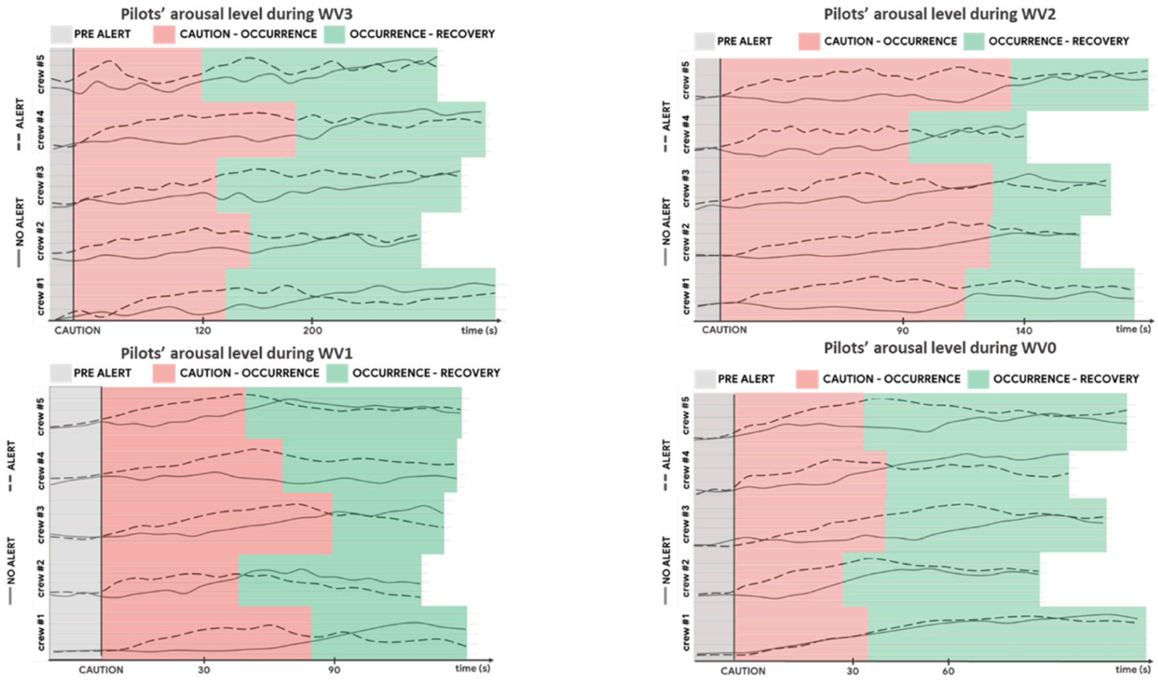


Fig. 16. Crews' arousal over the time from 5 seconds before the caution (vertical line) to the end of the recovery. The crews' arousal is reported in dashed line for WV, and in solid line for NO WV under the different caution conditions (imminent -W0, 1 minute - WV1, 2 minutes - WVs and 3 minutes - WV3).

Alert (WVA) on pilots' operations and mental states. The goal was to enhance aviation safety by mitigating the risks associated with wake vortex encounters (WVEs). The study employed a multidimensional approach, including flight simulations, to evaluate the alert's impact on pilots' behavioural, subjective and neurophysiological measures. The findings of this study align well with the existing body of research on wake vortex encounters (WVE) and their impact on aviation safety. Here are the key points of alignment which have been described in detail in the Introduction:

➢ *Severity of Wake Vortex Encounters:* similar to previous research, the study confirms that WVEs can cause severe disturbances, including uncommanded roll moments that may exceed the aircraft's control authority, especially during takeoff and landing. Historical data has shown several wake vortex-related accidents and incidents can result in fatalities and significant aircraft damage.

- ➢ *Effectiveness of Alerts and Training:* the study's results indicated that the WVA system was effective in enhancing pilots' situational awareness and preparation for WVEs, which is consistent with the literature emphasizing the importance of timely information and training to manage wake turbulence encounters.
- ➢ *Pilot and Aircraft Response:* consistent with other studies, the research highlighted the importance of pilots' appropriate reactions to wake encounters. It was found that pilot reactions, if timely and informed by alerts, could significantly reduce the severity of aircraft upsets.

The study also presented some unexpected findings, which warrant further interpretation:

- ➢ *Increased Mental Workload and Stress:* while the WVA was expected to reduce overall stress and workload, the study found that these metrics increased immediately after the alert was received. This is likely due to the preparation required to handle the impending wake vortex encounter. However, stress and workload levels decreased during the actual encounter, suggesting that the alert helped pilots prepare more effectively. This aligns with the concept that anticipatory stress can initially increase mental workload, but proper preparation mitigates overall stress during the critical phase of the encounter.
- ➢ *Variable Pilot Acceptance:* the study found that while most pilots reported an improvement in workload and situational awareness due to the WVA, a small percentage (10 %) felt that it increased their workload. This discrepancy may stem from the additional cognitive load imposed by processing the alert and preparing for the encounter, which some pilots might find challenging depending on their experience and training. This suggests that individual differences in cognitive capacity and stress management skills could influence how pilots perceive and respond to wake vortex alerts.

4.2. *Operational impact*

The presence of the alert did not impact on the roles of the pilots. The responsibilities of the flight crew increased in the lead up to the wake onset with the alert. However, these actions were not unfamiliar duties (e.g., instructions to the cabin or checking aircraft parameters), and so the presence of the alert did not change their responsibilities. Operating methods were different with the alert because there were actions to undertake in the lead up to the turbulence with the alert. These methods were not dissimilar to standard tasks currently and usually conducted on the flight deck by flight crews. In terms of flight upset, the pilots recovered the aircraft from all the wake turbulence events, even from the high severity events which caused severe bank angles for the aircraft. The flight crew's actions and reactions to the presentation of the wake alert and the aircraft upset were not predefined in this experiment. The pilots developed therefore a strategy for responding to the wake alert over the course of the exposure to each of the different scenarios. The response to the alert always involved an element of warning the cabin crew and an element of cockpit/ aircraft preparation, but differed subtly between crews. However, the response to the onset of the wake turbulence was always handled according to the pilots' training and SOPs for general aircraft upset. Therefore, the latter was consistent across crews.

4.3. *Pilots acceptance*

Fully 90 % of pilots reported that having the alert brought an improvement in understanding aircraft state, managing the aircraft, monitoring displays, making flight control inputs, recognising threats, communications and decision-making (Fig. 9). Pilots suggested that the significant improvements were especially made in the situations with the 3-, 2-, and 1-minute warnings. It was stated that the less time they had from the alert time horizon, the more difficult it was to prepare for the wake, especially for example when the cabin does not respond immediately to a call from the flight deck. Some pilots felt that the longest time horizon (3 minutes - WV3) was too long and that they would not remain focussed on the impending aircraft upset. Some claimed that their attention would get drawn in by the clock, whilst anticipating the time until the wake upset. The pilots reported that the most appropriate conditions were therefore the 1 - and 2 - minute cautions. Although this evidence came from questionnaire, it is important to note that almost all the pilots considered acceptable the use of the WVA.

4.4. *Subjective perception impact*

Pilots were asked "How did the presence of the alert impact on your workload?". According to Fig. 10, 40 % of respondents stated that the alert made a significant improvement to their workload, 30 % stated that it made a moderate improvement, 20 % stated that it made a minor improvement and 10 % stated that it acted as a minor hindrance to their levels of workload. This was for all pilots, regardless of crew role (PF vs PM) and all runs. Therefore although 90 % of respondents suggested that there was an improvement in their workload, while 10 % said there was a worsening of workload with the alert. The basis for the latter observation, is entirely due to the fact that the alert caused an increase in workload in the lead up to the wake encounters, which was the preparation for the WV events. Without the alert (NO WV), the pilots would otherwise be oblivious to the fact that they were going to encounter a wake, and so they would most likely be in relatively low level of workload, typical of the cruise phase of flight. Both these observations were supported by the neurophysiological results (Fig. 12 ÷ Fig. 16). Pilots were also asked "How did the presence of the alert impact on your Situational Awareness?". According to Fig. 11, the wake alert brought a significant ($p < 0.001$) improvement in pilots' situational awareness (SA). This was for all pilots, regardless of crew role (PF vs PM) and all runs.

4.5. *Peculiarities of pilot's control*

Analysis of flight simulation data highlighted the following important observations. Pilot recovery control with wake vortex alert (WVA) showed a statistically significant decrease in angle of attack deviation of about 0.8 degrees. This is equivalent to reducing the normal load factor by 0.3–0.4. As a result, the WVA improved the margin of safety by preventing the aircraft from stalling. After recovery from the WVE, the pilot stabilized the level flight with a high level of agitation for 30–40 s, which may be associated with excessive stress in the process of recovery from WVE to FL. This brings to mind the so-called pilot-induced oscillation (PIO) phenomenon. The results showed that the duration of PIO after returning the aircraft to level flight was shorter with WVA (WV) compared to the case without WVA (NO WV).

4.6. *Cognitive impact*

The results showed an overall increase in the three mental states (mental workload, stress and arousal) immediately after the wakes were enunciated (i.e. caution) until the wake onset (Fig. 12 ÷ Fig. 16). These increases were significantly different from the no alert situation (NO WV) for the pilots' stress ($p = 0.03$) and arousal (all $p < 0.02$). The increased mental workload and stress level after the cautions likely corresponded to the activity of planning for the wake encounter (informing the cabin crew to secure the passengers, checking the aircraft parameters, and preparing for the wake onset). After this phase, the pilots were aware of what was going to happen and prepared to deal with it, and so their mental workload and stress decreased when the wake occurred.

4.7. Further steps and limitations

Although the interesting and promising results, the relatively small sample of ten flight crews did not allow us to draw a substantial conclusion on the impact of the wake vortex alert. For this reason, other experiments will be performed to further support and improve the current results. In particular, pilots from other airlines will be recruited and more data (subjective, behavioural, log – file and neurophysiological) will be acquired to enhance the accuracy in assessing the impact and limitations of the WVA. For example, it could be interesting to investigate how to deal with WVA malfunctions to better train the pilots.

Additionally, the outcomes of the study will be used for the development of new operational concepts and technology demonstrating how Human Factors (HFs) - based design elements should be adequately considered to ensure acceptable human performance when operating the new concepts.

5. Conclusions

The study demonstrated the real-world application of a technological concept, namely the wake vortex alert (WVA), focusing on Aviation contexts. In terms of the WVA function, the flight crews unanimously expressed a desire to see this solution come into operational service. They saw huge benefits of the alert from the point of view of aircraft management and the reduction in risk of injuries in the cabin. The study also allowed the generation of a series of requirements that are evidence-based. In fact, the results suggested the integration of multimodal measures to validate the impact of new systems and technologies from a human-centric design perspective, where the users directly inform the requirements through real - time simulations. This will in turn bring about an increased level of acceptance by the end - users, which should result in greater success and effectiveness in their use. The findings also highlighted the importance of tailored training programs that address individual differences among pilots to maximize the effectiveness of technological interventions like the Wake Vortex Alert (WVA) system. Continuous advancements in alert systems and training protocols are essential to further enhance Aviation safety in the context of wake turbulence.

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CRediT authorship contribution statement

Jonathan Pugh: Writing – review & editing, Validation, Supervision. **Mikhail Goman:** Writing – review & editing, Validation, Supervision, Formal analysis, Data curation. **Vincenzo Ronca:** Writing – review & editing, Formal analysis. **Géraud Granger:** Writing – review & editing, Methodology, Data curation. **Gianluca Borghini:** Writing – review & editing, Writing – original draft, Validation, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Nikolay Abramov:** Writing – review & editing, Validation, Formal analysis, Data curation. **Andrea Giorgi:** Formal analysis, Data curation. **Diana Paola Moreno Alarcon:** Writing – review & editing, Validation, Supervision, Conceptualization. **Gianluca Di Flumeri:** Writing – review & editing, Methodology. **Simone Pozzi:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition. **Pietro Aricò:** Writing – review & editing, Methodology. **Elizabeth Humm:** Writing – review & editing, Validation, Data curation. **Frédéric Rooseleer:** Writing – review & editing, Validation, Supervision, Resources, Funding acquisition, Conceptualization. **Rossella Capotorto:** Writing – review & editing, Data curation. **Fabio Babiloni:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition. **Ivan De Visscher:** Writing – review & editing, Validation, Supervision, Software, Methodology, Investigation, Conceptualization. **Barry Kirwan:** Writing – review & editing, Validation, Supervision, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of Competing Interest

Declarations of interest: none

Data availability

The data that has been used is confidential.

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Institutional Review Board Statement

The experiment was conducted following the principles outlined in the Declaration of Helsinki of 1975, as revised in 2008, and it received the approval of the Institutional Review Board (or Ethics Committee) of the SAFEMODE Project (protocol code 2022/04.7 on the 12/04/2022)

Informed Consent Statement

All the participants signed the informed consent and the related information sheet, in which the study was explained, before participating in the experiment.

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