safety

MDPI

Article

Degraded States of Engagement in Air Traffic Control

Yannick Migliorini [1,2], Jean-Paul Imbert [3,*], Raphaëlle N. Roy [2], Alex Lafont [2] and Frédéric Dehais [2]

[1] Direction des Services de la Navigation Aérienne—Direction de la Technique et de l'Innovation, 1 Av., 31100 Toulouse, France; yannick.migliorini@aviation-civile.gouv.fr
[2] ISAE-SUPAERO, Université de Toulouse, 31400 Toulouse, France; raphaelle.roy@isae-supaero.fr (R.N.R.); alex.lafont@isae-supaero.fr (A.L.); frederic.dehais@isae-supaero.fr (F.D.)
[3] École Nationale de l'Aviation Civile, 7 Édouard-Belin, 31055 Toulouse, France
* Correspondence: jean-paul.imbert@enac.fr

Abstract: Safety studies have identified attention as a recurring cause of incidents and accidents in air traffic control. However, little is known of the precise attentional states that lead to degraded ATC performance. Therefore, we surveyed 150 French en route air traffic controllers on the causes of and impacts on perceived cooperation, safety, and performance of seven degraded attentional states from the literature: task-related and task-unrelated mind wandering, mental overload, inattentional deafness and blindness, attentional entropy, and perseveration. Our findings indicated that task-related and task-unrelated mind wandering were the most prevalent but had the least impact on perceived safety. Conversely, inattentional blindness and attentional entropy were less reported but were considered a significant safety concern, while inattentional deafness affected cooperation. Most states were experienced in workload levels consistent with the literature. However, no other factor such as shift work was identified as a cause of these states. Overall, these findings suggest that "attention" is not a specific enough subject for ATC, as attentional issues can occur in various conditions and have different impacts. As far as safety is concerned, inattentional blindness should be the prime target for further research. Neuroergonomics in particular could help develop dynamic countermeasures to mitigate its impact.

Keywords: air traffic control; performance; safety; inattentional blindness; mind wandering; inattentional deafness; prevalence; impact

Citation: Migliorini, Y.; Imbert, J.-P.; Roy, R.N.; Lafont, A.; Dehais, F. Degraded States of Engagement in Air Traffic Control. *Safety* **2022**, *8*, 19. https://doi.org/10.3390/safety8010019

Academic Editor: Raphael Grzebieta

Received: 11 January 2022
Accepted: 4 March 2022
Published: 8 March 2022

1. Introduction

Eleven million commercial aircraft flew in Europe in 2019 [1]. Even with the massive flight reduction due to the global pandemic, air traffic is expected to revert to 2019 levels within less than five years [2]. "En route" air traffic controllers (ATCOs) play a crucial role in supervising and ensuring an efficient flow of these aircraft while maintaining adequate separation to prevent collisions [3]. ATCOs generally work in pairs and mainly use radar screens in order to provide safe and efficient trajectories for all aircraft. A variety of tools have been implemented over the years in order to help them perform this task. This results in a multitude of information being displayed in various locations using several colors and symbolic codes, thus making air traffic control demanding in terms of attention.

Unsurprisingly, safety analyses stress the importance of attention-related issues in air traffic control (ATC). Indeed, [4] found that attentional lapses were the most common types of errors made by ATCOs in accidents and incidents. The same result was found by [5] for operational irregularities. [6] reported that a lack of visual detection was the most commonly reported error by professional ATCOs, and the most described error in Airprox analysis (i.e., a near collision between two or more aircraft). [7] also found that the failure to detect information on the radar represented over 15% of causal factors of operational errors.

Several studies have identified that the level of workload [8–10], decreased vigilance [11] induced by time on task [12] or shift work-related issues [13,14] can account for this impairment of ATC performance. Indeed, cognitive neuroscience studies (see [15] for a review) provide evidence that these factors can disrupt key cerebral areas supporting attentional networks [16], leading to degraded attentional states such as mind wandering, mental overload, inattentional blindness and deafness, perseveration, and attentional entropy [15,17].

The onset of these impaired attentional states can negatively affect task engagement [15,17], which represents effortful striving directed toward task goals [18]. Operators can thus yield to either task disengagement or over-engagement [15,17].

More specifically, task disengagement encompasses mind wandering, mental overload, and attentional entropy. Mind wandering is defined as "engaging in cognitions unrelated to the current demands of the external environment" [19] and can lead individuals to give up on the task at hand [20,21]. Indeed, during mind wandering episodes, individuals show reduced responsiveness to external stimuli, a phenomenon known as perceptual decoupling [19,22,23]. Mind wandering mostly occurs in conditions of low workload [20] and may start with thoughts related to the task at hand (thus labeled task-related mind wandering: [24]) or thoughts completely unrelated to the task (task-unrelated mind wandering). Mind wandering is generally associated with degraded performance [20,21,25], but task-related mind wandering may also allow prospective planning of the task [25,26] and, therefore, benefit future performance.

Attentional disengagement has also been shown to occur when task demands exceed the human operators' processing capacity. This can lead to mental overload [27] which may cause operators to give up on their current goal [28]. For example, [27,29] disclosed evidence of prefrontal deactivation during episodes of mental overload that was mirrored by task disengagement. The mental overload phenomenon was also reported by [30] with military ATCOs in simulations. In actual operations, the possibility of fatal consequences probably provides an additional motivation source for controllers that does not exist during simulations. However, the possibility that mental overload could occur in actual working conditions for air traffic controllers cannot be discarded, even though its prevalence and manifestations may be slightly different from what was observed in simulations.

Some studies have suggested the existence of attentional entropy, an inattentional state resulting in a failure to engage attention towards relevant information [17]. This state can be described in a vernacular fashion as a "panic mode" whereby operators are unable to locate and process essential information. This state is associated with a reduced number of ocular fixations and excessive saccadic activity [31], which makes this state an extreme case of task disengagement. To the authors' knowledge, this phenomenon has never been studied in the context of air traffic control but only with pilots experiencing a cognitive conflict with automation [31]. However, given the gradual automation in Air Traffic Control and the pressure for automation, this phenomenon is of concern for air traffic control.

On the other side of the engagement spectrum is over-engagement, also known as "attentional tunneling" [32]. Attentional tunneling encompasses various inattentional phenomena such as inattentional blindness [33] or inattentional deafness [34]. Inattentional blindness is the inability to notice salient but unexpected visual stimuli. This phenomenon was illustrated by the "invisible Gorilla" from [35], where participants counting passes between basketball players failed to notice a Gorilla crossing the scene and thumping its chest amid the players. Inattentional blindness has been observed in ATC simulations [36,37]. These attentional limitations can also affect auditory perception, a phenomenon known as inattentional deafness, which is the failure to notice a perceptible but unexpected audible sound. It has been shown to take place in high load settings [34,38] and can lead pilots [39] and ATCOs [40] to miss critical auditory warnings.

Over-engagement states also include perseveration (for a review, see [41]). Perseveration is defined as the failure to revise one's goal despite evidence that it is not relevant anymore [42]. For example, in aviation, pilots in visual flight rules (VFR) may keep flying into adverse weather [43], or professional pilots may end an unstabilized approach with a landing instead of going around [44]. This state is associated with mental rigidity and the attentional neglect of information that do not match one's perseverative strategy [45]. This phenomenon is known to occur during demanding multitasking scenarios or stressful settings. As the ability to flexibly modify initial plans is a key feature for skilled air traffic controllers [8], this behavior could be detrimental to ATCOs performance. However, to our knowledge, no study has yet investigated perseveration in air traffic control.

So, depending on their task engagement and the workload of the task at hand, ATCOs could theoretically experience a range of degraded states, which are summarized in Table 1. However, despite their theoretical prevalence, the actual occurrence of degraded states of engagement in air traffic control currently lacks empirical support. Indeed, only very few laboratory studies on task engagement have included actual air traffic controllers as participants. Hence, an estimation of the combined prevalence and impact of degraded states of engagement on ATCOs performance and safety in control rooms is not available. Additionally, there is a need to go further and investigate more precisely how exogenous (task demand, time on task, time of the day) and endogenous (fatigue, circadian rhythm) factors interact together to induce specific deleterious states of task engagement. Identifying the specific attentional states that actually occur in ATC could lead to the design and implementation of mitigating solutions [15] to preserve ATCOs' performance and, therefore, safety. We therefore researched the question of the extent of attentional issues in daily operations of en route air traffic control.

Table 1. Summary of degraded attentional states and relevant literature.

Degraded State	Workload Level	Engagement Level
Mind Wandering	Low [24,46,47]	Disengagement [20,24,48]
Mental overload	High [27,29,49],	Disengagement [27,49]
Attentional Entropy	High [31]	Disengagement [17,31]
Inattentional Deafness	High [38–40]	Over-engagement [50,51]
Inattentional Blindness	High [35,37,52]	Over-engagement [15,17]
Perseveration	High [44,53,54]	Over-engagement [45]

For that purpose, we conducted an exploratory survey of professional air traffic controllers to assess their experience of degraded states of engagement on duty. To that end, we specifically targeted the seven degraded states identified in the literature review: task-related mind wandering, task-unrelated mind wandering, mental overload, inattentional blindness, inattentional deafness, perseveration, and attentional entropy. We hypothesized that ATCOs would mostly report task-related and task-unrelated mind wandering since they experience shift work and prolonged episodes of sustained attention, which in return induce fatigue [13], hypovigilance [14,55], and boredom [12]. However, it is difficult to predict their impact on perceived safety since there are contradictory findings regarding their overall positive and negative effects on cognition and performance [26]. As safety reports (e.g., [6]) disclosed that perceptual errors were the most frequent causes of incidents, we also hypothesized that inattentional blindness and associated phenomena would have the highest perceived impact on safety. However, there is a lack of evidence regarding their frequency of occurrence that needs to be assessed, as most human errors in ATC are unreported [6].

Interrogating ATCOs on their everyday experience can provide valuable information on these exploratory research questions [6], so we queried the participants about the frequency of occurrence of each degraded mental state during air traffic control sessions. Then the conditions of these experiences with regards to the factors known to degrade engagement (i.e, task demand, time on task, time of the day, fatigue) were researched. Finally, the perceived impact of these degraded mental states on air traffic controllers' activity was collected.

2. Method

This questionnaire was approved by the Ethics Committee of the University of Toulouse (project n° 2019-191).

2.1. Participants

The participants were 150 air traffic controllers (85 men, 65 women) from Direction Générale des Services de la Navigation Aérienne (DSNA), the French Air Navigation Service Provider. Age ranged from 25 to 57 years (M = 41.35 years, SD = 6.85). All were certified in an en route air traffic control center (years of certification : M = 13.29, SD = 6.80). As required by the Ethics Committee, participants to this questionnaire had the right to withdraw from the research at any point without any explanations. Consequently, a few controllers stopped participating before the end of the survey. Since the survey was taken online, no supervision was present to collect the reasons why controllers stopped answering. However, since the demographic data of the group who completed the whole questionnaire and the group who only partially did, the decision was made to keep the unfinished questionnaires in our data. The number of respondents to the last question was therefore N = 131.

Flyers were passed out in control rooms in all five en route air traffic control centers of DSNA giving a very brief description of the aim of the study and inviting only certified air traffic controllers to take the online survey. The flyers also included the URL of the questionnaire and a QR code leading to it. Participants did not receive any compensation for taking part in this study.

2.2. Procedure

Upon accessing the first page of the questionnaire, participants were presented with a short paragraph explaining its purpose and were asked to read a consent form and accept it electronically. No question was asked prior to this acceptance, and participants could disconnect from the survey at any point. Then demographic data were gathered and a reminder that all answers were strictly anonymous was presented.

Finally, questions regarding degraded states of engagement were asked. From this point on, all questions were optional, and no default answer was proposed. The questionnaire also comprised a few questions pertaining to engagement for internal use at DSNA (not presented here). A total of 11 pages were presented, three of which only displayed information to the participants, two requested short written answers, and six included boxes to be ticked. The whole survey lasted approximately 20 min.

2.3. Materials

Given the absence of a prior survey on engagement in air traffic control, no existing material could be used as a reference. Moreover, as this study was entirely exploratory and was not meant to quantify the occurrences of degraded attentional states precisely, the reliability and validity of the material were not statistically investigated. As the targeted audience (professional air traffic controllers) mostly had no background knowledge in psychology or neuroscience, the degraded states of engagement presented above were framed in the ATC operational context. This was performed by the first author, who was a certified en route air traffic controller for 10 years. The questionnaire was tested on two former ATCOs without a background in psychology or human factors whose results were not included, and then approved by an ATC Subject Matter Expert from the French Civil Aviation Authorities that allowed ATCOs participation.

For example, inattentional blindness was described as "you were totally focused on a radar situation and did not perceive, or belatedly perceive other signals elsewhere on the screen, such as a Short Term Conflict Alert or a newly added tag on a label" and task-unrelated mind wandering as "your thoughts disconnected from the present traffic and "wandered" towards matters unrelated to control". The description for all seven states is available in Appendix A.

In order to assess the prevalence of degraded engagement states for ATCOs, direct questions were asked (i.e., "Did it ever happen that you were totally focused your radar screen and did not perceive, or belatedly perceive other signals elsewhere on the screen, such as a Short Term Conflict Alert or a newly added tag on a label?"). The answer was given on a 5-point frequency scale (from "Never" to "Almost every work session").

If the participant reported having experienced a degraded state "several times per year" (i.e., rating 3 of 5 on the frequency scale) or more often, follow-up questions were asked about these experiences (so the total number of responses to these questions is higher than the number of participants). Firstly, the workload conditions were investigated: ATCOs were asked to rate their workload when the degraded state occurred on a 4-level scale ("low", "average", "high", "no pattern").

The impact of shift work and fatigue was then investigated. Controllers were asked at which moment in the day (available answers were "morning", "afternoon", "evening", "night", "no pattern"), in the control session (that usually last around two hours. Available answers were "just after the beginning", "just after the sector was split", "by the end of the session", "no pattern"), in the shift ("in the beginning", "in the middle", "by the end", "no pattern") and in the work cycle (i.e, a sequence of 3–4 shifts before rest days. Options were "in the beginning", "in the middle", "by the end", "no pattern") the degraded states occurred.

Finally, the impact of degraded states of engagement on ATC operations was assessed. Given the sensitive nature of these questions (that included admitting to having jeopardized safety) all degraded states were presented in the third person (i.e., "The thoughts of a controller disconnect from the present traffic and "wander" towards matters unrelated to control".) in order to reduce personal misreporting [56]. Then for each state, participants had to tick a checkbox if they thought this state had a significant impact on safety, cooperation and control performance.

2.4. Data Collection and Analysis

The questionnaire was implemented on a Limesurvey server hosted by ISAE-SUPAERO. Data were collected between November 2019 and March 2020. The raw results were reformatted with Python 3.7.3 using pandas 0.24.2. Descriptive statistics were computed with numpy 0.16.4 and statsmodel 0.10.0. Inferential statistics were computed with R version 3.6.3, using MASS 7.3-51.6 for the ordinal logistic regression. As one exploratory hypothesis was tested in this study for the distribution of occurrences of degraded engagement, seven more in the ordinal regression of degraded engagement against age, and three for the Cochran's Q test on the impacts of degraded states, a Bonferroni correction to the significance threshold was applied to mitigate the type I error. A value of $\alpha = 0.05/(1+7+3) \simeq 0.0045$ was thus retained for omnibus effects in this study.

3. Results

3.1. Experiences of Degraded Engagement

Seven states of degraded engagement were investigated in this survey. First and foremost, every single certified air traffic controller reported having experienced at least one of these states at least once in their career, and all seven states were experienced to some degree. About 40% of air traffic controllers reported at least one experience of degraded engagement every work cycle. Conversely, only 4% claimed to experience a degraded state of engagement in every work session.

As the dependent value in this question was ranked on an ordinal scale, a value of 0 to 4 by increment of 1 was attributed to the answers from the lowest frequency of occurrences ("never") to the highest ("every work session"), and a Friedman test was conducted to evaluate differences among the frequency of occurrences of all seven states of degraded engagement. The distributions as well as medians and quartiles of all seven states are represented in Figure 1.

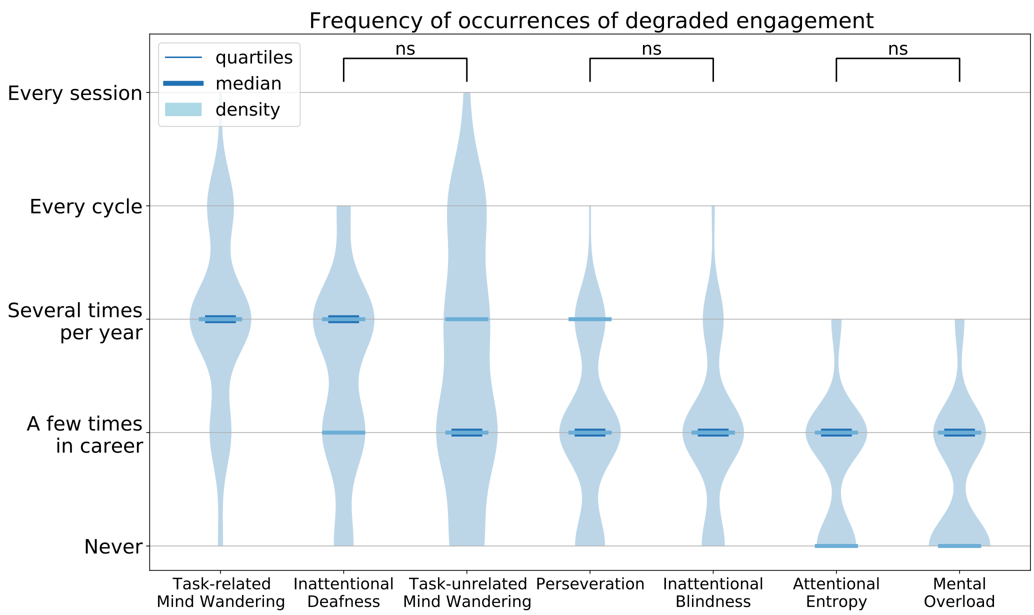

Figure 1. Frequency of occurrences of the seven degraded attentional states (N = 150). All pairwise comparisons were statistically significant ($p < 0.0045$) unless specified otherwise. The response distributions were compared to rank the degraded states from most to least frequently reported. The statistical analysis disclosed the existence of four main groups (from most to least frequent): task-related mind wandering, inattentional deafness and task-unrelated mind wandering, perseveration and inattentional blindness, attentional entropy and mental overload. *Note*: ns = no significant difference.

The Friedman test was significant $\chi^2(4) = 314.10$, $p < 0.001$. Post-hoc pairwise comparisons were conducted using a Wilcoxon signed-rank test and controlling for the Type I errors using the Holm procedure. All but 3 pairwise comparisons were significant: task-related mind wandering (*Mdn* = 2, $p < 0.0001$ for all pairwise comparisons) was the most frequently reported state, then inattentional deafness (*Mdn* = 2) and task-unrelated mind wandering (*Mdn* = 1), between which the difference was not significant ($z = 0.40$, $p = 1$). Less frequent then were perseveration and inattentional blindness (both *Mdn* = 1), with a non significant difference between them ($z = 0.14$, $p = 1$). Finally, the least frequently reported states were attentional entropy (*Mdn* = 1) and mental overload (*Mdn* = 1), for which the difference did not reach significance ($z = 2.66$, $p = 0.02 > 0.05/11$). This is in line with our first hypothesis that mind wandering would be the most reported state.

An ordinal logistic regression was then performed in order to investigate the influence of age on the reported experiences of each degraded states of engagement. Age was not a significant predictor for any of the states. The detailed results of the regression are available in Table A1 of Appendix B.

3.2. Workload Experienced during Degraded States

These questions were only asked for degraded attentional states for which controllers had reported an experience of at least "several times a year", so the number of respondents greatly varied between the seven states under investigation. Details on the numbers of respondents for each state and results are visible in Figure 2.

The controllers reported experiencing three of the degraded states during high workload: all eight respondents declared high workload while suffering from mental overload, 91.67% for inattentional deafness (72 respondents), and 70.37% for inattentional blindness (27 respondents). For attentional entropy (11 respondents), seven controllers reported experiencing it in conditions of high workload, but also two in medium, and one in low workload. On the other hand, task-unrelated mind wandering (66 respondents) was experienced in conditions of low workload by 90.91% controllers. Finally, for experiences of task-related mind wandering (104 respondents) and perseveration (33 respondents), all workload conditions were reported, but in both cases the most frequent answer was "no answer" (51.92% for task-related mind wandering and 39.39% for perseveration).

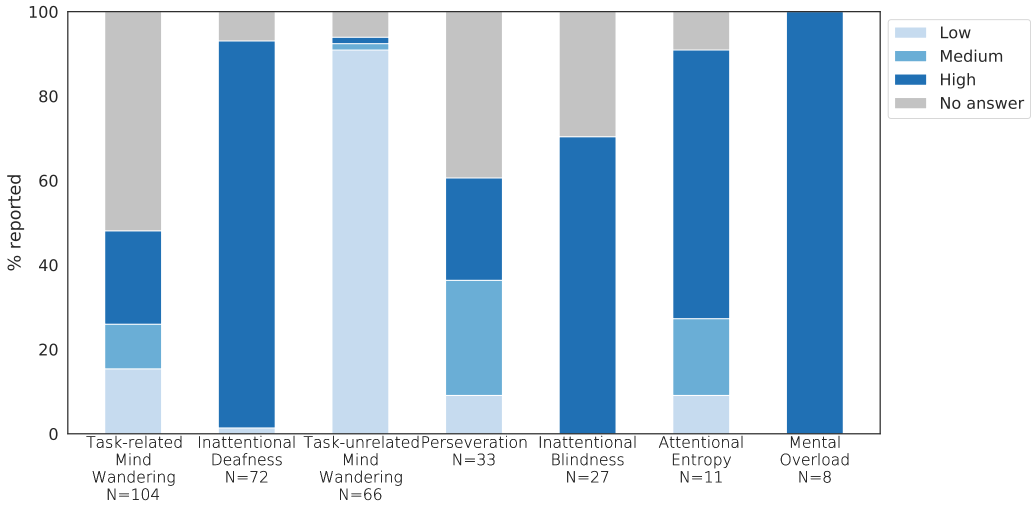

Figure 2. Workload experienced during degraded engagement states.

3.3. Time of Occurrence of Degraded Attentional States

Again, the questions pertaining to the time of occurrence (within a day, a shift, or a work cycle) were asked only to respondents for the states they had reported to have experienced "several times a year" or more frequently (i.e, with similar number of respondents as the questions on workload). However, for all questions, the answer "no pattern" was by far the most prevalent (from 72.36% for the occurrence within the shift to 90.00% for the moment within the work cycle) of given answers. Therefore, according to this data, the circadian rhythm and time on task did not influence the occurrence of degraded states. No further analysis was thus performed on this data.

3.4. Impact of Degraded States on the Controllers' Activity

All degraded states were assessed as having an impact on safety, performance, and cooperation by at least 25% of licensed ATCOs. The results are illustrated in Figure 3.

Therefore a Cochran's Q test was run for each of the three investigated domains (safety, performance and cooperation) to check whether the reported impacts of all degraded states were significantly different. All three tests showed similar results, showing that the reported impacts of the seven attentional states related to engagement were different on safety ($\chi^2(6) = 253.53$, $p < 0.001$), performance ($\chi^2(6) = 143.37$, $p < 0.001$) and cooperation ($\chi^2(6) = 173.82$, $p < 0.001$). Pairwise post-hoc comparisons were then performed to assess the significance of the difference between the mode and the other modalities in each domain. p values were adjusted with a Holm correction for multiple comparisons.

Inattentional deafness was the most often reported state (89.31%) as having an impact on cooperation, and the difference with all other degraded states was significant ($\chi^2(1) > 33.33$, $p < 0.0001$). It was also the only state for which cooperation was the most reported impacted domain.

Control performance (e.g., flight optimization, ...) was the most reported impact for mind wandering (62.60% for task-unrelated mind wandering and 79.39% for task-related mind wandering) and perseveration (91.60%), which was the highest impact for this domain. However, the differences between perseveration and task-related mind wandering ($\chi^2(1) = 7.53$, $p = 0.01$), mental overload ($\chi^2(1) = 9.97$, $p = 0.005$) or attentional entropy ($\chi^2(1) = 7.26$, $p = 0.12$) were not significant.

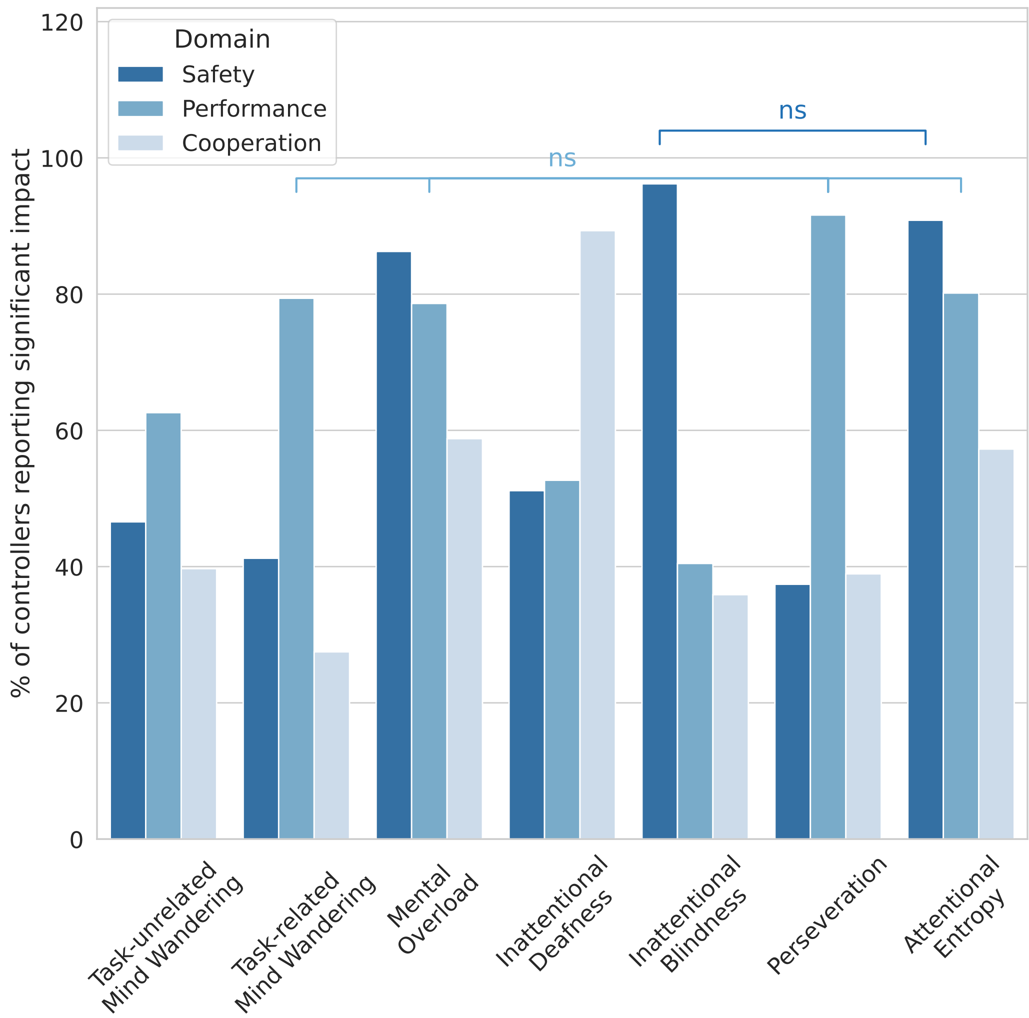

Figure 3. Impacts of degraded engagement states reported by ATCOs (N = 131). For each domain, all pairwise comparisons with the most reported state were statistically significant ($p < 0.0045$) unless specified otherwise. According to ATCOs, inattentional blindness and attentional entropy are the main threat to safety, and inattentional deafness has the most impact on cooperation. Four states reportedly had the most significant impact on control performance. Note: ns = no significant difference.

Finally, safety was reported as the most impacted domain for mental overload (86.23%), attentional entropy (90.84%) and inattentional blindness (96.18%), which was the most reported impact in this study, thus confirming our second hypothesis. However, the difference between inattentional blindness and attentional entropy ($\chi^2(1) = 3.77$, $p = 0.05$) did not reach statistical significance.

4. Discussion

The motivation of this study was to investigate air traffic controllers' attentional management issues in actual operations. Indeed, degraded attentional states have been studied in experiments and ATC simulations, but little is known about their actual prevalence and impact on everyday operations. This study aimed at providing such operational data, as identifying which states have significant prevalence and repercussions could lead to targeted countermeasures to help air traffic controllers cope with the variability of their working conditions while maintaining a high level of performance.

We surveyed professional French air traffic controllers about their career experience of seven degraded attentional states linked to task engagement issues. We also aimed at identifying some contributing factors to these degraded engagement states, such as the workload conditions and circadian rhythm. Finally, the perceived impact of these states on safety, cooperation, and performance were investigated.

The results showed very heterogeneous frequencies and operational consequences of the degraded attentional states. In terms of prevalence, four groups of diminishing frequency of occurrence emerged: firstly, task-related mind wandering was the most prevalent degraded state. Then inattentional deafness and task-unrelated mind wandering were reported with similar frequencies. The third most reported group was composed of perseveration and inattentional blindness. Finally, the least frequently reported states were attentional entropy and mental overload. In terms of operational impact, air traffic controllers considered inattentional blindness and attentional entropy were the biggest threats to safety, and that cooperation was most impended by inattentional deafness. Four out of seven states also reportedly had high impact on control performance. The four more frequently reported states had the least reported impact on safety but ATCOs found them to degrade control performance. Moreover, states with the highest impact on safety were mostly experienced in conditions of high workload, what is in line with the results of [57], who found that more operational errors occurred in en route ATC when workload was high. So overall, we believe that inattentional blindness, which was reported as having a significant impact on safety by over 96% of ATCOs, is a prime candidate for further safety research as its impact on it is markedly higher than that of more frequent states.

In line with our first hypothesis, task-related mind wandering constituted the first group of reported prevalence, and task-unrelated mind wandering was in the second most prevalent group, making it a valuable research topic. As a matter of fact, recent works in air traffic control dealt with it through various means [58,59]. The reported frequency of mind wandering experiences was however low compared to previous experiments. Indeed, previous studies found that up to 50% of waking hours consist of mind wandering [60], a figure that was also found during a sustained attention task [61]. However, both task-related and task-unrelated mind wandering were reported to occur in every work session by less than 3% of professional air traffic controllers, which is clearly incompatible with the previous results. A first explanation to account for these differences is that the data from [60,61] involved laboratory experiments or every day life scenarios that were not as critical as ATC operational situations. Indeed, mind wandering is probably less frequent on the job, especially when human lives are at stake as in ATC, than during less demanding activities (e.g., attending a meeting or reading a book). So, these results suggest that either air traffic controllers somehow prevent their minds from wandering when working, or that they might not be systematically aware of its occurrence when on the job (both hypotheses not being mutually exclusive). Even though the first hypothesis cannot be discarded and should be investigated, massive under-reports of mind wandering due to the participants being unaware of it are actually quite common (e.g., [22]), and meta-awareness of mind wandering (i.e., the explicit knowledge that one's mind is wandering) is only intermittent [19].

Task-unrelated mind wandering was overwhelmingly reported in conditions of low workload, and hence low external demands, which fits the existing literature. However, no clear workload conditions emerged for task-related mind wandering, with high, low and medium workload being reported about equally, and "no answer" being the most frequent reply. Furthermore, less than half of air traffic controllers reported an impact of mind wandering on safety or cooperation, and the highest impact was reported on global performance. Given the extent of the domains adversely impacted by mind wandering (for a review, see Table 1 in [26]), again, either professional air traffic controllers have developed ways to mitigate its costs, or are unaware of them. Ref. [62] suggested that expert pilots would learn to identify "appropriate times" to mind wander during their monitoring duties. They would confine mind wandering to periods where its impact would be minimal, but let it happen whenever possible. It could be the case that expert air traffic controllers have adopted the same strategy, thus explaining the low reported impact on safety, and possibly its prevalence in most workload conditions. This would be compatible with the low reported impact on cooperation: by choosing appropriate times to mind wander, controllers could rely on their colleague to maintain an acceptable performance in situations that require little time to assess and explain if need be. Mind wandering could also provide relief from boredom during a tedious task, which is corroborated by the fact that task-unrelated mind wandering was overwhelmingly ($\simeq$90%) reported in conditions of low workload. Another possible explanation is that the benefits of mind wandering outweigh its costs in this activity. Indeed, according to [26], mind wandering promotes future thinking and prospective planning, which is necessary in air traffic control. They also suggest that it could help maintain goal-appropriate behaviors for multiple goals at a time through attentional cycling -again, a desirable feature in ATC. These results lean towards the fact that even though mind wandering is a fairly prevalent state, its impact is not so adverse that it needs eliminating from actual real world tasks. We still believe that the actual impact (both deleterious and beneficial) in ecological conditions should be further investigated, even more so after the dramatic drop in traffic following the global pandemic, which should greatly increase periods of (very) low workload.

The inattentional phenomena (blindness and deafness) were ranked in the second and third most prevalent groups, significantly lower than task-related mind wandering. In actual working conditions, stimuli such as visual notifications or visual alerts may be impacted by blindness. However, as no auditory alarm has yet been implemented in the control facilities that were surveyed, inattentional deafness would manifest itself through missed verbal communications with colleagues or missed pilot calls. These episodes were mostly reported in conditions of high workload, in accordance with previous literature. Indeed, high load settings induced missed aircraft notifications [36,37,40] as well as auditory sounds in simulated ATC situations [40]. These states were perceived as being the most critical in terms of safety (inattentional blindness) and cooperation (inattentional deafness), what confirms our second hypothesis. The criticality of inattentional blindness seems logical if one considers the consequences of a missed proximity alert, which can lead to separation infringements between aircraft and ultimately airborne collisions (even though not all visual notifications can have such dire consequences). Again, this is consistent with the results of [6,7] who identified the lack of perception of alarms as one of the major causes of incidents. The fact that the auditory channel is mainly dedicated to communications with colleagues, pilots and other staff members, could explain the high impact on cooperation of inattentional deafness. However, safety could be impacted in the future should auditory alarms be implemented. Studies could be performed in facilities already benefiting from such alarms, where safety concerns have already been raised [63]. So these reports constitute evidence that inattentional blindness and deafness are a concern in air traffic control as, even though their prevalence seems rather limited, their impact can have extreme consequences.

Perseveration was found to be in the third most prevalent group of degraded states of engagement. In actual operations, it can correspond to a controller carrying on a resolution strategy for one or more conflict(s) despite evidence (from colleagues or pilots) that it is no longer appropriate considering the evolution of the tactical situation. One has to consider that ATCOs may have to solve several conflicts at the same time and so often have to make a lot of quick decisions over a few minutes. No predominant workload condition was reported for perseveration, even though most laboratory experiments generating this behavior in pilots used high workload conditions (e.g., [44]). However, [41] reported that perseverative behaviors can also occur if workload is too low, which could explain these results. It is noteworthy that safety seems little impacted by perseveration for air traffic controllers while it is a prime concern for pilots. Yet air traffic controllers report that it has a high impact on global performance. This may be explained by the large difference in the nature of perseverative behaviors between ATC and piloting. While pilots have (among others) one hugely critical decision to make (landing or not: [44,54]) that needs to be regularly reassessed, controllers rather have sequences of decisions to make regarding several problems, rendering the impact of one perseverative (sub-par) decision less important. Furthermore, these results tend to show that a sub optimal strategy in ATC makes the overall task harder but may still maintain an acceptable level of safety, suggesting that controllers keep some room to recover from poor decisions.

Finally, the least frequent degraded states according to air traffic controllers were mental overload and attentional entropy. They were both reported (albeit by very few respondents) to occur in high workload conditions, in line with our model of engagement and previous studies (e.g., [15]). They were mostly reported to impact the safety domain. The low prevalence of mental overload may be explained by considering the motivational aspect of task engagement [18]. Indeed, conditions of high workload are mainly associated with a high number of aircraft under responsibility with a high number of problems between them. In these conditions, providing effective air traffic control is literally a matter of life and death. This must elicit great motivation and hence maintain the high level of engagement that is required to perform the task. The low frequency of occurrences of attentional entropy may be related to the lack of implementation of automation tools to assist air traffic controllers, as ATC systems in Europe are still notoriously relying on humans for most tasks despite large-scale attempts to introduce automation in ATC facilities [64]. Indeed, attentional entropy has been mainly shown to occur when conflicts between humans and automated systems arise (i.e., "automation surprise"), confusing the human operators [31]. However, this phenomenon could become a real concern in the near future with the gradual automation of ATC.

In a nutshell, the main results are as follows :

- All degraded states of engagement were experienced by air traffic controllers, and all these states can have a significant impact;
- States of over-engagement had fairly low prevalence but a high perceived impact, making them a prime target for future studies;
- These results advocate for the implementation of countermeasures to degraded attentional states in order to maintain a high level of safety, cooperation and performance.

4.1. Limitations

The reports in this article were, however, subject to several limitations. First of all, the personal and sensitive nature of some of the responses are obvious: task-unrelated mind wandering on the job or missing an alarm could be perceived as professional malpractice (even though this is not the authors' view), which professionals may be reluctant to admit [56]. Hence, some respondents may have censored their responses. Another limitation is that the recall of errors in one's career may also have been subject to forgetting, as we already put forward to explain some absence of results. Indeed, air traffic controllers may have difficulty remembering perceptual failures or mind wandering states that occurred long ago. This may explain the almost total absence of results regarding the factors other than workload contributing to degraded engagement. Even though there is ample evidence of deleterious effects of shift work or time on task on safety and performance (e.g., [65]), no such pattern was reported in this study.

Additionally, the impacts of degraded attentional states, including safety, are entirely subjective as they were based on the perceived experience reported by ATCOs, and not from objective systematic studies such as risk analysis.

Finally, these data may to a certain extent only be applicable to air traffic controllers in a given set of conditions. Indeed, all participants were working for the same Air Navigation Service Provider (but from five different facilities), with a limited variability in terms of typologies of traffic and equipment. It is possible that the results could be slightly different in other locations with other tools at their disposal and different levels of automation. ATCOs could also choose the time and place to answer this questionnaire, so their answers might have been influenced by their rest level or their last shift at work.

4.2. Perspectives

Despite these limitations, the present study advocates for further research on degraded attentional states in air traffic control. Inattentional phenomena should be investigated, as they have a high impact on safety and cooperation. The prevalence of mind wandering may increase due to the recent traffic drop, and its impact on air traffic control needs to be clarified. Future studies should also characterize perseveration, that appears to be fairly different from what was observed on pilots.

Neuroergonomic studies could identify markers of degraded states with a high impact on safety in order to implement adaptive automation based on the principle of [66] and dynamically trigger countermeasures that mitigate their deleterious effects [15]. For instance, [36,37] successfully designed adaptive notifications to prevent the occurrence of ATCOs' inattentional blindness. Similar solutions, based on information removal, were proposed by [67] to mitigate perseveration in the context of flying and operating robots. In terms of neuroergonomics, [58,68] developed an on-line vigilance index computed from EEG signal to drive the level of automation so as to maintain ATCOs in their comfort engagement zone. Finally, neurofeedback could be used to inform ATCOs on their mental states so that they can regulate their level of engagement [69–71]. So this study is a first step towards mitigating the prevalence and adverse impacts of deleterious attentional states.

5. Conclusions

Noticing the lack of operational data on degraded attentional states in air traffic control, we conducted an exploratory survey of professional air traffic controllers in actual operations in order to assess the prevalence, conditions and impact of such states. In accordance with the incident and operational error studies, inattentional phenomena were found to have a significant adverse impact on perceived safety and cooperation by ATCOs, thus making them a major subject of investigation.

Mind wandering was the most reported state but its prevalence however appeared to be much lower than the existing literature suggested. It reportedly impacted more global performance than safety, but potential benefits from it should be further investigated. Finally perseveration in air traffic control seems to be quite different from perseveration in pilots and should be further characterized. These results have applications in the design of user interfaces for air traffic control, which should try and mitigate the most deleterious effects of degraded states that are actually encountered in real operations.

Author Contributions: Conceptualization, F.D., J.-P.I. and R.N.R.; methodology, F.D., J.-P.I., R.N.R. and Y.M.; software, Y.M. and J.-P.I.; validation, F.D., J.-P.I. and R.N.R.; formal analysis, Y.M.; investigation, Y.M.; resources, Y.M.; data curation, Y.M.; writing—original draft preparation, Y.M. and A.L.; writing—review and editing, F.D., J.-P.I., R.N.R. and Y.M.; visualization, Y.M. and A.L.; project administration, F.D., J.-P.I. and R.N.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the Ethics Committee the University of Toulouse (project n° 2019-191).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to confidential issues.

Acknowledgments: The authors thank Direction des Services de la Navigation Aérienne for supporting this research.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

- Task-unrelated mind wandering :
  Did it ever happen that your thoughts disconnected from the present traffic and "wander" towards topics unrelated to air traffic control ?
- Task-related mind wandering:
  Did you ever integrate a new flight by browsing through its parameters without being concentrated on it, and realize later that your integration was so incomplete that you had to perform it again?
- Inattentional deafness:
  Did it ever happen that you were totally focused your radar screen and did not perceive verbal coordinations directed at you? For example, you did not the coordinations from your planning controller or information from the supervisor.
- Inattentional blindness:
  Did it ever happen that you were totally focused your radar screen and did not perceive, or belatedly perceive other signals elsewhere on the screen, such as a Short Term Conflict Alert or a newly added tag on a label?
- Perseveration :
  Did you ever get involved for several minutes in an obviously costly strategy (for example, solving a conflict with evolving aircraft with numerous heading instructions), while external elements (slow reactions from a pilot, many radio calls from other pilots, advice from your PC) urged you to switch to a simpler solution (for example, stopping a climb)?
- Attentional entropy:
  Did you ever fail to (or wrongly) anticipate the general situation in your sector and the forthcoming problems, and felt "lost" on the sector?
- Mental Overload:
  Did it ever happen that you could not handle all the incoming problems on the sector, even with a lot of effort ?

Appendix B

Table A1. Ordinal logistic regression of age against reported occurrences of degraded engagement (N = 141).

Degraded State	Value	σ	t	p
Task unrelated Mind Wandering	−0.05	0.02	−2.06	0.04
Task related Mind Wandering	0.03	0.02	1.17	0.24
Mental overload	0.02	0.02	0.66	0.51
Inattentional Deafness	−0.00	.02	−0.19	0.85
Inattentional Blindness	0.05	0.02	1.85	0.06
Perseveration	−0.02	0.02	−0.86	0.39
Attentional Entropy	0.05	0.02	1.86	0.06

Note: The threshold value in this study was α = 0.0045.

References

1. EUROCONTROL. *Performance Review Report 2019*; Technical Report; Eurocontrol: Brussels, Belgium, 2020.
2. EUROCONTROL. *EUROCONTROL Five-Year Forecast 2020–2024*; Technical Report; EUROCONTROL: Brussels, Belgium, 2021.
3. International Civil Aviation Organization. *Annex 11 to the Convention on International Civil Aviation*; International Civil Aviation Organization: Montreal, QC, Canada, 2018.
4. Pape, A.M.; Wiegmann, D.A.; Shappell, S. Air Traffic Control Related Accidents and Incidents: A Human Factors Analysis. In Proceedings of the 11th International Symposium on Aviation Psychology, Columbus, OH, USA, 5–8 March 2001.
5. Stager, P.; Hameluck, D. Ergonomics in Air Traffic Control. *Ergonomics* **1990**, *33*, 493–499. [CrossRef]
6. Shorrock, S.T. Errors of Perception in Air Traffic Control. *Saf. Sci.* **2007**, *45*, 890–904. [CrossRef]
7. Scarborough, A.; Bailey, L.; Pounds, J. *Examining ATC Operational Errors Using the Human Factors Analysis and Classification System*; DOT/FAA/AM-05/25; FAA Civil Aerospace Medical Institute: Oklahoma City, OK, USA, 2005.

8. National Research Council. *Flight to the Future: Human Factors in Air Traffic Control*; National Academies Press: Washington, DC, USA, 1997. [CrossRef]
9. Athenes, S.; Averty, P.; Puechmorel, S.; Delahaye, D.; Collet, C. ATC Complexity and Controller Workload: Trying to Bridge the Gap. In Proceedings of the International Conference on HCI in Aeronautics, Cambridge, MA, USA, 23–25 October 2002; AAAI Press: Cambridge, MA, USA, 2002; pp. 56–60.
10. Edwards, T.; Homola, J.; Mercer, J.; Claudatos, L. Multifactor Interactions and the Air Traffic Controller: The Interaction of Situation Awareness and Workload in Association with Automation. *IFAC-PapersOnLine* **2016**, *49*, 597–602. [CrossRef]
11. Edwards, T.; Martin, L. The Relationship between Workload and Performance in Air Traffic Control. *Proc. Hum. Factors Ergon. Soc. Annu. Meet.* **2017**, *61*, 1609–1613. [CrossRef]
12. Marcil, I.; Vincent, A. *Fatigue in Air Traffic Controllers: Literature Review*; Technical Report TP 13457; Transport Canada Air Navigation Services and Airspace; Transport Canada: Montreal, QC, Canada, 2000.
13. Cruz, C.E.; Della Rocco, P.S.; Hackworth, C. Effects of Quick Rotating Shift Schedules on the Health and Adjustment of Air Traffic Controllers. *Aviat. Space Environ. Med.* **2000**, *71*, 400–407. [PubMed]
14. Cruz, C.E.; Boquet, A.; Detwiler, C.; Nesthus, T. Clockwise and Counterclockwise Rotating Shifts: Effects on Vigilance and Performance. *Aviat. Space Environ. Med.* **2003**, *74*, 606–614.
15. Dehais, F.; Lafont, A.; Roy, R.; Fairclough, S.H. A Neuroergonomics Approach to Mental Workload, Engagement and Human Performance. *Front. Neurosci.* **2020**, *14*, 268. [CrossRef]
16. Petersen, S.E.; Posner, M.I. The Attention System of the Human Brain: 20 Years After. *Annu. Rev. Neurosci.* **2012**, *35*, 73–89. [CrossRef]
17. Stephens, C.; Dehais, F.; Roy, R.N.; Harrivel, A.; Last, M.C.; Kennedy, K.; Pope, A. Biocybernetic Adaptation Strategies: Machine Awareness of Human Engagement for Improved Operational Performance. In *International Conference on Augmented Cognition*; Schmorrow, D.D., Fidopiastis, C.M., Eds.; Springer International Publishing: Cham, Switzerland, 2018; Volume 10915, pp. 89–98. [CrossRef]
18. Matthews, G.; Campbell, S.E.; Falconer, S.; Joyner, L.A.; Huggins, J.; Gilliland, K.; Grier, R.; Warm, J.S. Fundamental Dimensions of Subjective State in Performance Settings: Task Engagement, Distress, and Worry. *Emotion* **2002**, *2*, 315–340. [CrossRef]
19. Schooler, J.W.; Smallwood, J.; Christoff, K.; Handy, T.C.; Reichle, E.D.; Sayette, M.A. Meta-Awareness, Perceptual Decoupling and the Wandering Mind. *Trends Cogn. Sci.* **2011**, *15*, 319–326 . [CrossRef]
20. Smallwood, J.; Davies, J.B.; Heim, D.; Finnigan, F.; Sudberry, M.; O'Connor, R.; Obonsawin, M. Subjective Experience and the Attentional Lapse: Task Engagement and Disengagement during Sustained Attention. *Conscious. Cogn.* **2004**, *13*, 657–690. [CrossRef] [PubMed]
21. Smallwood, J.; Schooler, J.W. The Restless Mind. *Psychol. Bull.* **2006**, *132*, 946–958. [CrossRef] [PubMed]
22. Smallwood, J.; McSpadden, M.; Schooler, J.W. When Attention Matters: The Curious Incident of the Wandering Mind. *Mem. Cogn.* **2008**, *36*, 1144–1150. [CrossRef] [PubMed]
23. Gouraud, J.; Delorme, A.; Berberian, B. Out of the Loop, in Your Bubble: Mind Wandering Is Independent From Automation Reliability, but Influences Task Engagement. *Front. Hum. Neurosci.* **2018**, *12*, 383. [CrossRef]
24. Gouraud, J.; Delorme, A.; Berberian, B. Influence of Automation on Mind Wandering Frequency in Sustained Attention. *Conscious. Cogn.* **2018**, *66*, 54–64. [CrossRef]
25. Schooler, J.W.; Mrazek, M.D.; Franklin, M.S.; Baird, B.; Mooneyham, B.W.; Zedelius, C.; Broadway, J.M. The Middle Way. In *Psychology of Learning and Motivation*; Elsevier: Amsterdam, The Netherlands, 2014; Volume 60, pp. 1–33. [CrossRef]
26. Mooneyham, B.W.; Schooler, J.W. The Costs and Benefits of Mind-Wandering: A Review. *Can. J. Exp. Psychol./Rev. Can. Psychol. Exp.* **2013**, *67*, 11–18. [CrossRef]
27. Fairclough, S.H.; Ewing, K.; Burns, C.; Kreplin, U. Neural Efficiency and Mental Workload: Locating the Red Line. In *Neuroergonomics*; Academic Press: Cambridge, MA, USA, 2019; pp. 73–77.
28. Wickens, C.D.; Tsang, P.S. Workload. In *APA Handbook of Human Systems Integration*; APA Handbooks in Psychology®; American Psychological Association: Washington, DC, USA, 2015; pp. 277–292. [CrossRef]
29. Durantin, G.; Gagnon, J.F.; Tremblay, S.; Dehais, F. Using near Infrared Spectroscopy and Heart Rate Variability to Detect Mental Overload. *Behav. Brain Res.* **2014**, *259*, 16–23. [CrossRef]
30. Wilson, G.F.; Russell, C.A. Operator Functional State Classification Using Multiple Psychophysiological Features in an Air Traffic Control Task. *Hum. Factors J. Hum. Factors Ergon. Soc.* **2003**, *45*, 381–389. [CrossRef]
31. Dehais, F.; Peysakhovich, V.; Scannella, S.; Fongue, J.; Gateau, T. "Automation Surprise" in Aviation: Real-Time Solutions. In Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems, Seoul, Korea, 18–23 April 2015; pp. 2525–2534. [CrossRef]
32. Wickens, C.D. Attentional Tunneling and Task Management. In Proceedings of the 2005 International Symposium on Aviation Psychology, 2005; pp. 812–817. Available online: https://corescholar.libraries.wright.edu/cgi/viewcontent.cgi?article=1130&context=isap_2005 (accessed on 10 January 2022).
33. Mack, A.; Rock, I. *Inattentional Blindness*; MIT Press/Bradford Books Series in Cognitive Psychology; MIT Press: Cambridge, MA, USA, 1998.
34. Macdonald, J.S.P.; Lavie, N. Visual Perceptual Load Induces Inattentional Deafness. *Atten. Percept. Psychophys.* **2011**, *73*, 1780–1789. [CrossRef]

35. Simons, D.J.; Chabris, C.F. Gorillas in Our Midst. Sustained Inattentional Blindness for Dynamic Events. *Perception* **1999**, *28*, 1059–1074. [CrossRef]
36. Imbert, J.P.; Hodgetts, H.M.; Parise, R.; Vachon, F.; Dehais, F.; Tremblay, S. Attentional Costs and Failures in Air Traffic Control Notifications. *Ergonomics* **2014**, *57*, 1817–1832. [CrossRef]
37. Saint-Lot, J.; Imbert, J.P.; Dehais, F. Red Alert: A Cognitive Countermeasure to Mitigate Attentional Tunneling. In Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems, Honolulu, HI, USA, 25–30 April 2020; pp. 1–6. [CrossRef]
38. Raveh, D.; Lavie, N. Load-Induced Inattentional Deafness. *Atten. Percept. Psychophys.* **2015**, *77*, 483–492. [CrossRef]
39. Durantin, G.; Dehais, F.; Gonthier, N.; Terzibas, C.; Callan, D.E. Neural Signature of Inattentional Deafness. *Hum. Brain Mapp.* **2017**, *38*, 5440–5455. [CrossRef]
40. Giraudet, L.; Imbert, J.P.; Tremblay, S.; Causse, M. High Rate of Inattentional Deafness in Simulated Air Traffic Control Tasks. *Procedia Manuf.* **2015**, *3*, 5169–5175. [CrossRef]
41. Dehais, F.; Rida, I.; Roy, R.N.; Iversen, J.; Mullen, T.; Callan, D. A pBCI to Predict Attentional Error Before It Happens in Real Flight Conditions. In Proceedings of the 2019 IEEE International Conference on Systems, Man and Cybernetics (SMC), Bari, Italy, 6–9 October 2019; pp. 4155–4160. [CrossRef]
42. Hauser, M.D. Perseveration, Inhibition and the Prefrontal Cortex: A New Look. *Curr. Opin. Neurobiol.* **1999**, *9*, 214–222. [CrossRef]
43. Goh, J.; Wiegmann, D. An Investigation of the Factors That Contribute to Pilots' Decisions to Continue Visual Flight Rules Flight into Adverse Weather. *Proc. Hum. Factors Ergon. Soc. Annu. Meet.* **2001**, *45*, 26–29. [CrossRef]
44. Reynal, M.; Rister, F.; Scannella, S.; Wickens, C.D.; Dehais, F. Investigating Pilot's Decision Making When Facing an Unstabilized Approach: An Eye-Tracking Study. In Proceedings of the 19th International Symposium on Aviation Psychology, Dayton, OH, USA, 8–11 May 2017; pp. 335–340.
45. Dehais, F.; Hodgetts, H.M.; Causse, M.; Behrend, J.; Durantin, G.; Tremblay, S. Momentary Lapse of Control: A Cognitive Continuum Approach to Understanding and Mitigating Perseveration in Human Error. *Neurosci. Biobehav. Rev.* **2019**, *100*, 252–262. [CrossRef] [PubMed]
46. Durantin, G.; Dehais, F.; Delorme, A. Characterization of Mind Wandering Using fNIRS. *Front. Syst. Neurosci.* **2015**, *9*, 45. [CrossRef] [PubMed]
47. Smallwood, J.; Beach, E.; Schooler, J.W.; Handy, T.C. Going AWOL in the Brain: Mind Wandering Reduces Cortical Analysis of External Events. *J. Cogn. Neurosci.* **2008**, *20*, 12. [CrossRef]
48. Seli, P.; Konishi, M.; Risko, E.F.; Smilek, D. The Role of Task Difficulty in Theoretical Accounts of Mind Wandering. *Conscious. Cogn.* **2018**, *65*, 255–262. [CrossRef] [PubMed]
49. Fairclough, S.H.; Moores, L.J.; Ewing, K.C.; Roberts, J. Measuring Task Engagement as an Input to Physiological Computing. In Proceedings of the 2009 3rd International Conference on Affective Computing and Intelligent Interaction and Workshops, Amsterdam, The Netherlands, 10–12 September 2009; pp. 1–9. [CrossRef]
50. Dehais, F.; Roy, R.N.; Durantin, G.; Gateau, T.; Callan, D. EEG-Engagement Index and Auditory Alarm Misperception: An Inattentional Deafness Study in Actual Flight Condition. In *International Conference on Applied Human Factors and Ergonomics (AHFE 2017)*; Springer: Cham, Switzerland, 2018. [CrossRef]
51. Duprès, A.; Roy, R.N.; Scannella, S.; Dehais, F. Pre-Stimulus EEG Engagement Ratio Predicts Inattentional Deafness to Auditory Alarms in Realistic Flight Simulator. In Proceedings of the 3rd International Mobile Brain/Body Imaging Conference, Berlin, Germany, 12–14 July 2018; pp. 1–3.
52. Imbert, J.P.; Hodgetts, H.M.; Parise, R.; Vachon, F.; Tremblay, S. The LABY Microworld: A Platform for Research, Training and System Engineering. *Proc. Hum. Factors Ergon. Soc. Annu. Meet.* **2014**, *58*, 1038–1042. [CrossRef]
53. Dehais, F.; Causse, M.; Vachon, F.; Tremblay, S. Cognitive Conflict in Human–Automation Interactions: A Psychophysiological Study. *Appl. Ergon.* **2012**, *43*, 588–595. [CrossRef] [PubMed]
54. Dehais, F.; Tessier, C.; Christophe, L.; Reuzeau, F. The Perseveration Syndrome in the Pilot's Activity: Guidelines and Cognitive Countermeasures. In *Human Error, Safety and Systems Development*; Palanque, P., Vanderdonckt, J., Winckler, M., Eds.; Springer: Berlin/Heidelberg, Germany, 2010; Volume 5962, pp. 68–80. [CrossRef]
55. Helton, W.S.; Shaw, T.; Warm, J.S.; Matthews, G.; Hancock, P. Effects of Warned and Unwarned Demand Transitions on Vigilance Performance and Stress. *Anxiety Stress Coping* **2008**, *21*, 173–184. [CrossRef] [PubMed]
56. Tourangeau, R.; Yan, T. Sensitive Questions in Surveys. *Psychol. Bull.* **2007**, *133*, 859–883. [CrossRef]
57. Rodgers, M.D. *An Examination of the Operational Error Database for Air Route Traffic Control Centers*; Technical Report AD-A275 986; Civil Aeromedical Institute Federal Aviation Administration: Oklahoma City, OK, USA, 1993.
58. Di Flumeri, G.; De Crescenzio, F.; Berberian, B.; Ohneiser, O.; Kramer, J.; Aricò, P.; Borghini, G.; Babiloni, F.; Bagassi, S.; Piastra, S. Brain–Computer Interface-Based Adaptive Automation to Prevent Out-Of-The-Loop Phenomenon in Air Traffic Controllers Dealing With Highly Automated Systems. *Front. Hum. Neurosci.* **2019**, *13*, 296. [CrossRef]
59. Pop, V.L.; Stearman, E.J.; Kazi, S.; Durso, F.T. Using Engagement to Negate Vigilance Decrements in the NextGen Environment. *Int. J. Hum.-Comput. Interact.* **2012**, *28*, 99–106. [CrossRef]
60. Killingsworth, M.A.; Gilbert, D.T. A Wandering Mind Is an Unhappy Mind. *Science* **2010**, *330*, 932–940. [CrossRef]
61. Gouraud, J.; Delorme, A.; Berberian, B. Autopilot, Mind Wandering, and the Out of the Loop Performance Problem. *Front. Neurosci.* **2017**, *11*, 541. [CrossRef]

62. Casner, S.M.; Schooler, J.W. Vigilance Impossible: Diligence, Distraction, and Daydreaming All Lead to Failures in a Practical Monitoring Task. *Conscious. Cogn.* **2015**, *35*, 33–41. [CrossRef]
63. Ahlstrom, V.; Panjwani, G. *Auditory Alarms in an Airway Facilities Environment*; Technical Report DOT/FAA-CT-TN04/04; Federal Aviation Administration, William Hughes Technical Center, Atlantic City Airport: Atlantic County, NJ, USA, 2003.
64. SESAR Joint Undertaking. *European ATM Master Plan*; SESAR Joint Undertaking: Brussels, Belgium, 2020; p. 650097 [CrossRef]
65. Della Rocco, P.S. *The Role of Shift Work And Fatigue in Air Traffic Control Operational Errors and Incidents*; Technical Report DOT/FAA/AM-99/2; Federal Aviation Administration Civil Aeromedical Institute: Oklahoma City, OK, USA, 1999.
66. Pope, A.T.; Bogart, E.H.; Bartolome, D.S. Biocybernetic System Evaluates Indices of Operator Engagement in Automated Task. *Biol. Psychol.* **1995**, *40*, 187–195. [CrossRef]
67. Dehais, F.; Causse, M.; Tremblay, S. Mitigation of Conflicts with Automation: Use of Cognitive Countermeasures. *Hum. Factors J. Hum. Factors Ergon. Soc.* **2011**, *53*, 448–460. [CrossRef] [PubMed]
68. Aricò, P.; Borghini, G.; Di Flumeri, G.; Colosimo, A.; Pozzi, S.; Babiloni, F. A Passive Brain–Computer Interface Application for the Mental Workload Assessment on Professional Air Traffic Controllers during Realistic Air Traffic Control Tasks. In *Progress in Brain Research*; Elsevier: Amsterdam, The Netherlands, 2016; Volume 228, pp. 295–328. [CrossRef]
69. Egner, T.; Gruzelier, J.H. Learned Self-Regulation of EEG Frequency Components Affects Attention and Event-Related Brain Potentials in Humans. *Neuroreport* **2001**, *12*, 4155–4159. [CrossRef] [PubMed]
70. Egner, T.; Gruzelier, J. EEG Biofeedback of Low Beta Band Components: Frequency-Specific Effects on Variables of Attention and Event-Related Brain Potentials. *Clin. Neurophysiol.* **2004**, *115*, 131–139. [CrossRef]
71. Gruzelier, J.H. EEG-neurofeedback for Optimising Performance. I: A Review of Cognitive and Affective Outcome in Healthy Participants. *Neurosci. Biobehav. Rev.* **2014**, *44*, 124–141. [CrossRef] [PubMed]