To cite this version :

Lorrys BERTHON, Fabien BERNARD, Sylvain FLEURY, Raphaël PAQUIN, Simon RICHIR - Multi-dimensional measurement of mental workload in industrial context: an experiment in the field of helicopter maintenance - Applied Ergonomics - Vol. 129, p.104599 - 2025

Applied Ergonomics 129 (2025) 104599

Contents lists available at ScienceDirect

Applied Ergonomics

journal homepage: www.elsevier.com/locate/apergo

Multi-dimensional measurement of mental workload in industrial context: an experiment in the field of helicopter maintenance

Lorrys Berthon [a,b,*], Fabien Bernard [a,b], Sylvain Fleury [b], Raphaël Paquin [a], Simon Richir [b]

[a] *Airbus Helicopters, Marignane, 13700 France*
[b] *Arts et Métiers, Sciences et Technologies, LAMPA, F-53810, Changé, France*

ARTICLE INFO

Keywords:
Mental workload
Maintenance
Human factors
Heart rate variability
NASA-TLX

ABSTRACT

Assessing mental workload is essential for optimizing the design of complex systems, particularly in aeronautical maintenance, where operators' activities serve as a crucial safety barrier to ensure optimal system safety levels. One of the roles of human factors in maintainability is, therefore, to anticipate maintenance activities and human behavior from the start of the design cycle. This study pursues a dual objective: firstly, to identify relevant for evaluating mental workload in an industrial maintenance environment, and secondly, to determine which of these indicators correlate with performance degradation. Ten participants performed five maintenance tasks of varying complexity on a helicopter, involving the removal, installation of components and a detailed inspection. Subjective measures (NASA-TLX), performance metrics (completion time), and cardiovascular data (heart rate, heart rate variability) were analyzed. We observed longer completion times and higher NASA-TLX scores for complex maintenance conditions. Regarding cardiovascular data, the results in the time domain of heart rate variability follow a similar trend compared to two other types of measurements. These results will be discussed in depth in this article. This study represents a further step in the multidimensional measurement of mental workload in maintenance within a realistic industrial context.

1. Introduction

Assessing mental workload plays a vital role in improving complex technologies, designing intricate systems, and enhancing human-machine collaboration. This approach allows for a more accurate detection of situations where users face significant cognitive demands (Young et al., 2015; Wickens, 2017; Longo et al., 2022). Assessing mental workload in the early design phases of a system enhances task coordination, minimizes errors, boosts efficiency, and improves the overall user experience. Nevertheless, in real-world operations, a mismatch between resources and workload can cause disengagement or overload-related incidents, highlighting the need to account for the full operational context when developing methods to assess mental workload (Yerkes and Dodson, 1908; Dehais et al., 2020). A thorough evaluation of mental workload integrates diverse measurement approaches, providing a detailed insight into operator strain and facilitating the efficient collection of cognitive data to support the integration of Human Factors and Ergonomics (HFE). This is particularly true in the aviation sector, especially for piloting tasks, where mental workload has been studied and measured for several years (Sirevaag et al., 1993; Di Nocera et al., 2007; Luzzani et al., 2024). However, Aviation maintenance is a field that remains insufficiently explored (Bernard et al., 2021; Berthon et al., 2024), especially considering that maintenance errors account for 15 %–20 % of failures, incidents, and accidents (Nkosi et al., 2020). This high-risk activity requires an optimized design focused on human capabilities, as they represent the first line of defense against potential incidents and accidents. Internal factors resulting from interaction with a component, in terms of maintainability, can increase workload, leading to unnecessary stress, poor performance, and human errors (Hobbs and Williamson, 2002; Yiannakides and Sergiou, 2019; Santos and Melicio, 2019; Hobbs, 2021). Maintainability, which differs from maintenance, refers to an element's ability, under specific usage conditions, to be kept or restored to a state where it can perform its intended function, provided maintenance is carried out under defined conditions (Dhillon, 1999; Zaki et al., 2019). External factors, such as time pressure, nature of the work, environmental conditions, and rest periods, can also affect operators' workload. Therefore, if the design and human-machine interaction related to maintainability are not carefully considered, these external factors, which demand significant mental resources such as decision-making, memory, and attention, can significantly worsen the

---

* Corresponding author. Airbus Helicopters, Marignane, 13700 France.
E-mail address: lorrys.l.berthon@airbus.com (L. Berthon).

https://doi.org/10.1016/j.apergo.2025.104599
Received 23 January 2025; Received in revised form 23 June 2025; Accepted 11 July 2025

situation. Certain maintenance tasks, often involving multiple subtasks, are particularly demanding on cognition, memory, and interpretation, posing additional challenges for operators. This is especially true in the complex maintenance systems of helicopters, where the most critical components, such as main rotors, tail rotors, transmission systems, and engines, are also the most vulnerable to maintenance errors (Rashid, 2010). This is why, in this article, we have explored this issue further and try to fill the gap in knowledge regarding the measurement of mental workload in maintenance within an aviation context.

2. Context

Within an aviation manufacturer, we study maintenance activities with the aim of improving flight and maintenance operators' safety. It is now essential to validate a method for assessing mental workload in an operational context with the aim of optimizing maintenance activities. Critical tasks, such as removal and installation, can present significant challenges in terms of human-machine interaction (Reason, 2020). Anticipating users' cognitive behavior could thus help enhance human reliability. The physical dimension of HFE into maintainability has already studied and contributed to successful human-centered design (Bernard et al., 2023).

2.1. History of mental workload measures

Historically, mental workload measures were not consistently multidimensional, often relying on only one or two methods, which proved insufficient for a comprehensive capture of human cognitive data. For instance, unidimensional self-report measures exhibit low diagnostic capability, potentially failing to identify the source or type of workload (Cain, 2007; Cegarra and Chevalier, 2008; Cegarra, 2012; Longo et al., 2022). Similarly, while physiological measures are more sensitive to workload fluctuations, they can be influenced by numerous extraneous factors, thus limiting their diagnostic power (Cain, 2007; Cegarra, 2012; Charles and Nixon, 2019; Longo et al., 2022). Performance measures are not always adequate for assessing workload, especially when task demands exhibit minimal variability, making it difficult to induce significant performance changes (Longo et al., 2022). Likewise, secondary task performance measures can introduce unintended strategic shifts, potentially skewing primary task performance (Longo, 2015). Although numerous theories attempt to elucidate various facets of mental workload, a universally accepted global theory remains elusive, primarily due to the inherent complexity and multidimensional nature of the construct, demanding extensive knowledge, data, and technical expertise for thorough understanding. Consequently, the contemporary trend in multidimensional mental workload measurement is moving towards the integrated use of diverse measures. The multidimensional approach underscores the critical need to investigate and gather more data on multi-dimensional mental workload, particularly within operational settings, given the existing data gaps during such activities.

2.2. Mental workload in aircraft maintenance

For this reason, it is essential to consider the cognitive dimension since we still have a limited understanding of the factors that lead to a bad human-machine interaction and maintenance errors. This underscores the importance of carefully tailoring mental workload assessment techniques to the specific demands of physical tasks, such as those encountered in maintenance operations. The dynamic nature of these tasks, which often require frequent posture changes and significant physical effort, can introduce variability that affects the accuracy and reliability of physiological measurements. Therefore, when optimizing the selection of mental workload measurement tools, it is crucial to account for these constraints to ensure the chosen methods are both appropriate for the operational context and capable of minimizing signal noise induced by physical activity (Berthon et al., 2024). This comprehensive approach highlights the value of integrating subjective assessments, performance metrics, and physiological data to accurately evaluate mental workload, providing deeper insight into human cognitive behavior (Cain, 2007; Cegarra, 2012; Young et al., 2015; Charles and Nixon, 2019; Tao et al., 2019; Longo et al., 2022; Berthon et al., 2024). To maximize the effectiveness of this assessment, it is essential to select measurement tools that adhere to the criteria of sensitivity, selectivity, and diagnosticity, ensuring a thorough and reliable evaluation of mental workload, particularly in complex operational environments (Xie and Salvendy, 2000; Cain, 2007; Cegarra and Chevalier, 2008; Longo et al., 2022; Berthon et al., 2024). In this direction, a first step has been taken, as under the effect of high mental workload in a laboratory context, the indicators of subjective mental workload, performance, and cardiovascular measures varied significantly (Berthon et al., 2024). As a result, we wondered whether these indicators would be likely to vary significantly in a real industrial context. In a design context, a system designed without considering the user, and likely to impose an excessive mental workload, can lead operators to make poor decisions, thereby compromising performance (Wickens, 2017).

2.3. Study objectives and hypotheses

Validating a multidimensional method for measuring mental workload in real maintenance environments will aim to test the effectiveness of our mental workload measurement combination, enabling the assessment of operators' workload and facilitating the development of an efficient, fully human-centered design method for maintainability. In this context, the first objective of this study was to identify the most relevant indicators for assessing mental workload in a real maintenance environment. Cardiovascular indicators, such as heart rate variability (HRV), were analyzed to assess participants' reactions to increased mental workload (Meshkati, 1988; Kramer, 1990). To pinpoint the specific sources of workload, the NASA-TLX scale was employed. Additionally, task completion times were recorded to assess how mental workload influenced overall performance. Secondly, the objective was to determine which of the mental workload indicators are correlated with a direct degradation of performance in terms of maintenance task completion time. To this end, this paper examines a specific hypothesis for each category in our multidimensional measure of mental workload. Under challenging maintenance conditions, we hypothesize that completion times will be longer. Additionally, we also expect to find significant differences across the various dimensions of workload in the NASA-TLX across the five tasks, allowing us to effectively diagnose the source of workload. Finally, we anticipate observing significant differences in cardiovascular indicators between difficult components that are difficult to interact with. Thus, we hypothesize that, in this industrial context, the mental workload will vary, and that certain indicators presumed to reflect mental workload will change accordingly.

3. Materials & methods

3.1. Participants

Ten participants (Mean age = 43.1, SD = ± 10.3) took part in this study. All professional aircraft technicians volunteered and were not compensated for their participation. Among them were 9 men and 1 woman. One participant had an artificial cardiac pacemaker, so their data were excluded from the evaluation of cardiovascular indicators. A lifestyle questionnaire was administered to participants to identify potential biases in cardiovascular measurements arising from systemic influences, specifically assessing sedentary behavior and psychoactive substance use as exclusion criteria. The average sedentary level, based on weekly physical activity including walking, was 5.3 ± 3.9 h. Compared to the reference data provided by IPSOS (2024), which indicates an average of 4 h of weekly physical activity in France, the level of physical activity in our study sample appears to be within the normal range. The data revealed that 80 % of participants were non-smokers, 90 % had not consumed alcohol in the last 24 h and 100 % reported no use of psychoactive substances.

3.2. *Experimental protocol*

The experiment lasted approximately 2 h for each participant (Fig. 1). Prior to the experiment, participants were briefed on the study and provided written consent. Each participant was outfitted with a BioHarness V.3 cardiovascular monitoring belt (Zephyr Technologies, USA), which tracked HR and HRV. These measurements helped evaluate autonomic nervous system activation as participants performed the experimentation on the helicopter (Fig. 2). A 5-min measurement of baseline physiological state was conducted for all participants under the same conditions to establish a reference point for participants' HRV, allowing for meaningful comparison with data collected under specific experimental tasks (Task Force of ESC&ASPE, 1996). The maintenance technicians did not go through a familiarization phase as they all have substantial experience in helicopter aeronautical maintenance. However, the specific objective of this study is not to assess the level of mental workload in a population of experienced maintenance technicians, but rather to assess the mental workload of maintenance technicians under the influence of interaction constraints with a system. Ultimately, the aim is to develop a method for measuring mental workload applicable in maintainability, in order to integrate the cognitive component into the design of maintenance systems. For the purposes of this study, participants encountered and engaged with the task for the first time on the day of the experiment.

All ten participants performed the same five maintenance tasks. To mitigate sequence effects between tasks, half of the participants followed the orange sequence while the other half followed the blue sequence (Fig. 1). This alternation was necessary due to practical constraints: it was not possible to perform the component installation and detailed inspection tasks on the aircraft if the components had not been previously removed. Additionally, a 5-min interval between each task was used to isolate the mental workload effect for each maintenance component and limit accumulated fatigue from successive maintenance tasks. These 5-min rest periods between each task also help to avoid impacting the completion time measurement, which could otherwise be influenced by task order effects. During these 5 min of rest, participants completed the NASA-TLX self-assessment workload questionnaire (Hart & Staveland, 1988). Based on our measurements, we will compare the removal and installation of a damper and a pitch rod (Fig. 3), as well as the detailed inspection of these same components and the measurement of the mechanical play of the ball joints. All participants had access to the same tools (Fig. 4) to complete each of the five maintenance tasks, with each task having a specific maintenance procedure (Appendix).

Fig. 2. A participant perform the maintenance task on helicopter.

In our study, the independent variables we proposed intentionally varied the physical and visual accessibility of components on an H225 helicopter tail rotor. The goal of this research is to highlight quantified differences in mental workload generated by interactions with different components in terms of maintainability during a maintenance task, using the multidimensional measurement approach of Berthon et collaborators (2024).

3.3. *Measurement's methods*

3.3.1. *Subjective measure*

At the end of each task, participants completed the NASA-TLX to assess their overall workload. This survey utilizes six separate subscales

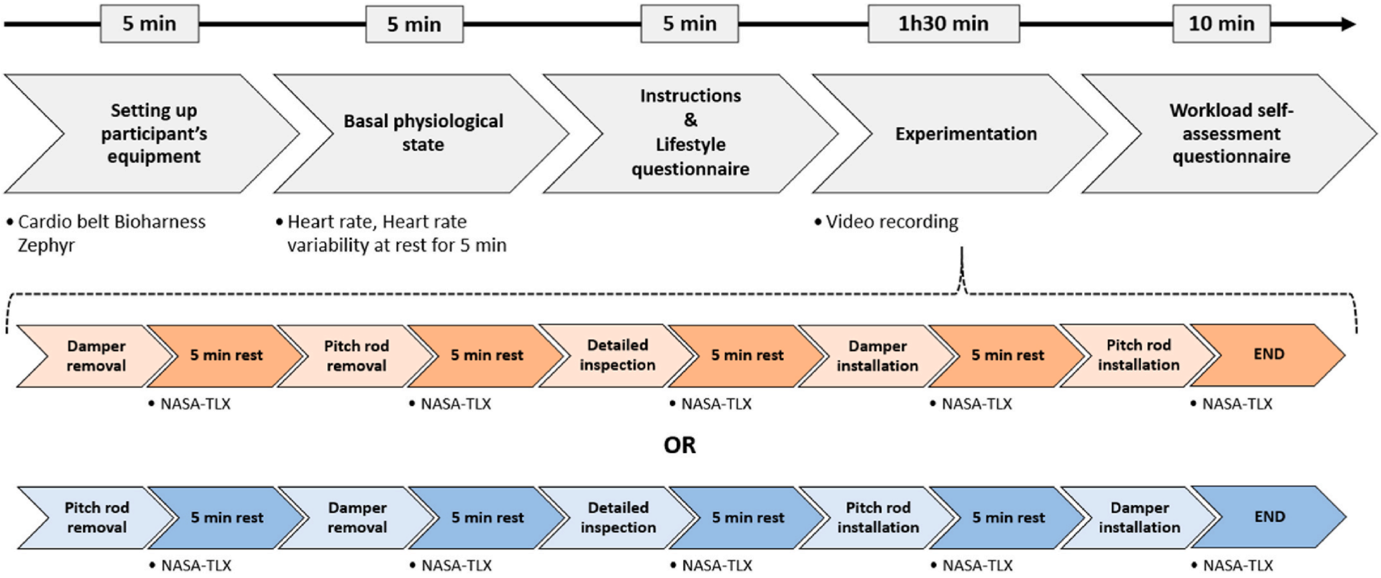

Fig. 1. Protocol design. The blue and orange colors represent the swapped order in which participants completed the tasks. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

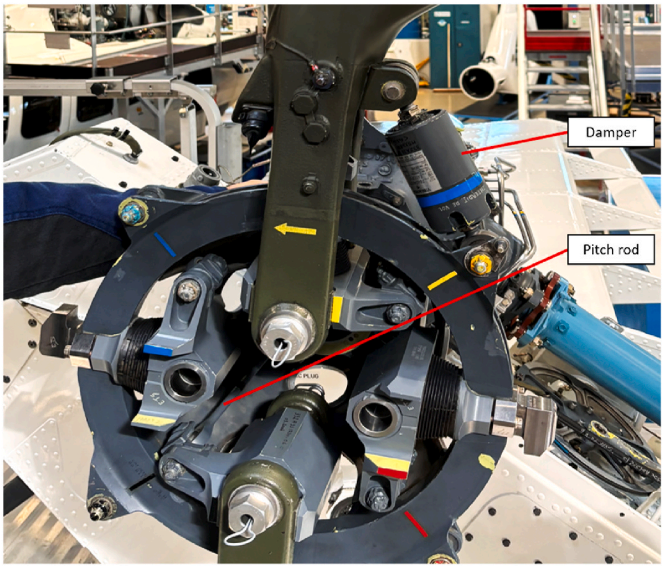

Fig. 3. Components to be removed and installed on helicopter.

to evaluate different aspects of workload, each scored from 0 to 100. These six areas cover distinct categories: Mental Demand (MD), Physical Demand (PD), Temporal Demand (TD), Performance (P), Effort (E), Frustration (F), and Overall Workload (OW). For the Overall Workload (OW), it was determined using a pairwise comparison procedure. After assigning scores to the six dimensions, participants were presented with pairs of dimensions (e.g., 'Mental Demand' vs. 'Physical Demand') and asked to select the one that contributed more to their overall workload. This process was repeated until all dimensions had been compared with each other. Finally, the average of all Overall Workload scores was calculated. To ensure clarity, the experimenter provided guidance to the participants to help them fully grasp each workload category.

3.3.2. *Performance measure*

The completion time for each task was measured during the experiment. The time required to perform a maintenance task serves as a relevant indicator for assessing both mental workload and the design efficiency of a component (Cain, 2007; Longo et al., 2022), especially since the two components with which the participants will interact have the same types of fastening, it is important to note that participants were not subjected to any time pressure during any of the conditions. The sole aim was to measure the mental workload associated with the different conditions and to observe the differences in this dependent variable. The difference in difficulty levels between the damper and the pitch rod is also justified by a very different physical and visual accessibility (Fig. 3); the pitch rod is much less accessible than the damper, and this, coupled with the fact that the number of steps for its removal and installation is higher than for the damper, further justifies a difference in complexity for the removal and installation tasks. Furthermore, the pitch rod cannot be removed or installed independently because it requires the prior removal and installation of the yoke (see. Appendix), which makes the component procedure more complex. Finally, regarding the detailed inspection task of the two components, it comprises 11 steps and is inherently complex due to the knowledge it generates for a reliable measurement of the ball joints mechanical play.

3.3.3. *Cardiovascular measure*

HR and HRV were tracked throughout the experiment. Cardiovascular data analysis relied on electrocardiogram (ECG) time-series information, focusing on a 5-min period beginning at a standardized point for each component. This time is chosen in connection with the guidelines recommended for short-term HRV measurement in relation to the measurement of mental workload (Task Force of ESC & ASPE, 1996; Castaldo et al., 2017; Delliaux et al., 2019; Tiwari et al., 2020).

- Damper Removal (DR): Recording starts from the removal of the split pins.
- Pitch Rod Removal (PRR): Recording starts from the removal of the split pins.
- Detailed Inspection (DET): Recording starts from the inspection of the damper.
- Damper Installation (DI): Recording starts from placing the damper on the rotor.
- Pitch Rod Installation (PRI): Recording starts from placing the pitch rod on the rotor.

ECG signals were sampled at 1000 Hz, and data were exported in.csv format. For HRV analysis, R-R intervals underwent initial correction using the low-artifact correction feature in Kubios HRV Scientific Lite version 4.1. Any detected artifacts were replaced through cubic spline interpolation (Matuz et al., 2021). HRV measures were calculated in both time and frequency domains. Time domain metrics included mean heart rate (MHR, beats/min), average R-R interval (MRR, m/s), average of maximum heart rate (Max HR, beats/min), the square root of the mean squared differences of consecutive R-R intervals (RMSSD, m/s), R-R interval standard deviation (SDNN, m/s), and Baevsky's Stress Index (SI) (Ognev et al., 2019), which indicates heart rate regulation centralization and primarily reflects sympathetic activity (Quendler et al., 2017). Frequency domain metrics included absolute high-frequency power (0.15Hz - .4 Hz; ms^2; HF), normalized high-frequency power (HFnu), absolute low-frequency power (0.07Hz–0.14Hz; ms^2; LF), normalized low-frequency power (LFnu), and the low-to-high frequency power ratio (rLF/HF). Cardiovascular data across the five tasks were compared to baseline (BASELINE) data recorded at the experiment's start. HRV analysis followed established guidelines (Task Force of ESC & ASPE, 1996).

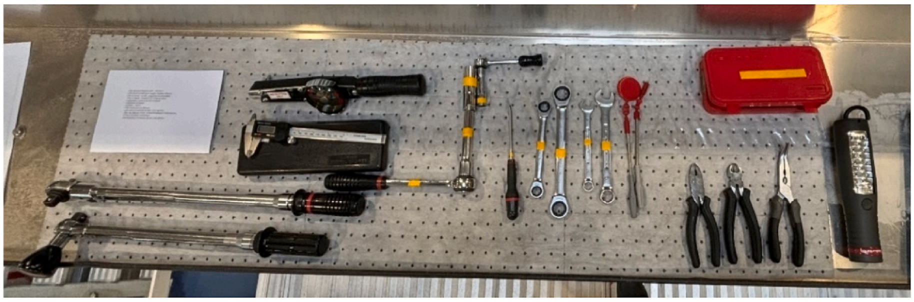

Fig. 4. Tools used during the experiment.

4. Results

4.1. Normality and homoscedasticity tests

Statistics were conducted using R software (R Core Team, 2020). When analyzing the NASA-TLX scores, the Shapiro-Wilk test revealed that, across the five tasks, some scores in each NASA-TLX category did not follow a normal distribution ($p < .1$). Therefore, due to the results obtained from the normality test, we will use the Kruskal-Wallis statistical test, which is followed by a post-hoc Dunn's test.

Regarding the completion time performance data, the Shapiro-Wilk test indicated a non-normal distribution for five of the tasks ($p < .1$). Therefore, due to the results obtained from the normality test, we used the Kruskal-Wallis statistical test, followed by a post-hoc Dunn's test.

For the HRV indicators, the normality of the data was tested across the five tasks and the BASELINE condition. Not all HRV indicators followed a normal distribution across the conditions ($p < .1$). Subsequently, the Levene's test results ($p < .1$) then confirmed the appropriateness of choosing a non-parametric test. As a result, a Kruskal-Wallis statistical test was conducted for all HRV indicators, and this was followed by a post-hoc Dunn's test. Finally, for all three measures, a Bonferroni correction was applied to the p-value results to control for family-wise error rates.

4.2. Subjective measures

The Kruskal-Wallis test for paired samples was used to compare perceived workload sources across different maintenance tasks and revealed significant differences (Fig. 5). The Kruskal-Wallis test showed significant results for the MD ($p < .001$, $r = .436$), P ($p < .001$, $r = .389$), E ($p < .001$, $r = .357$), F ($p < .001$, $r = .459$), and OW ($p < .001$, $r = .587$) dimensions. For the PD ($p = .0013$, $r = .305$) dimension, the difference obtained was significant. Finally, for the TD ($p = .027$, $r = .154$) dimension, the result was significant. Given the significant results of the Kruskal-Wallis test, we proceeded with a Dunn's test to perform pairwise comparisons and determine the exact differences between each of our conditions (Table I). Consequently, we observe significant differences between DET and the tasks involving the installation and removal of the damper. We also observe significant differences between DET and the tasks involving the installation and removal of the pitch rod. Lastly, we generally observe significant differences between the tasks involving the installation or removal of the damper and the pitch rod.

4.3. Performance measures

The Kruskal-Wallis test for paired samples was used to compare time completion across different maintenance tasks and revealed significant differences ($p < .001$, $r = .711$) (Fig. 6). Based on the significant Kruskal-Wallis test results, we conducted a Dunn's test to perform pairwise comparisons and identify the precise differences between each of our conditions. In general, the removal and installation of the damper required significantly less time compared to the removal and installation of the pitch rod. Specifically, DR required significantly less time than PRR ($p = .008$), while DI showed a more pronounced difference compared to PRI ($p = .0013$). As for DET, it required significantly more completion time than the DR removal task ($p < .001$) as well as the DI installation task ($p = .03$).

4.4. Cardiovascular measures

Table II presents the HRV indicators between the BASELINE, DR, PRR, DET, DI and PRI conditions, while Table III presents the statistical results compute by the post hoc Dunn's test (p value). The Kruskal-Wallis test indicated significant differences for Max HR ($p = .006$, $r = .206$). The MRR ($p = .027$, $r = .140$) and MHR ($p = .033$, $r = .131$) showed significant differences. Finally, the SDNN, RMSSD, SI, LF, HR, LFnu, HFnu, and RLF/HF were non-significant ($p > .05$). Following the several outcomes from the Kruskal-Wallis test, we applied a Dunn's test to analyze pairwise comparisons and pinpoint the specific distinctions among each of our conditions (Table III). For the removal and installation of the pitch rod, Dunn's test reveals notable significant differences in the time domain for indicators such as MRR, MHR, Max HR, SDNN, RMSSD, and SI when compared with the BASELINE. However, when observing and comparing the conditions among themselves without considering the BASELINE in the time domain, the SDNN indicator shows a significant difference between the PRR-DI pair ($p = .037$), as does the SI indicator for the PRR-DI pair ($p = .04$) and the DI-PRI pair ($p = .046$). These differences highlight an interesting contrast between the

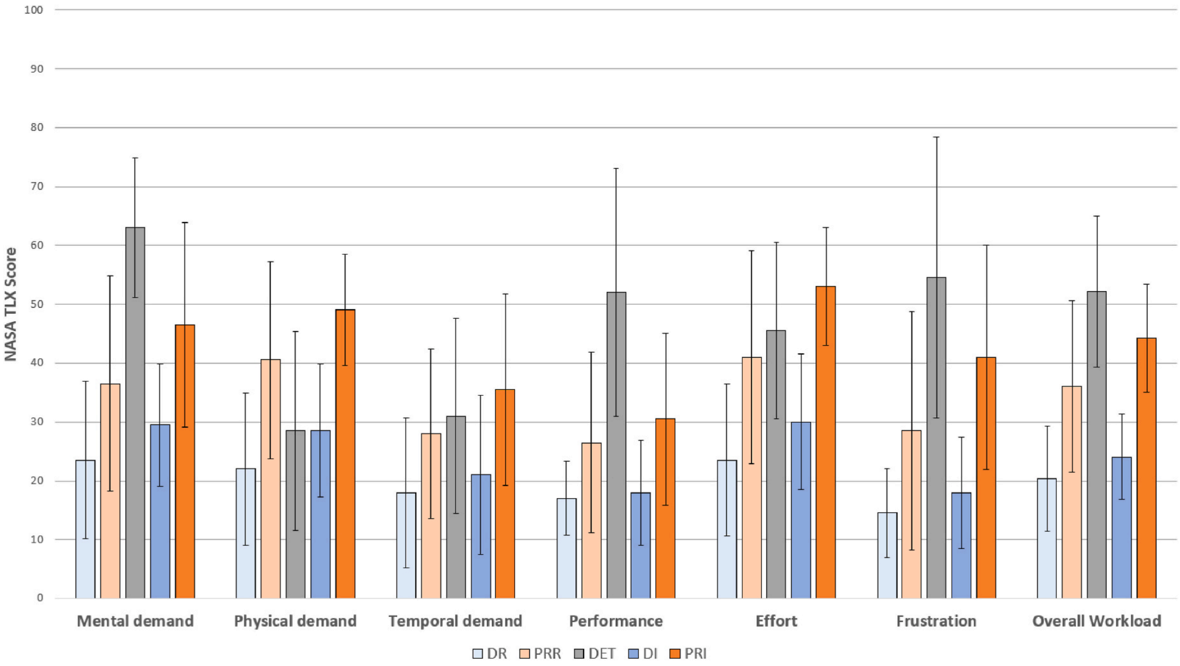

Fig. 5. Histogram of the subjective workload measure conducted by NASA-TLX.

Table 1
Statistical analysis results of NASA-TLX

Conditions	Mental demand	Physical demand	Temporal demand	Performance	Effort	Frustration	Overall workload
	Dunn's test post hoc						
DR-PRR	.113	.012 *	.056	.173	.024 *	.060	.021 *
DR-DET	<.001 ***	.379	.027 *	<.001 ***	.0046 **	<.001 ***	<.001 ***
PRR-DET	.0049 **	.100	.756	.006 **	.557	.026 *	.026 *
DR-DI	.436	.319	.571	.798	.408	.562	.554
PRR-DI	.418	.126	.180	.268	.155	.194	.087
DET-DI	<.001 ***	.907	.098	<.001 ***	.044 *	<.001 ***	<.001 ***
DR-PRI	.0075 **	<.001 ***	.0052 **	.042 *	<.001 ***	<.001 ***	<.001 ***
PRR-PRI	.277	.223	.377	.501	.083	.136	.147
DET-PRI	.084	.0042 **	.566	.040 *	.253	.463	.443
DI-PRI	.058	.006 **	.026 *	.075	.0016 **	.0053 **	.0015 **

All NASA-TLX dimensions were tested using Kruskal-Wallis tests and a Dunn's test post hoc. The p-values are indicated by asterisks.
$p < .05$ *.
$p < .01$ **.
$p < .001$ ***.

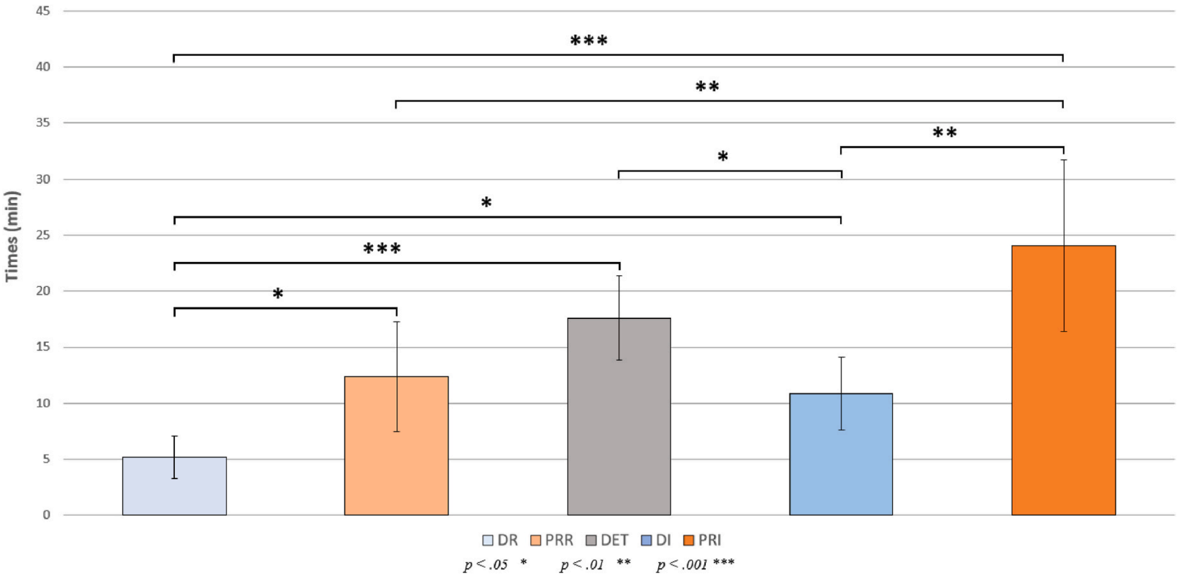

Fig. 6. Histogram of the times (minutes) completion performed across conditions.

Table 2
Cardiovascular indicators during the experiment.

	BASELINE (Mean ± SD)	DR (Mean ± SD)	PRR (Mean ± SD)	DET (Mean ± SD)	DI (Mean ± SD)	PRI (Mean ± SD)
Mean RR (ms)	750.6 ± 119.1	644.9 ± 70.7	588.9 ± 65.9	652.6 ± 55.8	653.3 ± 65.6	617.7 ± 81.1
Mean HR (beats/min)	81.7 ± 12.3	94 ± 10.7	103.1 ± 12	92.8 ± 8.8	93 ± 10	98.7 ± 13.8
Max HR (beats/min)	94.4 ± 13.4	108.4 ± 11.8	120.1 ± 14.4	107.3 ± 9.9	107.9 ± 10.9	119.4 ± 16.4
SDNN (ms)	37.9 ± 18.5	33.4 ± 10	25.6 ± 9.1	31.5 ± 10.1	36.4 ± 10.8	27.5 ± 10.3
RMSSD (ms)	27.2 ± 19.2	18.5 ± 7.6	14.1 ± 6.9	16.5 ± 6.8	22 ± 13.7	14.1 ± 6.3
Stress Index	12.8 ± 5.1	15.2 ± 4.7	18.8 ± 6.8	16.4 ± 6.2	13.8 ± 4.5	19.3 ± 8.3
LF (ms^2)	723.1 ± 501.1	506.1 ± 354	364.8 ± 275.7	514.4 ± 451.4	778.6 ± 440.6	377.6 ± 269.4
HF (ms^2)	460.4 ± 116	114.3 ± 80.2	102.4 ± 90.6	90.3 ± 58.9	183 ± 181.3	94.7 ± 65.8
LF (nu)	57.7 ± 11.1	54.2 ± 11.2	49.6 ± 13.5	57.6 ± 20	56.4 ± 13.2	51.6 ± 19.9
HF (nu)	20.3 ± 14.9	13 ± 6.4	13.4 ± 8.8	15.1 ± 13.7	12.7 ± 8.7	13.4 ± 6.6
Ratio LF/HF	4.2 ± 2.5	5.2 ± 3.3	5.9 ± 5.7	6.6 ± 5.6	6.8 ± 5.9	5.9 ± 5.1

Here are the HRV indicators during 5 min of each condition. The data are presented as mean (SD). In the time domain, mean heart rate (MHR), mean R-R interval (MRR), mean maximum heart rate (Max HR), root mean square of successive differences (RMSSD), standard deviation of NN intervals (SDNN), and Baevsky's stress index (SI) were measured. In the frequency domain, absolute high frequency power (HF), absolute low frequency power (LF), normalized high frequency power (HFnu), normalized low frequency power (LFnu), and the ratio of LF to HF power (rLF/HF) were assessed.

two components tested. Finally, in the frequency domain, no significant differences were observed except for the LF indicator, where the PRR-DI comparison showed a significant difference ($p = .041$).

4.5. Correlation between times and mental workload indicators

We used repeated measures correlation (rmcorr; Bakdash and Marusich, 2017) to assess the within-subject association between subjective workload and cardiovascular measures with task completion time. This

Table 3
Statistical analysis results of heart rate variability indicators.

Conditions	Mean RR (ms)	Mean HR (beats/min)	Max HR (beats/min)	SDNN (ms)	RMSSD (ms)	Stress Index	LF (ms^2)	HF (ms^2)	LF (nu)	HF (nu)	Ratio LF/HF
	Dunn's test post hoc										
DR-PRR	.105	.099	.904	.112	.235	.149	.386	.652	.51	.848	.818
DR-DET	.804	.857	.906	.553	.581	.691	.858	.621	.619	.935	.715
PRR-DET	.069	.075	.081	.334	.536	.310	.504	.967	.261	.791	.563
DR-DI	.791	.894	.993	.607	.791	.528	.225	.559	.720	.803	.607
PRR-DI	.060	.075	.092	.037 *	.148	.040 *	.041 *	.309	.314	.665	.466
DET-DI	.993	.959	.912	.275	.419	.313	.175	.289	.881	.872	.893
DR-PRI	.405	.379	.121	.207	.225	.173	.474	.607	.72	.596	.987
PRR-PRI	.416	.427	.863	.716	.991	.904	.863	.962	.755	.747	.806
DET-PRI	.291	.301	.105	.528	.531	.355	.605	.996	.399	.552	.727
DI-PRI	.272	.311	.119	.076	.139	.046 *	.053	.272	.474	.436	.618
DR-BASELINE	.082	.100	.072	.821	.379	.286	.388	.213	.708	.143	.544
PRR-BASELINE	<.001 ***	.0012 **	<.001 ***	.071	.041 *	.013 *	.088	.097	.307	.219	.72
DET-BASELINE	.151	.157	.103	.417	.160	.152	.309	.089	.893	.133	.340
DI-BASELINE	.141	.131	.073	.773	.538	.663	.726	.508	.987	.087	.263
PRI-BASELINE	.010 *	.011 *	<.001 ***	.137	.036 *	.015 *	.114	.078	.464	.350	.533

All HRV indicators were tested using Kruskal-Wallis tests and a Dunn's test post hoc. The p-values are indicated by asterisks.
p < .05 *.
p < .01 **.
p < .001 ***.

method accounts for the non-independence of repeated observations within participants. A correlogram plot, showing the relationship between the mental workload indicators and the times in Fig. 7. The correlation analysis revealed several significant associations. MD showed a positive correlation of $r = .62$ ($p < .001$). PD exhibited a positive correlation of $r = .57$ ($p < .001$). TD was positively correlated with $r = .7$ ($p < .001$). P displayed a positive correlation of $r = .44$ ($p < .01$). E showed a strong positive correlation of $r = .70$ ($p < .001$), and F also exhibited a positive correlation with $r = .54$ ($p < .001$). OW was positively correlated at $r = .68$ ($p < .001$) and SI displayed a positive correlation of $r = .40$ ($p = .016$). In contrast, SDNN showed a negative correlation of $r = -.42$ ($p = .013$), and LF was negatively correlated with $r = -.35$ ($p = .038$).

5. Discussion

This study examined the impact of mental workload across multiple dimensions during a maintenance task conducted in a real-world setting, including physical constraints. Our predictions focused on whether our measures could identify and quantify elevated mental workload across various maintenance activities conducted on a helicopter in a real-world maintenance environment. As a result, we have demonstrated that poorly accessed components would lead to an increase in mental workload, which would be reflected in longer maintenance task completion times. We also expected to see varying levels of perceived workload, reflecting distinct sources of workload associated with differing levels of task complexity. Lastly, we anticipated notable shifts in cardiovascular metrics, serving as indicators of autonomic nervous system activation. Through these measurements, we aimed to verify whether the indicators used in the multidimensional method, in a laboratory context (Berthon et al., 2024), could also be applied in an industrial context.

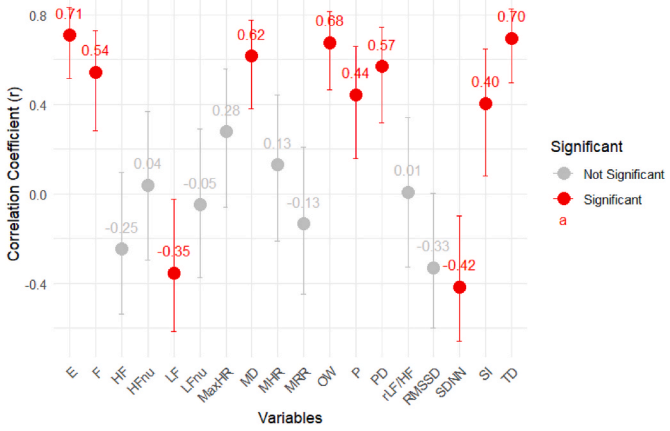

Fig. 7. Correlations between times and mental workload indicators.

5.1. Self-measurement and mental workload

Most of the workload factors in the NASA-TLX revealed significant differences across the five tasks. Clear differences between the various sources of subjective workload are highlighted between the damper and the pitch rod. For mental demand, frustration, and effort the high score in the detailed inspection task clearly indicates the complexity of this maintenance task, as well as the measurements of the mechanical play of the ball joints performed. All participants had significant difficulty following the procedure in an intuitive way. Regarding the pitch rod component, the removal and installation of this part generated significantly higher mental demand and frustration compared to the removal and installation of the damper. The same applies to the physical demand dimension, where the data does not change compared to mental demand, except for the detailed inspection task, where the physical demand of this task is much lower. As a result, the link between physical and mental demand is once again confirmed in maintenance activity (Sugiharto, 2019; Reason, 2020; Bernard et al., 2021; Berthon et al., 2024). For temporal demand, the more complex the task and the higher the workload, the more participants will overestimate the time required to complete their task (Baldauf et al., 2009). For performance, the highly significant difference between detailed inspection task and the other tasks is directly related to the uncertainty about achieving the correct mechanical play value by the participants, reflecting the complexity of the detailed inspection procedure. Finally, regarding overall workload, it transposes the different sources of workload and clearly distinguishes the differences between conditions. Especially since the installation tasks generally led to a higher overall workload compared to the removal tasks, these clear trends confirm our hypothesis about the subjective workload assessment. This is consistent with Reason's (2020) observations, which indicate that installation tasks in maintenance require a significantly higher workload and are more prone to errors than removal tasks. Although both systems have the same fastening systems, the visual and physical accessibility of the pitch rod is inadequate for an efficient human operation. This demonstrates that the design of this system, not conceived with the main user, can directly cause detrimental mental demand on the operator, as the design cannot always fully prioritize maintenance activities due to other priorities related to aerodynamics, hydraulics, and architecture (Bernard et al., 2020). The use of the NASA-TLX in our study highlighted the constraints caused by a design that is not suited to maintenance operators, while also demonstrating its diagnostic ability to identify weaknesses in a maintenance system from the user's perspective (Xie and Salvendy, 2000; Cegarra and Chevalier, 2008; Longo et al., 2022). This approach enhances communication with the design office to establish compromises and develop tailored recommendations focused on improving maintenance efficiency from a human-centered perspective. (Wickens, 2017; Yiannakides and Sergiou, 2019; Peach and Visser, 2020). In this case, there was difficulty in reaching the elements to be interacted with and an inability to remove the pitch rod independently.

5.2. Times completion and mental workload

Measuring operators' objective behavior in real-life situations is crucial and represents a first step toward predicting operator performance during operational scenarios that may directly impact aviation safety. Comparing a performance indicator with a subjective and/or physiological measure of mental workload is essential for understanding the complex interactions between humans and tasks (Dehais et al., 2020). The significant differences in completion time between the various tasks once again highlight the relevance of a performance indicator in measuring mental workload (Cain, 2007). We observe the same data pattern between the tasks as the results provided by the NASA-TLX, where installation tasks require significantly more time than removal tasks. Additionally, when comparing the completion time between the removal and installation of the damper with the pitch rod, we see a significantly larger gap for the pitch rod component. This is due to the design of the tail rotor, which does not facilitate efficient maintenance of this component by the operator. The completion time for the detailed inspection task simply reflects the complexity differences compared to the other four tasks. This follows the same pattern as the NASA-TLX results, which show that the detailed inspection tasks generally required a higher overall workload than the damper removal, pitch rod removal, and damper installation tasks. Furthermore, our analysis revealed several significant correlations between task completion time and certain mental workload indicators. Regarding the NASA-TLX, completion time was positively correlated with all measured dimensions. For the HRV measures, we observed a positive correlation between completion time and the SI, while two negative correlations were noted for SDNN and the LF component. So, all of these results confirmed our hypothesis that under challenging maintenance conditions, completion time significantly increased. This is why a complex system, such as that of aeronautical maintenance where the technician must disassemble and reassemble a large number of components, must be optimized to the maximum in order to improve interaction efficiency for all maintenance tasks on a helicopter. In our case, the evaluation of this performance indicator highlighted the suboptimal design of this system, which would facilitate the development of recommendations aimed at improving the design of new systems from the early stages of the design cycle in maintainability (Gramopadhye and Drury, 2000; Peach and Visser, 2020; Bernard et al., 2023).

5.3. Cardiovascular data and mental workload

Our objective was to analyze whether HRV indicators can detect and thus measure the variation in mental workload induced by a suboptimal maintenance component design compared to an optimal design. HRV measurements, associated with mental workload levels, reveal information about the activity of the sympathetic and parasympathetic nervous systems (SNS & PNS), which drive physiological responses in individuals (Kramer, 1990; Roeser et al., 2012; Paxion et al., 2014; Delliaux et al., 2019). Analysis in both time and frequency domains can indicate shifts in autonomic balance, showing whether SNS or PNS influence is stronger, often in response to cognitive demands, emotional states, or stress (Kostenko, 2017; Dehais et al., 2020; Li et al., 2022). Among the time-domain indicators, several HRV measures reveal valuable data across different maintenance tasks. While the literature generally agrees that an increase in mental workload tends to activate the SNS and/or inhibit the PNS, this effect may be observed in the time domain as an increase in MHR, Max HR, and SI, along with a decrease in MRR, SDNN, and RMSSD (Fairclough et al., 2005; Durantin et al., 2014; Paxion et al., 2014; Shaffer and Ginsberg, 2017; Delliaux et al., 2019; Dehais et al., 2020; Fan et al., 2020; Li et al., 2022). In line with our other measurements, compared to the BASELINE, we observe significant differences with pitch rod removal and pitch rod installation for HRV indicators such as MRR, MHR, Max HR, RMSSD, and SI, but no significant differences with DI, DR, and detailed inspection. Regarding the SDNN and RMSSD indicators, in short-term measurements, these reflect PNS activity. Therefore, a decrease in these values indicates inhibition of the parasympathetic branch and, inversely, activation of sympathetic activity due to a significant, stress or mental workload (Shaffer and Ginsberg, 2017; Pham et al., 2021; Salazar-Martínez et al., 2024). This leads us to confirm that the pitch rod removal and pitch rod installation tasks triggered a higher SNS activation than the damper removal and damper installation tasks, which is consistent with the results from the subjective workload assessment and our performance indicator. Moreover, when comparing the tasks, for the pitch rod removal and damper installation combination, we observe a significant difference for the SDNN and SI indicators in the time domain. Finally, for the damper installation and pitch rod installation combination, we also observe a significant difference for the SI indicator, which is calculated from RR interval data (median, minimum, maximum, and histogram) and reflects the sympathetic branch activity of the autonomic nervous system (Quendler et al., 2017; Awad et al., 2022). Regarding the frequency domain, among the HRV measurements, only the LF indicator for the pitch rod removal and damper installation combination showed a significant difference, which is still correlated in our results with the SDNN and SI indicators in the time domain for this combination. Otherwise, despite clear trends when comparing with the BASELINE for the tasks related to the removal and installation of the pitch rod, no other task reflected a significant difference for the LF, HF, LFnu, HFnu, and rLF/HF indicators. As for the lack of significant results for the detailed inspection task, this could be explained by a lower proportion of physical activity in this task, which involves a detailed check on the table as well as measuring the mechanical play of the two components' ball joints. However, despite the absence of significant differences, clear trends were identified for the detailed inspection for the SDNN, RMSSD, SI, and HF indicators. Despite this, these results further confirm our hypothesis, as they are also in agreement with the qualitative feedback expressed by the technician participants during the experiment, several expressed their frustration with the task of removing and installing the pitch rod. Additionally, for the detailed inspection, measuring the mechanical play of the ball joints with the comparator positioning, along with the lack of information in the manufacturer's manual, also contributed to mental workload for the participants. However, this aspect was not clearly reflected in the cardiovascular measures obtained. In general, the lack of optimization in the design of this component, focused on the user, encourages this type of reaction, which can lead to a decrease in the operator's attention and potentially reduce their performance, thereby increasing the risk of a serious maintenance error that could jeopardize the helicopter's safety (Wickens, 2017).

5.4. General discussion - assessment of mental workload in maintainability

This study presents an interesting continuity in the ability of this multidimensional combination of tools to measure and diagnose the mental workload of maintenance operators in an operational context. Each measurement tool provides a level of detail that allows for identifying the constraints experienced by maintenance operators depending on the type of interaction. Adopting a more analytical approach aimed at identifying the most discriminant mental workload indicators among our various measures, it is notable that the 'mental demand,' 'frustration,' and 'overall workload' dimensions exhibit the largest effect sizes. These indicators are thus shown to be more sensitive than temporal and HRV measures, even despite the significant differences also observed with these latter measures between the various tasks. Regarding our measurement tools, the NASA-TLX once again is useful for identifying the various sources of workload across the multiple types of operational maintenance tasks, thus facilitating the collection of operators' perceptions to quantify the strains generated by the constraints. Regarding completion time measurement, it is essential to monitor a performance indicator to correlate it with mental workload measures, thereby enhancing the reliability of the conclusions drawn from our various measurement types (Young et al., 2015; Dehais et al., 2020). In the context of considering inter- and intra-individual characteristics, HRV measurement is helpful for assessing individuals' mental workload. Although the physical aspect of maintenance activities prevents a complete isolation of mental workload when measured using cardiovascular tools, several studies have highlighted the relationship between mental workload and postural/physical workload, indicating that it is currently difficult to isolate the measurement of mental workload in an operational context. Indeed, constraining postural demands or degraded visual accessibility, inherent in certain complex assembly tasks such as those we used, can induce additional mental workload. This additional mental workload is linked to the need to plan and execute precise movements in non-optimal physical or visual conditions, to manage postural balance, and to the increased visuo-spatial attention required, potentially diverting cognitive resources from the main assembly task and influencing mental workload measurements. Degraded visual accessibility and postural demands have been shown to lead to a higher mental workload, thus decreasing task performance (Kahya et al., 2018; Kang et al., 2021). Furthermore, the study by Biondi and colleagues (2021) in a complex assembly condition showed an increase in muscle activity alongside indicators of mental workload. In addition, the NASA-TLX helps overcome the limitation of HRV in isolating cognitive behavior by providing diagnostic information on the cognitive aspects. Within this framework, our results provide empirical insight into the specific application of HRV measurement in operational contexts that combine physical and mental workloads, which is typical of maintenance activities. Our observations suggest that while HRV is a valuable tool, its sensitivity to physiological variations induced by physical exertion can complicate the precise isolation of the mental workload component. This finding highlights a potential limitation of cardiovascular measures in such scenarios and calls for a cautious interpretation of the results. Building on this, our study specifically highlighted differences between two tasks that involved similar maintenance actions but were subjected to distinct physical and visual accessibility constraints, as revealed by these measurements. Regarding the potential generalization of our findings to tasks not directly investigated in this study, several elements are important to consider. The observations derived from our analysis provide valuable insights that can now guide the design of maintenance processes with a stronger focus on human factors. Indeed, highlighting the specific difficulties associated with certain task configurations enables targeted ergonomic improvements. Furthermore, our results significantly illuminate the impact of the physical and visual accessibility of a component on operator performance. The observed correlation between suboptimal accessibility and performance degradation underscores the crucial importance of this aspect in the design of maintenance procedures. Nevertheless, it is important to note an inherent limitation due to the specificity of our study. The conclusions we draw, rooted in the particular context of aeronautical maintenance tasks, cannot be directly transposed to guide the design of systems that do not share fundamental characteristics with this application domain. Thus, in the context of analyzing and quantifying human factors, cardiovascular measurements could be relevant for assessing both physical and mental strain during maintenance activities in operational settings (Abdul Samad et al., 2022 Berthon et al., 2024). However, despite clearly identified differences, we are not yet able to perfectly dissociate physical strain from mental strain. In cases where a maintenance task involves minimal physical activity, interpreting results related to mental workload becomes more effective. Conversely, when a maintenance task is predominantly physical, cardiovascular variations caused by this activity are not solely attributed to physical effort, as every task inherently involves mental activity (DiDomenico and Nussbaum, 2011; Mehta and Agnew, 2012). Furthermore, in addition to cardiovascular measures, the use of subjective and performance evaluation methods helps mitigate this limitation. Moreover, this combination of tools highlights the versatility in detecting both physical and mental workload of this approach across various types of maintenance tasks, whether it involves removal operations, installations, or detailed inspections, both in operational settings and laboratory environments.

5.5. Limits & perspectives

The study has certain limitations. As previously mentioned, one of the main limitations of heart rate variability measurements is their ability to isolate mental workload. This ability to dissociate physical and mental strain depends on the proportion of physical activity involved in the analyzed task. Moreover, considering the identified sensitivity of HRV to physical exertion as a potential confounding factor, it would be interesting to continue research in this area by exploring and validating the use of alternative physiological measurement tools inherently less susceptible to variations induced by physical activity. The adoption of such indicators could allow for a more specific targeting of mental effort assessment in complex and physically demanding tasks like aeronautical maintenance, thus contributing to a more precise and isolated understanding of mental workload. Furthermore, to enhance the measurement of nervous system activity, it could be beneficial to incorporate neurophysiological measures, provided that signal noise sources can be significantly reduced in a field maintenance context. The use of ocular measurements could also prove relevant for identifying and analyzing the visual behavior of maintenance operators subjected to the effects of detrimental mental workload. Ultimately, therefore, the identification of relevant mental workload indicators in maintenance will enable the design of methods for combining mental workload indicators to improve the reliability of cognitive data measurements from maintenance operators, with the aim of enhancing complex systems. Similarly, the number of participants in this study represents another limitation, due to the difficulty of mobilizing people in this constrained industrial context. Looking ahead, for this line of research, it would be necessary to solidify the obtained statistical results by including more participants of the same gender to enhance the reliability of the HRV data. It would also be beneficial to broaden the sample to other categories of users based on age, expertise level, or gender. This is why, in a context where the number of participants could be greater, it would be interesting to evaluate mental workload across multiple representative maintenance tasks to further strengthen the versatility of this combination of measurement tools.

6. Conclusion

Our findings indicate that this multidimensional approach was effective in assessing mental workload within a real-world operational maintenance context. This study represents a further advancement in the combined use of diverse tools and measurement methods to comprehensively diagnose the factors that increase mental workload and significantly reduce performance. It is crucial for system designers and aircraft manufacturers to understand the various forms of human fallibility and the unpredictability of maintenance tasks, especially during disassembly and installation operations (Reason, 2020). They must recognize that while maintenance is essential for safety, it also carries risks. Until systems are designed with these challenges in mind, human errors will continue to cause serious accidents. It's clear that external factors beyond the maintenance tasks themselves, such as team organization, human and material resources, the working environment, and time pressure, can directly impact operators' mental workload (Santos and Melicio, 2019; Sugiharto, 2019; Peach and Visser, 2020). Assessing the effectiveness of their interaction with the future maintenance system early in the design phase is now essential to create a system truly suited to its users. This approach would also help mitigate the impact of external factors on the mental workload imposed by operational maintenance. As part of our effort to integrate HFE throughout the maintainability design cycle, validating this multidimensional mental workload measurement approach in an operational context is a further step towards a comprehensive anticipation of cognitive behaviors in maintenance. The next step will be to replicate this experiment in a virtual reality simulation to deepen our assessment and anticipation of maintenance operators' cognitive behavior.

CRediT authorship contribution statement

Lorrys Berthon: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Fabien Bernard:** Supervision. **Sylvain Fleury:** Supervision. **Raphaël Paquin:** Supervision. **Simon Richir:** Supervision.

Declaration of competing interest

The author is an Editorial Board Member/Editor-in-Chief/Associate Editor/Guest Editor for this journal and was not involved in the editorial review or the decision to publish this article.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: No financial/personal interest is likely to affect the objectivity of this study.

APPENDIX

Note: The descriptive technical drawings (referred to as "Figdure" in the text) will not be available here due to industrial confidentiality reasons.

Damper removal (DR)

1) Unsafety the bolts (4) and (9) and discard the split pins (2) and (7).
2) On the blade side, remove the nut (6), the washer (8) and the bolt (4).
3) On the shaft side, remove the nut (3), the lug of the electrical bonding braid support (11) and the bolt (9) equipped with the balancing washers.
4) Remove the lead-lag damper (1).

Damper installation (DI)

1) Install the damper (1).
2) On the shaft side, install the bolt (9) equipped with the balancing washers as identified during removal.
3) Place the nut (3).
4) Tighten the nut (3) to the specified torque.
5) On the blade sleeve side, place the bolt (4), the washer (8), and the nut (6).
6) Tighten the nut (6) to the specified torque.
7) Secure the nut (3) with the pin (2) and the nut (6) with the pin (7).

Detailed inspection (DET)

Pitch rod inspection

1) Make sure that there are no:
   - Corrosion
   - Impact marks
   - Scratches
2) Make sure that there are no cracks.
3) Make sure that the dimension "X" is between 18.72 mm and 18.74 mm (.73701 in and .73779 in) and that the diameter "Y" is between 10 mm and 10.015 mm (.39371 in and .39429 in) (Figdure 3).
4) Measure the axial play of the spherical bearings with the comparator for clearances and tolerances [703A94-0000-00].
   - When an axial play of the spherical bearing on the pitch horn side reaches .12 mm (.0047 in), install the rod with the play of .12 mm (.0047 in) on the control plate side. If both spherical bearings have an axial play greater than .12 mm (.0047 in), install the spherical bearing which has the greatest play on the control plate side. If the axial play is greater than .15 mm (.0059 in), the play measurement inspection gap as per sub-task 64-20-00-221-021 of MMA 64-20-00-211 must be divided by two (refer to MSM). Discard if the play is greater than or equal to .25 mm (.0098 in).
5) On the upper and lower attachment screws (3) Figdure 7, make sure that there are no:
   - Corrosion
   - Fretting
6) On the upper and lower attachment screws (3), make sure that there are no cracks.

Damper inspection

1) On the frame, make sure that there are no:
   - Impact marks, scratches or cracks
   - Corrosion, spalling or fretting, especially on the mating surfaces
2) Make sure that there are no cracks.
3) On the end fitting, locknut and nut retainer, make sure that there are no:
   - Impact marks or scratches
   - Corrosion, spalling or fretting, especially on the mating surfaces
4) Make sure that there are no cracks on the end fitting.
5) Measure the axial play of the spherical bearing with the comparator for clearances and tolerances [703A94-0000-00].
   - If the axial play is greater than .15 mm (.0059 in), the play measurement inspection gap as per sub-task 64-20-00-221-091 of MMA 64-20-00-211 must be divided by two (refer to MSM). Replace the ball end fitting as if the axial play is greater than or equal to .25 mm (.0098 in).

Pitch rod removal (PRR)

Figd. 1.

1) Position the control plate (4) to reach the bolt (11) through the opening (3) of the tapered shaft (5).
2) On the control plate (4) side:
3) remove the split pin (7), the nut (8), the washer (9) and the bolt (11),

4) discard the split pin (7),
5) remove the pitch rod (2) from the control plate (4).
6) Removal of the yoke (5): (Figdure 2)
7) Remove the split pin (7), the nut (8), and the washer (6),
8) Discard the split pin (7).
9) Removal of the pitch rod (2) from the yoke (1): (Figdure 1)
10) Remove the pin (13), the nut (14), the washer (15), and the bolt (6),
11) Discard the split pin (13).

Pitch rod installation (PRI)

Figd. 1.

1) Installation of the yoke on the link:
2) Place the split pin (6) of the yoke (1) in the link on the blade side,
3) Place the washer (15) and the nut (14),
4) Tighten the nut (14) to the specified torque and secure with a split pin (13).
5) Installation of the link with yoke on the spherical bearing:

Figd. 2.

6) Fix the applied end fitting (5) in the spherical stop, place the washer (6) and the nut (8),
7) Tighten the nut (8) to the specified torque and secure with a split pin (7).
8) Control plate side (4) (Figdure 1):
9) Place the pitch rod (2) on the control plate (4),
10) Place the split pin (11), the washer (9), and the nut (8),
11) Tighten the nut (8) to the specified torque,
12) Install the split pin (7)

References

Abdul Samad, A.G., Azizan, M.A., Khairuddin, M.H., Johari, M.K., 2022. Effect of mental workload on heart rate variability and reaction time of aircraft maintenance personnel. In: Human-Centered Technology for a Better Tomorrow: Proceedings of HUMENS 2021. Springer, Singapore, pp. 613–625. https://doi.org/10.1007/978-981-16-4115-2_50.

Awad, G., Pohl, R., Darius, S., Thielmann, B., Varghese, S., Wacker, M., et al., 2022. Activation of the stress response among the cardiac surgical residents: comparison of teaching procedures and other (daily) medical activities. J. Cardiothorac. Surg. 17 (1), 112. https://doi.org/10.1186/s13019-022-01873-z.

Bakdash, J.Z., Marusich, L.R., 2017. Repeated measures correlation. Front. Psychol. 8, 456. https://doi.org/10.3389/fpsyg.2017.00456.

Baldauf, D., Burgard, E., Wittmann, M., 2009. Time perception as a workload measure in simulated car driving. Appl. Ergon. 40 (5), 929–935. https://doi.org/10.1016/j.apergo.2009.01.004.

Bernard, F., Zare, M., Sagot, J.C., Paquin, R., 2020. Using digital and physical simulation to focus on human factors and ergonomics in aviation maintainability. Hum. Factors 62 (1), 37–54. https://doi.org/10.1177/001872081986149.

Bernard, F., Zare, M., Murie, C., Sagot, J.-C., 2021. Dimensions physiques et cognitives : vers une nécessaire prise en compte en maintenabilité aéronautique. Archives des Maladies Professionnelles et de l'Environnement. https://doi.org/10.1016/j.admp.2020.10.004.

Bernard, F., Zare, M., Paquin, R., Sagot, J.C., 2023. A new approach for human factors integration into design for maintenance: a case study in the aviation industry. Int. J. Hum. Factors Ergon. 10 (2), 144–164. https://doi.org/10.1504/IJHFE.2023.130537.

Berthon, L., Bernard, F., Fleury, S., Paquin, R., Richir, S., 2024. Mental workload: a prerequisite for future maintenance design. In: Human Factors and Simulation, 139. AHFE. Human Factors and Simulation, pp. 65–74. https://doi.org/10.54941/ahfe1005025, 2024, 65.

Biondi, F.N., Cacanindin, A., Douglas, C., Cort, J., 2021. Overloaded and at work: investigating the effect of cognitive workload on assembly task performance. Hum. Factors 63 (5), 813–820. https://doi.org/10.1177/0018720820929928.

Cain, B., 2007. A Review of the Mental Workload Literature. DTIC Document.

Cegarra, J., Chevalier, A., 2008. The use of Tholos software for combining measures of mental workload: toward theoretical and methodological improvements. Behav. Res. Methods 40 (4), 988–1000. https://doi.org/10.3758/BRM.40.4.988.

Castaldo, R., Montesinos, L., Wan, T.S., Serban, A., Massaro, S., Pecchia, L., 2017. Heart rate variability analysis and performance during a repeated mental workload task. In: EMBEC & NBC 2017: Joint Conference of the European Medical and Biological Engineering Conference (EMBEC) and the Nordic-Baltic Conference on Biomedical Engineering and Medical Physics (NBC). Springer, Singapore, pp. 69–72. https://doi.org/10.1007/978-981-10-5122-7_18. Tampere, Finland, June 2017.

Cegarra, J., 2012. De la gestion de la complexité à son assistance: Contributions en psychologie ergonomique. Unpublished habilitation à diriger des recherches). Université de de Toulouse II-Le Mirail. Toulouse, France.

Charles, R.L., Nixon, J., 2019. Measuring mental workload using physiological measures: a systematic review. Appl. Ergon. 74, 221–232. https://doi.org/10.1016/j.apergo.2018.08.028.

Dehais, F., Lafont, A., Roy, R., Fairclough, S., 2020. A neuroergonomics approach to mental workload, engagement and human performance. Front. Neurosci. 14, 268. https://doi.org/10.3389/fnins.2020.00268.

Delliaux, S., Delaforge, A., Deharo, J.C., Chaumet, G., 2019. Mental workload alters heart rate variability, lowering non-linear dynamics. Front. Physiol. 10, 565. https://doi.org/10.3389/fphys.2019.00565.

Dhillon, B.S., 1999. Engineering Maintainability: How to Design for Reliability and Easy Maintenance. Gulf Professional Publishing.

DiDomenico, A., Nussbaum, M.A., 2011. Effects of different physical workload parameters on mental workload and performance. Int. J. Ind. Ergon. 41 (3), 255–260. https://doi.org/10.1016/j.ergon.2011.01.008.

Di Nocera, F., Camilli, M., Terenzi, M., 2007. A random glance at the flight deck: pilots' scanning strategies and the real-time assessment of mental workload. J. Cogn. Eng. Decis. Mak. 1 (3), 271–285. https://doi.org/10.1518/155534307X2556.

Durantin, G., Gagnon, J.F., Tremblay, S., Dehais, F., 2014. Using near infrared spectroscopy and heart rate variability to detect mental overload. Behav. Brain Res. 259, 16–23. https://doi.org/10.1016/j.bbr.2013.10.042.

Fairclough, S.H., Venables, L., Tattersall, A., 2005. The influence of task demand and learning on the psychophysiological response. Int. J. Psychophysiol. 56 (2), 171–184. https://doi.org/10.1016/j.ijpsycho.2004.11.003.

Fan, X., Zhao, C., Zhang, X., Luo, H., Zhang, W., 2020. Assessment of mental workload based on multi-physiological signals. Technol. Health Care 28 (S1), 67–80. https://doi.org/10.3233/THC-209008.

Gramopadhye, A.K., Drury, C.G., 2000. Human factors in aviation maintenance: how we got to where we are. Int. J. Ind. Ergon. 26 (2), 125–131. https://doi.org/10.1016/S0169-8141(99)00062-1.

Hart, S.G., Staveland, L.E., 1988. Development of NASA-TLX (task load index): results of empirical and theoretical research. In: Human Mental Workload. Elsevier. https://doi.org/10.1016/S0166-4115(08)62386-9.

Heart rate variability: standards of measurement, physiological interpretation and clinical use. Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology. Circulation 93 (5), 1996, 1043–1065. https://doi.org/10.1161/01.CIR.93.5.1043. PMID: 8598068.

Hobbs, A., Williamson, A., 2002. Skills, rules and knowledge in aircraft maintenance: errors in context. Ergonomics 45 (4), 290–308. https://doi.org/10.1080/00140130110116100.

Hobbs, A., 2021. Aircraft Maintenance and Inspection.

IPSOS, 2024. Baromètre Sport-Santé 2024 de la fédération française d'éducation physique et de gymnastique volontaire. Retour sur plus de 10 ans de pratique sportive des français. Retrieved April 10, 2025, from. https://www.ipsos.com/sites/default/files/ct/news/documents/2024-04/Barometre_Sport_Sante_Janvier_2024.pdf.

Kostenko, A.S., 2017. Évaluation multidimensionnelle et dynamique de la maitrise de la situation par l'opérateur: création d'un indicateur temps réel de charge mentale pour l'activité de supervision de drones. Doctoral dissertation, Université de Bretagne Sud) 1, 0–253.

Kahya, M., Wood, T.A., Sosnoff, J.J., Devos, H., 2018. Increased postural demand is associated with greater cognitive workload in healthy young adults: a pupillometry study. Front. Hum. Neurosci. 12, 288. https://doi.org/10.3389/fnhum.2018.00288.

Kang, S.H., Lee, J., Jin, S., 2021. Effect of standing desk use on cognitive performance and physical workload while engaged with high cognitive demand tasks. Appl. Ergon. 92, 103306. https://doi.org/10.1016/j.apergo.2020.103306.

Kramer, A.F., 1990. Physiological metrics of mental workload: a review of recent progress. Multiple task performance 279–328.

Li, W., Li, R., Xie, X., Chang, Y., 2022. Evaluating mental workload during multitasking in simulated flight. Brain and Behavior 12 (4), e2489. https://doi.org/10.1002/brb3.2489.

Longo, L., 2015. A defeasible reasoning framework for human mental workload representation and assessment. Behav. Inf. Technol. 34 (8), 758–786. https://doi.org/10.1080/0144929X.2015.1015166.

Longo, L., Wickens, C.D., Hancock, G., Hancock, P.A., 2022. Human mental workload: a survey and a novel inclusive definition. Front. Psychol. 13, 883321. https://doi.org/10.3389/fpsyg.2022.883321.

Luzzani, G., Buraioli, I., Demarchi, D., Guglieri, G., 2024. A review of physiological measures for mental workload assessment in aviation: a state-of-the-art review of mental workload physiological assessment methods in human-machine interaction analysis. Aeronaut. J. 128 (1323), 928–949. https://doi.org/10.1017/aer.2023.101.

Matuz, A., van der Linden, D., Kisander, Z., Hernadi, I., Kazmer, K., Csatho, A., 2021. Enhanced cardiac vagal tone in mental fatigue: analysis of heart rate variability in Time-on-Task, recovery, and reactivity. PLoS One 16 (3), e0238670. https://doi.org/10.1371/journal.pone.0238670.

Mehta, R.K., Agnew, M.J., 2012. Influence of mental workload on muscle endurance, fatigue, and recovery during intermittent static work. Eur. J. Appl. Physiol. 112, 2891–2902. https://doi.org/10.1007/s00421-011-2264-x.

Meshkati, N., 1988. Heart rate variability and mental workload assessment. In: Advances in Psychology, 52. North-Holland, pp. 101–115. https://doi.org/10.1016/S0166-4115(08)62384-5.

Nkosi, M., Gupta, K., Mashinini, M., 2020. Causes and impact of human error in maintenance of mechanical systems. In: MATEC Web of Conferences, 312. EDP Sciences, 05001. https://doi.org/10.1051/matecconf/202031205001.

Ognev, A.S., Zernov, V.A., Likhacheva, E.V., Nikolaeva, L.P., Rudenko, M.Y., Dymarchuk, D.D., et al., 2019. Cardiometric detection of effects and patterns of emotional responses by a human individual to verbal, audial and visual stimuli. Cardiometry 14, 79–86. https://doi.org/10.12710/cardiometry.2019.14.7986.

Pham, T., Lau, Z.J., Chen, S.A., Makowski, D., 2021. Heart rate variability in psychology: a review of HRV indices and an analysis tutorial. Sensors 21 (12), 3998. https://doi.org/10.3390/s21123998.

Paxion, J., Galy, E., Berthelon, C., 2014. Mental workload and driving. Front. Psychol. 5, 1344. https://doi.org/10.3389/fpsyg.2014.01344.

Peach, R.H., Visser, J.K., 2020. Measuring human factors in maintenance: a literature review. S. Afr. J. Ind. Eng. 31 (4), 104–114. https://doi.org/10.7166/31-4-2325.

Quendler, E., Trieb, K., Nimmerichter, A., 2017. Validation of automated detection of physical and mental stress during work in a Huhnermobil 225. Ann. Agric. Environ. Med. 24 (2). https://doi.org/10.5604/12321966.1235183.

Rashid, H.S.J., 2010. Human factors effects in helicopter maintenance: proactive monitoring and controlling techniques. http://hdl.handle.net/1826/4497.

Reason, J., 2020. Maintenance-related errors: the biggest threat to aviation safety after gravity?. In: Aviation Safety, Human Factors-System Engineering-Flight Operations-Economics-Strategies-Management. CRC Press, pp. 465–470.

Roeser, K., Obergfell, F., Meule, A., Vögele, C., Schlarb, A.A., Kübler, A., 2012. Of larks and hearts—morningness/eveningness, heart rate variability and cardiovascular stress response at different times of day. Physiol. Behav. 106 (2), 151–157. https://doi.org/10.1016/j.physbeh.2012.01.023.

Salazar-Martínez, E., Naranjo-Orellana, J., Sarabia-Cachadiña, E., 2024. Heart rate variability: obtaining the stress score from SDNN values. Isokinet. Exerc. Sci. 32 (4), 301–307. https://doi.org/10.3233/IES-230088.

Santos, L., Melicio, R., 2019. Stress, pressure and fatigue on aircraft maintenance personal. http://hdl.handle.net/10174/26911.

Shaffer, F., Ginsberg, J.P., 2017. An overview of heart rate variability metrics and norms. Front. Public Health 5, 258. https://doi.org/10.3389/fpubh.2017.00258.

Sirevaag, E.J., Kramer, A.F., Reisweber, C.D.W.M., Strayer, D.L., Grenell, J.F., 1993. Assessment of pilot performance and mental workload in rotary wing aircraft. Ergonomics 36 (9), 1121–1140. https://doi.org/10.1080/00140139308967983.

Sugiharto, F.M., 2019. The Relationship between Mental Workload and Occupational Stress among Aircraft Maintenance Officers at PT X Hubungan Beban Kerja Mental dengan Stres Kerja pada Tenaga Kerja Bagian Perawatan Pesawat di PT X. The Indonesian Journal of Occupational Safety and Health 8 (2), 233–239.

Tao, D., Tan, H., Wang, H., Zhang, X., Qu, X., Zhang, T., 2019. A systematic review of physiological measures of mental workload. Int. J. Environ. Res. Publ. Health 16 (15), 2716. https://doi.org/10.3390/ijerph16152716.

Team, R.C., 2020. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria, 2020.

Tiwari, A., Cassani, R., Gagnon, J.F., Lafond, D., Tremblay, S., Falk, T.H., 2020. Prediction of stress and mental workload during police academy training using ultra-short-term heart rate variability and breathing analysis. In: 2020 42nd Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC). IEEE, pp. 4530–4533. https://doi.org/10.1109/EMBC44109.2020.9175414, 4530-4533.

Wickens, C.D., 2017. Mental workload: assessment, prediction and consequences. In: Human Mental Workload: Models and Applications: First International Symposium, H-WORKLOAD 2017, Dublin, Ireland, June 28-30, 2017, Revised Selected Papers 1. Springer International Publishing, pp. 18–29. https://doi.org/10.1007/978-3-319-61061-0_2.

Xie, B., Salvendy, G., 2000. Prediction of mental workload in single and multiple tasks environments. Int. J. Cognit. Ergon. 4 (3), 213–242. https://doi.org/10.1207/S15327566IJCE0403_3.

Yerkes, R.M., Dodson, J.D., 1908. The Relation of Strength of Stimulus to Rapidity of Habit-Formation.

Yiannakides, D., Sergiou, C., 2019. Human Factors in Aircraft Maintenance. CRC Press.

Young, M.S., Brookhuis, K.A., Wickens, C.D., Hancock, P.A., 2015. State of science: mental workload in ergonomics. Ergonomics 58 (1), 1–17. https://doi.org/10.1080/00140139.2014.956151.

Zaki, R., Barabadi, A., Qarahasanlou, A.N., Garmabaki, A.H.S., 2019. A mixture frailty model for maintainability analysis of mechanical components: a case study. International Journal of System Assurance Engineering and Management 10, 1646–1653. https://doi.org/10.1007/s13198-019-00917-3.