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Mental Workload: A Prerequisite for Future Maintenance Design

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ABSTRACT

Maintenance is a technical and complex activity which involves risks and can lead to workplace accidents or even affect flight safety. To improve performance and working conditions, Human Factors & Ergonomics (HFE) can be used to anticipate and optimize the interaction between operators and system components in terms of maintainability. Studies have already highlighted the necessity to assess physical workload, as a criteria impacting performance and working conditions. However, this is not the only workload that maintenance operators experience. The mental workload, if not taken into account, can have negative consequences on maintenance activity and can lead to human errors which can pose a serious threat to system safety. However, in maintainability, it seems that no certified method for measuring mental workload has yet emerged. Therefore, anticipating the assessment of these dimensions provides a better collaboration with the design office, and as such improves the integration of HFE recommendations throughout the design cycle. The use of digital simulation tools makes it possible to anticipate maintainability and would encourage the study of the relationship between the operator and the maintenance environment. This paper will detail in which context the measurement of mental workload is crucial in the design of maintenance and will define what could be the most suitable method for measuring mental workload for maintenance activity. These data will ultimately allow us to improve the anticipation of human errors in maintenance in order to design more robust and fault-tolerant systems to ensure the protection of the physical and mental integrity of the workers and aviation safety.

Keywords: Mental workload, Human factors, Maintenance, Maintainability, Digital simulation tools

INTRODUCTION

The European Agency for Safety and Health at Work (2010) states that 15–20% of workplace accidents are maintenance-related, and 10–15% of these incidents result in fatalities. Due to the specialized expertise and knowledge required, maintenance activities induce significant occupational stress (Sugiharto, 2019). Maintenance represents complex and technical tasks involving potential risks that can lead to incidents and accidents, threatening the safety of operators and systems. Recognizing the necessity of evaluating physical workload becomes imperative for enhancing performance and working conditions, aiming at effective anthropocentric design (Bernard et al., 2021). However, considering the mental workload in advance during the design phase is equally important. The succession of maintenance tasks, whether simple or complex, demands mental resources such as decision-making, memory, and attention. The link between physical and mental workload exists within the activity, the individual and the surrounding environment with which they interact (Causse & Dehais, 2010; Sugiharto, 2019; Bernard et al., 2020). Taking into account Human Factors & Ergonomics (HFE) during the design cycle allows for the anticipation and optimization of interactions between operators and system components in terms of maintainability. In order to better anticipate, simulating maintenance tasks in an immersive environment, using digital simulation tools (Virtual Reality, Augmented Reality, Mixed Reality), and physical simulation (mock-up), encourages the exploration of the relationship between the user and the maintenance environment (Chedmail, 2002; Zwingmann, 2005; Bernard et al., 2020). On the cognitive side, the measurement of mental workload for maintenance design purposes is not deeply studied in the literature. Only few studies introduce a subjective assessment (Bernard et al., 2020). It is undisputed that the evaluation of HFE must take account the workload from a multidisciplinary point of view, but the cognitive aspect deserves to be studied in more detail. In this study, we are interested in optimizing the assessment of mental workload of maintenance activities, a key element in the study of HFE that could influence the design cycle in maintainability. Therefore, we will present the various existing methods for measuring mental workload and how these methods need to be adapted based on the constraints of maintenance activities (physical constraints, work organization, environmental constraints). This method will precisely and efficiently measure the mental workload of a maintenance operator while taking into account the constraints linked to their activity.

EFFICIENT MAINTAINABILITY FOR SAFE MAINTENANCE

Maintenance Activity

Maintenance includes all technical, administrative, and management operations necessary to ensure or restore a property, equipment, or installation to a level that allows it to perform its function (INRS, 2023a). Maintenance operators work in a riskier environment than most other professions. This work requires physical strength, agility, balance, and diverse technical skills (Sugiharto, 2019; Bernard et al., 2020; Hobbs, 2021). Maintenance tasks can also occur under demanding working conditions (temperature variations, height work, restricted spaces, poorly designed documentation, etc.) which can increase workload and cause professional stress (Hobbs & Williamson, 2003; Sugiharto, 2019). In his study, Sugiharto (2019) outlined that 73.2% of maintenance agents reported a significant mental workload. In detail, maintenance operators in the aviation sector operate in demanding environments, requiring their physical and mental abilities, under constant workload and pressure. The operators' health and safety becomes increasingly important in the future of maintenance design (Bernard et al., 2020). Maintenance activities can be divided into two main categories (INRS, 2023a):

- Preventive maintenance: carried out at specific times to minimize the risks of deterioration or failure of the equipment;
- Corrective maintenance: undertaken following the detection of a failure with the aim of restoring the equipment to a functional state.

To optimize the quality and efficiency of maintenance, it is essential to understand the skills and limitations of maintenance operators during task execution. Sometimes, failures in maintenance quality may go undetected for months or even years until they are discovered or lead to an operational incident (Hobbs et al., 2021). Anticipating the operators' interaction with the maintenance environment will facilitate the progress of future maintenance activities and improve operator safety. However, to achieve this, it is crucial to understand and diagnose the workload that an operator may experience during their activity.

Maintenance Workload

The concept of workload has two aspects: constraint and strain. Constraint generally refers to a factor or set of factors external to the task itself, while strain represents the resultant, i.e., the "cost" linked to the effects of this constraint on the individual (DIN FR ISO 10075–1: 2017). Workload can be classified into two categories: physical workload and mental workload (Sperandio, 1987; Sugiartho, 2019).

- Physical workload: caused by efforts, postures, movements, and carrying loads due to the operator's activity;
- Mental workload: caused by reflections, memorization, and planning due to the operator's activities.

Workload can be affected by the complexity of the task, temporal pressure, work time, rest time, posted work, task succession, and the work environment (Hobbs & Williamson, 2003). These interdependent factors can be symptoms of an activity generating stress or fatigue and can therefore lead to the occurrence of dangerous acts, contributing to errors on the part of maintenance operators (Yiannakides & Sergiou, 2019). In conditions where mental workload levels are reduced (underload), operators may see their concentration capabilities deteriorate and not ensure the necessary performance level (Delignières & Deschamps, 2000). Mental workload and stress are both related. Stress is present when there is an imbalance between the demands of the environment and a person's individual capacities. It refers to the emotional tension associated with a state of anxiety in response to the threat of an unpredictable negative event over which the individual has no control (Mandrick et al., 2016). Therefore, it could be suggested that stress in maintenance comes from three main factors (Yiannakides & Sergiou, 2019):

- **The operator** refers to the personal characteristics, culture, resources of the operator. But also the technical skills and knowledge;
- **The task** refers to the type of work, its complexity, its repetitiveness and the temporal constraints related to it;

- **The environment** refers to the social interactions in the work environment, the material and ambient conditions of the workplace.

The Role of Maintainability

Maintainability is defined as the ability of an element, under specific conditions of use, to be preserved or restored to a state that allows it to perform a required function, provided that maintenance is carried out under defined conditions (Dhillon, 1999; Zaki et al., 2019). In other words, maintainability is a part of the design office defining the future maintenance. Poorly studied maintainability is likely to lead directly or indirectly to maintenance errors. Examples of poor designs include (Hobbs et al., 2021):

- Difficult-to-reach components;
- Obstruction to vision due to the position of the components;
- Incorrectly installed components.

HFE play an important role in both intrinsic and extrinsic maintainability of equipment. Intrinsic maintainability refers to characteristics related to maintenance equipment (low accessibility, disassembly, etc.). Extrinsic maintainability concerns characteristics related to the overall maintenance environment (restricted workspace, height work, access means, etc.) (INRS, 2023b). The late detection of maintainability problems leads to higher costs, highlighting the importance of anticipating maintainability to anticipate the impacts of design on system repair. Various approaches have been used to evaluate maintainability and can be classified into three categories (Zwingmann, 2005):

- Interpolation: predicts the performance of the new product based on experience gained with similar equipment;
- Sum of times: decomposes the maintenance effort into elementary tasks and adds the average durations for each task;
- Checklist: provides the important characteristics of a system to evaluate according to maintainability index criteria.

However, the quality of the maintainability analysis will depend on the designer's ability to envisage and visualize the future maintenance situation to be evaluated. This is why the use of digital simulation tools (Virtual Reality, Augmented Reality, and Mixed Reality) seems to be effective for simulating human/system interaction. Bernard et al. (2023) develops the PEAM (Preliminary Ergonomics Analysis in Maintainability) approach allowing to integrate HFE through the use of digital and physical simulation tools according to the stage of the design process. This process improves the integration of physical ergonomics into maintainability and makes designers more aware of the difficulties encountered by operators during the activity.

ANTICIPATION AND DIGITAL SIMULATION TOOLS

Digital simulation tools are essential for anticipating complex human interactions linked to maintenance actions (Chedmail, 2002; Zwingmann, 2005;

Bernard et al., 2021). The use of these tools reduces our dependence on physical mock-ups, which are a costly and time-consuming part of the design cycle (Chedmail, 2002; Paquin & Bernard, 2023). The simulation should provide sufficient information to the designer and/or operator, to appropriate the future environment and to discern all the subtleties of the interaction between human and the environment (Bernard et al., 2022). Anticipating these parameters allows us to perfect the design. For this, there are three main simulation tools: Virtual Reality (VR), Augmented Reality (AR) and Mixed Reality (MR). Each of these tools will provide a specific immersive experience to enhance the experience of the end user (Fuchs & Moreau, 2006; Fuchs et al., 2011; Lacoche, 2016). However, these tools may have sensory, motor and technical limitations in their use. In sensory-motor terms, these limitations are caused by a disparity between real and virtual experiences. On the one hand on the sensory level due to visuo-vestibular conflicts and on the other hand on the motor level due to an imbalance between real action and virtual feedback in the interaction with the virtual environment (Weech et al., 2019). On a technical level, the resolution of display devices, the limited field of view, brightness, contrast and ergonomics can interfere with the study of HFEs (Livingston, 2005). Concretely, in maintainability, an HFE analysis using MR technology was used to optimize the position of the foot and wrist steps on a helicopter (Paquin & Bernard, 2023). HFEs are working to improve design by taking operators into account and by creating assessment methods adapted to the use of digital simulation tools.

A METHOD FOR MEASURING MENTAL WORKLOAD ADAPTED TO THE MAINTENANCE ENVIRONMENT

Mental Workload Measurement

The International Ergonomics Association (2000) specifies that for a thorough analysis of Human Factors Engineering (HFE), it is necessary to consider all domains of specialties (Physical Factors, Cognitive Factors and Organisational Factors). In addition to physical factors, it is now essential to study the impact of cognitive factors on maintenance design. The research and use of new methods for collecting information on mental workload require considering the global operational environment as a source of information (Young et al., 2015). Measuring mental workload is fundamental to improving the design of complex systems and optimizing human-machine interaction (Longo et al., 2022). It is now essential to develop models for measuring mental workload to help reduce human error. Several categories of measures exist to evaluate mental workload, subjective measures, objective performance measures, and physiological measures (Young et al., 2015; Charles & Nixon., 2019; Longo et al., 2022).

Subjective Measure

Subjective measures include a participant who gives qualitative and/or quantitative feedback on their own experience in performing a primary and/or secondary task (Cain et al., 2007, Young et al., 2015; Longo et al., 2022).

Subjective measures are used because they are easy to implement, provide sensitive measurements and are theoretically validated (Hart & Staveland, 1988; Cain, 2007). In the majority of these methods, the operator has to complete a questionnaire after the task has been performed. This could lead to a memory bias and a reinterpretation of the sensations experienced as a result of the operator's mental workload (Mallat, 2019).

Performance Measure

Performance measures assess the operator's ability to perform a task at an acceptable level and indirectly measure their mental workload in isolation. This method allows for the extraction of dependent variables such as response times, task execution times, error rates, these types of variables are generally the most observed (Cegarra & Chevalier, 2008 ; Longo et al., 2022). Performance measures can be classified into two main categories. The primary tasks category provide a direct measure of performance and have high precision for evaluating long periods of mental workload. However, their disadvantage lies in their inability to discern the origin of mental workload variations when several tasks are performed simultaneously (Longo, 2015). The secondary tasks category relies on measuring the operator's residual capacity during the execution of the primary task (Sperandio, 1987; Wickens, 2008; Young et al., 2015). However, this method could cause alterations due to the increased level of vigilance caused by the sensory interference generated by divided attention between the primary and secondary tasks.

Physiological Measure

Some physiological measures are intrinsically linked to mental workload, they reflect the actions of the Sympathetic and Parasympathetic Nervous System (SNS & PNS) which will reflect the changes in cognitive functioning of the operator. The increase in mental workload will involve an increase in cognitive resources, which will be reflected in physiological activation (Kramer, 1990; Charles & Nixon, 2019). Different categories of physiological measures exist to measure mental workload. Cardiovascular measures, ocular measures, salivary measures, electrodermal measures, neurophysiological measures (Young et al., 2015; Charles & Nixon, 2019; Longo et al., 2022). However, it is evident that each measurement tool has limitations that can potentially bias the interpretation of the data. In fact, identifying the strengths and weaknesses of physiological measurement tools is necessary to facilitate the selection of measurement tools and methods. For ocular measurements, a stimulus such as light can affect pupillary dilation and bias the raw measurement of mental workload. For neurophysiological measures, the ElectroEncephaloGram (EEG) which allows the measurement of the electrical activity of the cerebral cortex requires that the participant remains immobile during the measurements. However, the operator's movement (muscular, ocular, etc.) can be a source of bias. The cardiovascular measures indicate the predominance of the PNS or SNS which can result, among others, from physical or mental activity, emotional nature (positive or negative) or stress

(Kostenko, 2017). In more detail, Heart Rate Variability (HRV) is a measure that has shown a correlation with mental workload. It is generally accepted that HRV decreases with increasing mental workload (Meshkati, 1988; Laouar-Zouyed, 2022). On the other hand, the multiplicity of factors (experience level, type of task, time of day, etc.) to which the cardiovascular system reacts reduces its selectivity and diagnostic capability (Charles & Nixon, 2019).

Criteria for Measuring the Mental Workload

Some categories of measures provide a single aspect of mental workload, while others offer a more detailed perspective on its dynamics (Cegarra & Chevalier, 2008). Any approach should provide a particular benefit when combined with another. This would provide valuable indications of the gap between the objective reaction and the physiological response of the participants in reality. However, in the context of a field study, using several measurement methods without interfering with the main task can become complex.

Quality Criteria in the Measurement of Mental Workload

Several researchers have defined measurement criteria concerning the quality of mental workload measurements (Xie & Salvendy, 2000; Cain, 2007; Cegarra & Chevalier, 2008; Longo et al., 2022). Among these multiple criteria, here are the most common:

- Sensitivity: Focuses on the ability to discern different levels of task demands. For example, variation in pupil diameter is considered to be a sensitive measure of mental workload;
- Selectivity: Requires the measurement to remain constant when the workload remains constant on its own. Pupil diameter variation is not selective because of light variation. But objective measures of performance are selective in their measurement of mental workload;
- Diagnosticity: Focuses on the measure's ability to determine the origin of the load in the task. Subjective measures have a relevant multidimensional diagnostic capacity. In particular, NASA-TLX identifies underload and overload in several dimensions. However, Heart rate measurement has a slightly limited diagnostic capacity due to its difficulty in differentiating between the causes of workload.
- Data quantity: Measuring mental workload using several methods in an adapted way will enable a more precise and comprehensive diagnosis of the type of workload. Assimilate and apply the measurement units (instantaneous load, average load, cumulative load, maximum load and overall load) is crucial in optimizing data acquisition (Xie & Salvendy, 2000). This will allow us to identify across a broader spectrum, each measurement specificity (Xie & Salvendy, 2000; Cegarra & Chevalier, 2008).

DISCUSSION & CONCLUSION

In the search of constant optimization of design in maintainability, understanding the maintenance activity, the workload of maintenance operators, and the development of methods for measuring workload is essential for designing a safer maintenance system. Anticipating the operator's activity within the maintenance environment will allow understanding the physical and mental workload constraints that could pose a threat to the maintenance operator (Bernard et al., 2021). The future challenge will be to design a method for measuring mental workload adapted to optimize maintainability. Diagnosing by anticipation the mental workload will facilitate the reduction of human errors in maintenance. An effective measure of mental workload results in a multidimensional appreciation of the operator's strain through the combination of multiple measurement requirements. Indeed, a combination of specific measurement methods of the mental workload would ensure optimal acquisition of the cognitive data of maintenance operator's to improve the integration of HFE during the design process. Therefore, in order to refine the choice of a pattern (combination of subjective measurement, performance objectives, and physiological) for measuring the mental workload of the operator, it is necessary to consider and anticipate the constraints of maintenance activity to improve the choice of methods for measuring mental workload and associated tools. On a broader scale, research in HFE improves the design of new systems thanks to a human-centered approach and resolves the problems of sub-optimal existing designs (Gramopadhye & Drury, 2000). Once implemented, this method will allow us to specifically determine a level of precision of the mental workload. Thanks to the immersive quality of digital simulation tools, it is possible to proactively replicate maintenance activities and thus measure the workload of operators. In this field, the fidelity of the parameters assessed between the real world and the simulation of the physical factors of HFEs has already been studied (Bernard et al., 2023). From a cognitive point of view, and as part of our research, we are very interested in being able to identify the fidelity of the level of mental workload in all these aspects between reality and simulation. This is why, in order to optimize design anticipation, the fidelity of measurements of maintenance operator's mental workload will have to be similar between real and simulated activity. Anticipating the reactions of maintenance operators will allow more robust and error-tolerant systems to be developed, to ensure the protection of the physical and mental integrity of operators and aviation safety (Yiannakides & Sergiou, 2019).

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