DIGITAL FATIGUE AS AN EMERGING OCCUPATIONAL RISK IN KNOWLEDGE-BASED WORK

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Abstract: *The accelerated transformations of the digital work environment have led to the emergence of emerging occupational risks, insufficiently addressed within traditional occupational safety and health methodologies. Among them, digital fatigue stands out as a complex phenomenon, driven by prolonged exposure to screens, high cognitive load, intensity of digital interactions, and multitasking specific to knowledge-based activities. This paper proposes an integrated approach to assessing this risk, by developing a quantitative model based on the Digital Fatigue Index (DFI), capable of capturing the dynamic and cumulative character of the phenomenon. The proposed model uses a mathematical formulation and a differential equation to describe the evolution of digital fatigue over time, including both accumulation and recovery processes. The conceptual validation of the model was achieved by simulating a typical scenario of working in a digital environment, highlighting the influence of factors such as frequent interactions and multitasking on the accelerated increase in fatigue. The results obtained underline the importance of introducing breaks and optimizing the organization of work to reduce the associated risks. Finally, the paper highlights the need to integrate digital fatigue into occupational risk assessment and provides a useful analytical tool to support occupational safety and health decisions in the context of the digital economy.*

Keywords: digital fatigue; occupational risk; cognitive load; technological stress; multitasking; occupational safety and health; mathematical model; Digital Fatigue Index (DFI)

1. INTRODUCTION

The accelerated transformations brought about by digitalisation and the widespread adoption of information technologies have profoundly redefined the nature of work in the knowledge-based economy. Professional activities in fields such as information technology, research, education or digital services predominantly involve continuous interaction with information systems, collaborative platforms and complex digital tools. In this context, prolonged exposure to screens, the increased volume of information and the intensification of technologically mediated communication have led to the emergence of new forms of cognitive and psychosocial demand.

Although concepts such as mental fatigue, cognitive overload or technological stress (technostress) have been investigated in the literature, the notion of *digital fatigue* is increasingly emerging as an emerging occupational risk, insufficiently defined and rarely systematically integrated into occupational health and safety assessments. Digital fatigue can be understood as a complex state of cognitive, visual and emotional exhaustion, determined by the intensive and prolonged use of interactive digital technologies, being amplified by factors such as multitasking, frequent interruptions and the pressure to respond quickly to multiple informational stimuli.

The current context of hybrid and remote work, accelerated by the organizational changes of recent years, has significantly intensified workers' exposure to such factors. Phenomena such as "Zoom fatigue", attention fragmentation or information overload highlight the need for an integrated approach to these risks from the perspective of cognitive ergonomics and occupational safety and health (OSH). Despite their impact on employee performance and well-being, these manifestations are often treated as individual discomforts, rather than as quantifiable and manageable occupational risks.

In this regard, there is a need to develop conceptual models and analytical tools that allow the systematic assessment of digital fatigue and its integration into existing risk management frameworks. Traditional approaches to occupational risk assessment are predominantly oriented towards physical, chemical or mechanical factors, while the emerging risks associated with digitalisation remain insufficiently addressed or difficult to quantify. Therefore, it is essential to expand these models to include dimensions such as cognitive load, intensity of digital interactions, and dynamics of multitasking.

This paper aims to contribute to this approach by defining and modeling the concept of digital fatigue as an emerging occupational risk in knowledge-based work environments. Specifically, it is proposed to develop a quantitative index of digital fatigue, capable of capturing the dynamic and multidimensional character of the phenomenon, as well as to integrate it into a risk assessment framework compatible with OSH principles. By using a mathematical approach and simulated scenarios, the study aims to highlight the mechanisms of digital fatigue accumulation and the impact of organizational and behavioral factors on it.

The relevance of the research is supported by the need to adapt occupational safety and health policies and practices to the new realities of digital work. In a professional environment characterized by permanent interconnectivity and high cognitive demands, identifying and effectively managing digital fatigue becomes essential to maintain performance, prevent errors and ensure the well-being of workers. Thus, the study contributes to strengthening the theoretical and applicative framework necessary to address this emerging risk in the context of Industry 4.0.

2. CURRENT STATE OF KNOWLEDGE

The concept of digital fatigue is at the intersection of several established research directions, such as cognitive load, technological stress and human-computer interaction, but without being fully formalized as a distinct field. In the literature, the effects of the intensive use of digital technologies are predominantly analyzed through the prism of the theory of cognitive load, the stress generated by technology and the impact of digital media on human attention and performance.

The Cognitive Load Theory, developed by John Sweller, provides a fundamental framework for understanding how the individual's limited cognitive resources are demanded during information processing. According to this theory, working memory overload leads to decreased performance and mental fatigue. In digital environments, characterized by continuous flows of information and multitasking, this overload becomes a common condition, favoring the appearance of digital fatigue.

Another relevant concept is that of technological stress (technostress), initially introduced by Craig Brod and later developed in empirical studies by Monideepa Tarafdar. Technostress is defined as the stress felt by users as a result of the use of information technologies and includes dimensions such as technological overload, invasion of personal life and complexity of digital systems. Studies by Tarafdar et al. highlight that excessive use of technology can lead to burnout, decreased job satisfaction, and reduced performance.

In the context of remote work, recent research has highlighted the phenomenon known as "Zoom fatigue", analyzed in detail by Jeremy N. Bailenson. It describes the fatigue associated with frequent participation in video conferences and is explained by factors such as intense eye contact, overexposure to one's own image and the need to process multiple nonverbal signals simultaneously. These mechanisms contribute to an increase in cognitive load and the depletion of mental resources.

From the perspective of human-computer interaction, the works of Stuart K. Card, Thomas P. Moran and Allen Newell have substantiated the understanding of how users process information in digital systems. The models developed in this field highlight the cognitive limitations of users and the importance of ergonomic interface design to reduce mental strain.

Also, studies on the attention economy, promoted by Herbert A. Simon, emphasize the fact that human attention is a limited resource, which becomes critical in the context of information overload. In today's digital environments, characterized by constant notifications and fragmentation of tasks, this resource is under continuous pressure, contributing to the onset of fatigue and decreased ability to concentrate.

More recently, research in the field of cognitive ergonomics and occupational health has begun to recognize digital fatigue as a distinct phenomenon with implications for occupational safety and health. Studies indicate that prolonged exposure to screens, combined with multitasking and frequent interruptions, can lead to human error, decreased alertness, and increased risk of accidents, especially in critical work environments.

However, the current literature has a number of limitations. First, most studies address isolated components of the phenomenon (e.g., only technological stress or just cognitive load), without proposing integrated models. Secondly, there is a lack of quantitative tools that allow dynamic assessment of digital fatigue in real time. Thirdly, the integration of these risks into occupational risk assessment methodologies is still insufficiently developed.

In this context, the need to develop interdisciplinary models that combine perspectives from cognitive psychology, human-computer interaction and occupational safety and health is highlighted. This paper responds to this need by proposing a mathematical model for assessing digital fatigue and integrating it into an occupational risk analysis framework, thus contributing to the expansion of the current state of knowledge in the field.

3. METHODOLOGY

3.1. Conceptual framework

This paper proposes a quantitative model for assessing digital fatigue as an emerging occupational risk in knowledge-based work environments. The approach is based on the assumption that digital fatigue is a dynamic and cumulative phenomenon, determined by the interaction of several factors, such as exposure to screens, cognitive load, intensity of digital interactions and the level of multitasking.

To capture these influences, a composite indicator called **the Digital Fatigue Index (DFI) is defined**, expressed as follows:

$$DFI(t) = \alpha S(t) + \beta\, C(t) + \gamma\, I(t) + \delta\, M(t) \quad (1)$$

where:

S(t) represents the duration of exposure to the screen,
C(t) expresses the level of cognitive load,
I(t) describe the intensity of digital interactions (online meetings, notifications),
M(t) indicates the level of multitasking,
α,β,γ,δ are weights that reflect the relative contribution of each factor.

3.2. Dynamic modelling of digital fatigue

Considering the evolutionary nature of fatigue, a dynamic model based on a first-order differential equation is introduced:

$$\frac{dDFI}{dt} = \underbrace{k_1 S_{(t)} + k_2 C_{(t)} + k_3 I_{(t)} + k_4 M_{(t)}}_{\text{Inflows}} - \underbrace{k_r R_{(t)}}_{\text{Outflow}} \quad (2)$$

where:

k1, k2, k3, k4 are accumulation coefficients,
R(t) represents the retrieval function,
kr is the recovery coefficient.

The recovery function is defined as follows:

$$R(t) = \begin{Bmatrix} 1, during\ break\ periods \\ 0, during\ the\ activity \end{Bmatrix}$$

This formulation allows simultaneous modeling of the processes of accumulation of fatigue during activity and partial recovery during rest periods.

3.3. Normalisation and risk classification

To allow comparability of the results, the digital fatigue index is normalized according to the relationship:

$$DFI_{norm} = \frac{DFI - DFI_{min}}{DFI_{max} - DFI_{min}} \quad (3)$$

The normalized value is classified into three risk levels:

- $Reduced\ fatigue$: $0 \le DFI_{norm} < 0.3$
- $Moderate\ fatigue$: $0.3 \le DFI_{norm} < 0.6$
- $Reduced\ fatigue$: $0.6 \le DFI_{norm} \le 1$

3.4. Simulation scenario

For the conceptual validation of the model, a simulation of a typical 8-hour working day was carried out in a knowledge-based environment (IT sector). The structure of the working day includes:

- periods of intense activity (high cognitive load),
- online meeting sessions (intense interaction),

- multitasking intervals (management of several tasks at the same time),
- scheduled breaks (recovery periods).

The model parameters were set as follows: (k1 = 0.4), (k2 = 0.3), (k3 = 0.2), (k4 = 0.1) (k_r = 0.5). These parameters reflect a realistic distribution of digital and cognitive demands in modern work environments.

In order to highlight the applicability of the proposed model, a numerical simulation on the evolution of the Digital Fatigue Index (DFI) during an 8-hour working day, specific to a worker in the IT sector, was developed. The simulation aims to identify how digital and cognitive factors contribute to the accumulation of fatigue, as well as to assess the effect of recovery periods on risk reduction.

The analyzed working day was structured on activity intervals, as follows:

Table 1. The simulation scenario used for the conceptual validation of the Digital Fatigue Index, DFI, model in a work environment specific to the IT sector

Time Interval	Main activity	Dominant factor
09:00–11:00	Programming (writing code) / intense concentration activity	High cognitive load
11:00–12:00	Online meetings	High digital interaction
12:00–13:00	Pause	Recovery
13:00–16:00	E-mail, multi-task, online collaboration	Multitasking and frequent interactions
16:00–17:00	Task Completion / Reporting	Moderate-high cognitive load

For each interval, the model variables were estimated on a relative scale, where higher values indicate a more intense stress. Thus, screen exposure S(t) was considered constant during active work periods, cognitive load C(t) was higher during periods of intense concentration, digital interaction I(t) increased during online meetings, and multitasking M(t) was dominant in the afternoon.

These coefficients reflect the hypothesis that screen exposure and cognitive load have a greater contribution to the accumulation of digital fatigue, while digital interactions and multitasking act as amplification factors.

For the simulation, two scenarios were analyzed:

Scenario A – working day with scheduled break: in this case, the recovery function (R(t)) becomes active between 12:00 and 13:00, which causes a partial reduction in the level of accumulated fatigue.

Scenario B – working day without a break: in this case, (R(t)=0) for the entire duration of the program, which leads to the continuous accumulation of digital fatigue.

The results of the simulation indicate that, in Scenario A, the level of DFI increases in the early hours of the day, especially during intense concentration activities and online sessions. The mid-day break causes a slowdown in the accumulation of fatigue and a temporary stabilization of the index. However, in the second part of the day, DFI is growing again at an accelerated pace, as a result of multitasking and frequent digital interactions.

In Scenario B, the absence of the break leads to an almost continuous accumulation of digital fatigue, and the high risk threshold is reached earlier. This result suggests that a lack of recovery may amplify the negative effects of digital exposure and increase the likelihood of errors, decreased attention, and reduced performance.

By normalizing DFI values, the results can be interpreted on three levels of risk:

Table 2. Comparative analysis of two work scenarios used to assess the impact of breaks on the accumulation of digital fatigue

DFInorm Value	Digital fatigue level	OSH Interpretation
0–0.3	Reduced	Controlled activity, low risk
0.3–0.6	Moderate	Requires regular monitoring and breaks
0.6–1.0	High	Significant occupational risk, requires intervention

The simulation shows that intervals with multitasking and intense digital interactions contribute the most to the transition from the moderate fatigue zone to the high-risk zone. Thus, digital fatigue should not be interpreted exclusively as a result of screen time, but as a combined effect of cognitive demand, frequency of interruptions, digital communication and work organisation.

From the perspective of occupational safety and health, the results support the need to introduce preventive measures, such as scheduling breaks, limiting consecutive sessions, reducing unnecessary notifications and organizing intense cognitive activities in intervals with high concentration capacity.

Table 3. Detailed results of the simulation of the evolution of the digital fatigue index, DFI, over a full working day

Time	Activity	Estimated DFI with pause	Risk level with pause	Estimated DFI without pause	Risk level without pause
09:00	Start of activity	0.00	Reduced	0.00	Reduced
10:00	Intense cognitive activity	0.22	Reduced	0.22	Reduced
11:00	Continuous deep work	0.38	moderate	0.38	moderate
12:00	Online meetings	0.55	moderate	0.55	moderate
13:00	Pause/No Pause	0.47	moderate	0.68	high
14:00	Multitasking + email	0.61	high	0.78	high
15:00	Multitasking + collaboration	0.72	high	0.86	high
16:00	Multiple Tasks	0.83	high	0.93	high
17:00	Task Completion	0.91	high	1.00	high

The simulated results confirm that the scheduled break plays an important role in temporarily reducing digital fatigue, but does not completely eliminate the cumulative effect of digital requests. In the pause scenario, the transition to the high-risk zone occurs after 14:00, while in the non-pause scenario this threshold is reached earlier, immediately after the interval 12:00–13:00. This difference highlights the impact of recovery periods on occupational risk management.

It is also noted that the 13:00–16:00 interval is the critical area of the workday, as it combines prolonged screen exposure, multitasking, and frequent digital interactions. This interval requires specific organizational measures, such as reducing consecutive meetings, limiting interruptions, and alternating tasks with different levels of cognitive complexity.

3.5. Integration in occupational risk assessment

To correlate digital fatigue with occupational safety and health, an associated risk function is proposed:

$$Riskdigital = DFInorm \times E \times S \quad (4)$$

where:

- (E) represents the frequency of exposure,
- (S) express the severity of the impact on performance and safety.

This relationship allows for the integration of digital fatigue into existing occupational risk assessment methodologies, helping to expand them to include emerging risks associated with digitalisation.

4. RESULTS AND DISCUSSIONS

The simulation based on the proposed model highlights the fact that digital fatigue is dynamic and non-linear during a typical working day. The evolution of the Digital Fatigue Index (DFI) indicates a progressive increase in periods of continuous activity, interspersed with temporary reductions in break intervals.

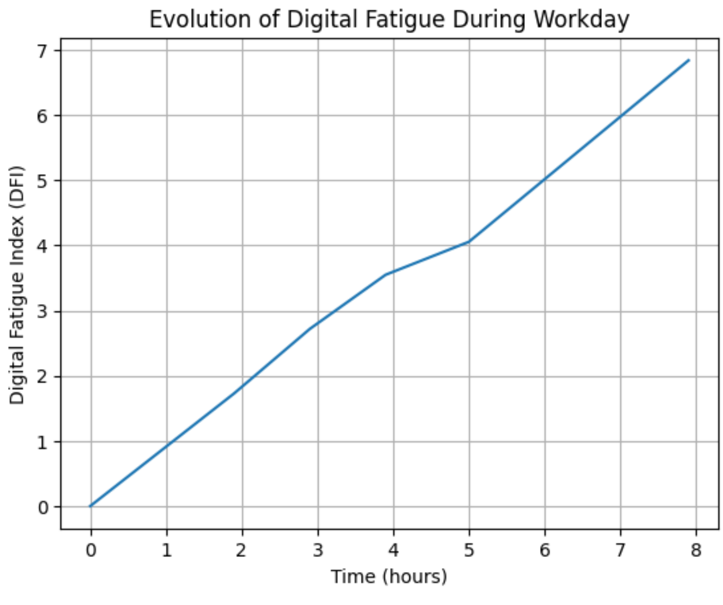

Figure 1. Evolution of the Digital Fatigue Index (DFI) during a working day.

The analysis of the DFI curve allows the identification of three distinct stages:

- **Initial accumulation phase (09:00–11:00):** At this stage, the increase in DFI is moderate and is predominantly determined by the cognitive load associated with deep work activities. The relatively stable level of digital interactions contributes to a controlled accumulation of fatigue.

• **Interaction intensification phase (11:00–12:00):** There are sharp increases in DFI, driven by participation in online meetings and an increase in the frequency of notifications. These variations confirm the significant impact of the intensity of interactions on digital fatigue.

• **Accelerated accumulation phase (13:00–17:00):** After the pause period, DFI increases at a faster rate as a result of the cumulative effect of prolonged screen exposure, multitasking, and reduced recovery capacity. This stage is characterised by reaching high risk thresholds.

Impact of recovery periods.

Introducing breaks into the simulation scenario has a significant effect on reducing the level of digital fatigue. In recovery intervals, the (R(t)) function contributes to the temporary decrease in DFI, preventing excessive fatigue accumulation. Compared to a scenario without breaks, the results indicate the delay in reaching the level of high fatigue (DFInorm > 0.6), the reduction of the maximum value of the index and the stabilization of the evolution of fatigue in the short term. These results confirm the essential role of recovery strategies in the effective management of digital fatigue.

Analysis of the determinants.

The results highlight that digital fatigue is not determined solely by the duration of screen exposure, but by the complex interaction between several factors:

- *cognitive load C(t)* influences the constant accumulation of fatigue during periods of intense concentration;
- *the intensity of interactions I(t)* generates sudden variations in DFI, especially during online meetings;
- *M(t) multitasking* contributes to the accelerated increase in fatigue in the second part of the day;
- *prolonged exposure to the S(t) screen* has a long-term cumulative effect.

This interdependence confirms the multidimensional nature of digital fatigue and the need for an integrated approach in its assessment.

Implications for occupational safety and health

From the perspective of occupational safety and health, the high values of the DFI index are associated with significant negative effects, such as: decreased ability to concentrate, increased probability of human errors, decreased quality of decisions, onset of cognitive exhaustion. The integration of the Riskdigital function into occupational risk analysis allows the impact of digital fatigue on performance and safety to be quantified. Thus, the proposed model offers a useful tool for identifying risk situations and for substantiating preventive measures.

Practical implications

The results of the study have direct implications for knowledge-based work environments, suggesting the need to:

- optimization of working hours by introducing regular breaks,
- reducing digital overload and excessive multitasking,
- redesign of digital workflows to limit disruptions,
- integration of digital fatigue into occupational risk management systems.

Overall, the analysis confirms that digital fatigue is an emerging occupational risk, quantifiable and manageable through appropriate assessment and control tools.

5. CONCLUSIONS

This paper addressed the issue of digital fatigue as an emerging occupational risk in knowledge-based work environments, highlighting the complexity and relevance of this phenomenon in the context of accelerated digital transformations. By integrating concepts from cognitive load theory, technological stress and human-computer interaction, the study proposed an interdisciplinary approach, capable of reflecting the multidimensional nature of digital fatigue.

One of the main results of the research is the development of a quantitative model – the Digital Fatigue Index (DFI) – which allows the dynamic assessment of the level of fatigue according to factors such as screen exposure, cognitive load, intensity of interactions and multitasking. The introduction of a differential equation for modeling the evolution of fatigue over time is a novelty, offering the possibility of simulating its behavior in different work scenarios.

The results of the simulation showed that digital fatigue does not evolve linearly but is cumulative and accelerated, especially in conditions of intense multitasking and frequent interactions. The essential role of recovery periods in reducing fatigue levels and preventing critical risk thresholds from being reached was also highlighted. These findings confirm that the organisation of working time and the management of digital tasks have a direct impact on workers' health and performance.

From an occupational safety and health perspective, the major contribution of the study is to integrate digital fatigue into occupational risk assessment. By defining a risk function associated with Riskdigital, the paper provides a conceptual tool that allows quantifying the effects of fatigue on performance and safety, facilitating the inclusion of this type of risk in existing methodologies. Thus, digital fatigue is treated not only as an individual discomfort, but as a relevant factor in preventing human errors and incidents in digital work environments.

However, the research has some limitations, in particular with regard to the use of estimated parameters in the simulation and the absence of empirical validation on real data. Also, the model does not explicitly integrate individual or organizational variables, which can significantly influence the level of fatigue. These aspects open important directions for future research.

In this regard, further developments should aim at validating the model through experimental studies and collecting data from real working environments, as well as integrating physiological and behavioural indicators. Also, expanding the model to include ergonomic, organisational and psychosocial factors could help create more robust tools for digital risk assessment.

In conclusion, the study highlights that digital fatigue represents an emerging occupational risk, with significant implications for the health, performance and safety of workers in the knowledge-based economy. The proposed approach provides a relevant theoretical and methodological framework for the analysis of this phenomenon and underlines the need for its integration into modern occupational safety and health policies and practices, in line with the specific requirements and challenges of the digital age.

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