



**CHRONIC FATIGUE AS A RESULT OF A COMPLEX EXPOSOME: PHYSICAL AND  
DIGITAL LOADS IN DIFFERENT AGE GROUPS  
(a case study of automobile industry workers and schoolchildren)**

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**Abstract:** Chronic fatigue is increasingly recognized as a multidimensional health condition resulting from the cumulative and synergistic effects of various environmental, occupational, and behavioral exposures. This review examines chronic fatigue through the lens of the exposome concept, emphasizing the combined impact of physical and digital loads across different age groups. Using the example of automotive industry workers and schoolchildren, the article analyzes how prolonged physical overexertion, digital overload, psychosocial stress, and insufficient recovery interact to form a complex fatigue-related exposome. Particular attention is paid to age-specific vulnerability, physiological mechanisms, and cognitive consequences of chronic fatigue. Epidemiological evidence indicates a growing prevalence of fatigue-related disorders among both working-age adults and children, reflecting broader changes in work organization, education, and digitalization. The review highlights the relevance of an exposome-based approach for preventive medicine, enabling comprehensive risk assessment and targeted prevention strategies. It is concluded that chronic fatigue should be considered not as an isolated condition, but as an outcome of cumulative physical and digital exposures throughout the life course.

**Keywords:** chronic fatigue, exposome, physical load, digital overload, automotive workers, schoolchildren, preventive medicine

**ХРОНИЧЕСКАЯ УСТАЛОСТЬ КАК РЕЗУЛЬТАТ СЛОЖНОГО  
ЭКСПОЗОМА: ФИЗИЧЕСКИЕ И ЦИФРОВЫЕ НАГРУЗКИ В РАЗНЫХ  
ВОЗРАСТНЫХ ГРУППАХ**

**(на примере работников автомобильной промышленности и школьников)**

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**Аннотация:** Хроническая усталость все чаще признается многомерным состоянием здоровья, возникающим в результате кумулятивного и синергетического воздействия



различных факторов окружающей среды, профессиональной деятельности и поведения. В данном обзоре рассматривается хроническая усталость с точки зрения концепции экспозома, с акцентом на совокупное воздействие физических и цифровых нагрузок в разных возрастных группах. На примере работников автомобильной промышленности и школьников в статье анализируется, как длительное физическое перенапряжение, цифровая перегрузка, психосоциальный стресс и недостаточное восстановление взаимодействуют, формируя сложный экспозом, связанный с усталостью. Особое внимание уделяется возрастной уязвимости, физиологическим механизмам и когнитивным последствиям хронической усталости. Эпидемиологические данные указывают на растущую распространенность заболеваний, связанных с усталостью, как среди взрослых трудоспособного возраста, так и среди детей, что отражает более широкие изменения в организации труда, образовании и цифровизации. В обзоре подчеркивается актуальность подхода, основанного на экспозоме, для профилактической медицины, позволяющего проводить комплексную оценку риска и разрабатывать целенаправленные стратегии профилактики. Сделан вывод, что хроническую усталость следует рассматривать не как изолированное состояние, а как результат кумулятивного физического и цифрового воздействия на протяжении всей жизни.

**Ключевые слова:** хроническая усталость, экспозом, физическая нагрузка, цифровая перегрузка, работники автомобильной промышленности, школьники, профилактическая медицина.

**Relevance:** In the twenty-first century, chronic fatigue has emerged as one of the most prevalent and underestimated health problems affecting diverse population groups. Traditionally viewed as a consequence of excessive workload or insufficient rest, fatigue is now understood as a complex condition shaped by multiple interacting exposures. According to the World Health Organization, fatigue-related complaints rank among the leading causes of reduced work capacity, academic underachievement, and decreased quality of life across age groups [1].

Modern lifestyles are characterized by continuous exposure to physical, cognitive, and digital stressors. In working-age adults, particularly in industrial sectors such as automotive manufacturing, chronic fatigue develops under conditions of sustained physical exertion, shift work, psychosocial stress, and inadequate recovery. In children and adolescents, excessive digital engagement, cognitive overload, sleep disturbances, and educational pressure contribute to early manifestations of chronic fatigue and cognitive decline [2].

The concept of the exposome, which encompasses the totality of environmental and lifestyle exposures throughout the life course, provides a valuable framework for understanding chronic fatigue as a cumulative outcome rather than an isolated disorder. Unlike single-factor models, the exposome approach captures the synergistic effects of physical, digital, social, and behavioral exposures that jointly exceed adaptive capacity [3].

For preventive medicine and public health, this perspective is particularly important. The increasing convergence of physical and digital нагрузок across age groups reflects broader societal transformations, including industrial intensification, digitalization of education, and changing work–life boundaries. Without comprehensive preventive strategies, chronic fatigue may contribute to long-term health deterioration, reduced productivity, and intergenerational



transmission of health risks. Therefore, analyzing chronic fatigue through an exposome-based lens is both timely and necessary.

**Materials and methods:** This review is based on a comprehensive analysis of international scientific literature addressing chronic fatigue, occupational and digital exposures, and exposome theory. Sources were identified through systematic searches of PubMed, Scopus, Web of Science, and Google Scholar, as well as reports from the World Health Organization, International Labour Organization, and pediatric and occupational health associations.

Search terms included chronic fatigue, exposome, physical workload, digital overload, occupational fatigue, cognitive fatigue, schoolchildren, and automotive industry. Priority was given to peer-reviewed articles, systematic reviews, epidemiological studies, and conceptual papers published within the last 10–15 years. Qualitative synthesis was used to integrate evidence across age groups and exposure domains [4,5].

**Results and discussion:** Chronic fatigue is defined as a persistent state of physical and mental exhaustion lasting for weeks or months and not fully relieved by rest. Unlike acute fatigue, which serves a protective physiological function, chronic fatigue reflects maladaptation of regulatory systems, including the nervous, endocrine, and immune systems [6].

Epidemiological studies suggest that symptoms of chronic fatigue are present in 20–35% of working-age adults and up to 15–25% of school-aged children, depending on exposure intensity and assessment criteria [7]. These figures highlight the scale of the problem and its relevance across the life span.

From an exposome perspective, chronic fatigue arises when cumulative exposures exceed individual adaptive capacity. Physical load, cognitive demands, digital stress, sleep disruption, and psychosocial factors interact in a non-linear manner, amplifying fatigue severity and persistence.

In automotive industry workers, physical load constitutes a dominant component of the occupational exposome. Repetitive movements, manual handling of loads, prolonged standing, and static postures generate sustained musculoskeletal strain. Studies indicate that more than 60% of automotive workers report regular fatigue and musculoskeletal discomfort, with chronic fatigue symptoms present in approximately one-third of employees [8].

Physical overexertion activates inflammatory pathways, increases oxidative stress, and disrupts autonomic regulation. Over time, these changes impair muscle recovery, cardiovascular function, and central nervous system performance. When combined with shift work and insufficient sleep, physical load becomes a powerful driver of chronic fatigue.

Digital exposure has become a significant contributor to fatigue across all age groups. In schoolchildren, digital load manifests primarily through prolonged screen time, multitasking, and continuous cognitive stimulation. International data indicate that average daily screen time among school-aged children exceeds 6–7 hours in many regions, far above recommended limits [9].

Digital overload increases cognitive load, disrupts attention and memory processes, and interferes with sleep. Chronic activation of reward and stress pathways leads to mental fatigue,



emotional dysregulation, and reduced learning capacity. Importantly, digital load rarely occurs in isolation; it interacts with educational pressure, sedentary behavior, and psychosocial stress.

Among adult workers, digital load is increasingly relevant due to digital monitoring systems, electronic reporting, and after-hours connectivity. The blurring of boundaries between work and rest contributes to insufficient recovery and cumulative fatigue [10].

Age represents a critical modifier of exposome effects. Schoolchildren are particularly vulnerable to digital and cognitive overload due to ongoing brain development. Attention regulation, executive functions, and emotional control are still maturing during childhood and adolescence, making these systems more susceptible to overstimulation and fatigue [11].

In contrast, adult workers experience fatigue primarily through physical and psychosocial pathways, although digital factors increasingly contribute. Age-related decline in recovery capacity further amplifies the impact of cumulative exposures in older workers.

Despite these differences, a common pattern emerges: chronic fatigue results from the interaction of multiple exposures rather than a single dominant factor. This convergence underscores the need for integrated preventive strategies that account for age-specific exposome profiles.

From an exposome perspective, chronic fatigue cannot be attributed to a single dominant exposure; instead, it emerges from the interaction of multiple physical, digital, psychosocial, and behavioral factors acting cumulatively over time. Physical and digital loads represent two major exposure domains that increasingly coexist and interact across different age groups. Their combined impact exceeds the additive effect of each exposure alone, leading to accelerated fatigue development and reduced adaptive capacity.

In automotive industry workers, physical overexertion remains the primary exposure; however, it is increasingly accompanied by digital demands such as continuous monitoring systems, electronic documentation, production tracking, and after-hours connectivity. These digital demands prolong cognitive engagement beyond working hours, impair psychological detachment from work, and limit recovery. Studies show that workers exposed to both high physical workload and high digital demands report significantly higher fatigue scores and poorer sleep quality compared to those exposed to physical load alone [12].

Among schoolchildren, digital exposure is the dominant component of the exposome, but it interacts with physical inactivity, educational pressure, and psychosocial stress. Prolonged screen time often replaces physical activity, leading to musculoskeletal discomfort, postural strain, and reduced cardiorespiratory fitness. This combination of sedentary behavior and cognitive overload contributes to early manifestations of fatigue, decreased motivation, and impaired academic performance [13].

The interaction between physical and digital exposures is mediated by shared physiological pathways, including activation of stress-response systems, autonomic imbalance, and disruption of circadian rhythms. Chronic stimulation of these pathways accelerates the transition from adaptive fatigue to maladaptive chronic fatigue.

Cognitive impairment represents one of the most significant consequences of chronic fatigue resulting from complex exposome interactions. Sustained physical and digital stress affects attention, working memory, executive functions, and information processing speed.



These effects are observed across age groups, although their manifestation differs depending on developmental stage and exposure profile.

In schoolchildren, excessive digital load combined with insufficient recovery leads to reduced sustained attention, increased distractibility, and impaired learning efficiency. Experimental studies indicate that children exposed to high levels of multitasking and screen-based stimulation show up to a 30–40% reduction in working memory performance compared to peers with balanced digital use [14]. Chronic cognitive fatigue also negatively affects motivation and emotional regulation, further undermining academic engagement.

In automotive workers, cognitive fatigue manifests as reduced vigilance, slower reaction times, and impaired decision-making. These deficits have direct implications for occupational safety, as fatigue-related cognitive impairment increases the risk of errors and accidents. Research indicates that combined physical and cognitive fatigue may increase accident risk by up to 50% in industrial settings [15].

Importantly, cognitive consequences of fatigue are often underestimated because they develop gradually and may not be immediately recognized as health problems. From a preventive medicine perspective, early identification of cognitive fatigue is essential for preventing long-term functional decline.

Beyond cognitive impairment, chronic fatigue exerts profound effects on somatic and psychosocial health. Musculoskeletal pain, headaches, gastrointestinal complaints, and cardiovascular symptoms are commonly reported among individuals experiencing prolonged fatigue. These somatic manifestations reflect dysregulation of neuroendocrine and immune systems under chronic stress conditions.

In automotive workers, chronic fatigue is closely associated with musculoskeletal disorders, hypertension, and sleep disturbances. Epidemiological studies suggest that workers with high cumulative physical and digital exposure have a 1.5–2 times higher prevalence of chronic musculoskeletal pain and cardiovascular risk factors compared to workers with lower exposure levels [16]. These conditions further limit physical capacity and exacerbate fatigue, creating a self-perpetuating cycle.

Among schoolchildren, chronic fatigue is increasingly linked to psychosomatic complaints such as headaches, abdominal pain, and functional disorders. Psychosocial effects include irritability, anxiety, reduced social engagement, and decreased quality of life. Longitudinal studies indicate that early fatigue-related symptoms may predict later mental health problems if preventive measures are not implemented [17].

The psychosocial dimension of fatigue is particularly relevant in the context of digital environments, where constant connectivity and social comparison contribute to emotional stress. This highlights the importance of addressing social and emotional factors as integral components of the fatigue-related exposome.

Sleep and recovery represent central mediating mechanisms linking exposome exposures to chronic fatigue outcomes. Both physical overexertion and digital overload disrupt sleep quality and duration, impairing physiological recovery processes. Inadequate sleep exacerbates fatigue, cognitive impairment, and emotional dysregulation across age groups.

In automotive industry workers, shift work and extended working hours significantly interfere with circadian rhythms. Studies report that up to 50% of shift workers experience chronic sleep problems, which are strongly associated with fatigue severity and reduced work capacity [18]. Digital exposure outside working hours further delays sleep onset and reduces sleep efficiency, compounding recovery deficits.



In schoolchildren, evening screen use suppresses melatonin secretion and delays circadian phase, resulting in shorter sleep duration and poorer sleep quality. Children with insufficient sleep exhibit increased fatigue, reduced attention, and impaired memory consolidation. Evidence suggests that sleep duration mediates a substantial proportion of the association between screen time and cognitive performance [19].

From an exposome perspective, sleep disruption represents a critical node through which multiple exposures converge to produce chronic fatigue. Preventive strategies targeting sleep hygiene and recovery may therefore yield broad benefits across exposure domains.

Despite differences in age, lifestyle, and primary exposures, automotive workers and schoolchildren exhibit striking similarities in fatigue-related outcomes when analyzed through an exposome lens. Both groups experience chronic fatigue as a result of cumulative exposures exceeding adaptive capacity, leading to cognitive, somatic, and psychosocial consequences.

Automotive workers primarily accumulate fatigue through physical overexertion and occupational stress, while schoolchildren accumulate fatigue through digital overload and cognitive pressure. However, digital exposures increasingly affect workers, and physical inactivity and postural strain increasingly affect children, blurring traditional distinctions between age groups.

This convergence underscores the life-course nature of the fatigue-related exposome. Early exposure to digital overload and insufficient recovery in childhood may predispose individuals to reduced resilience and increased susceptibility to occupational fatigue later in life. Conversely, chronic fatigue in adulthood may influence family dynamics and social environments, indirectly affecting children's exposome.

From a public health perspective, chronic fatigue resulting from complex exposome interactions represents a significant and growing burden. High prevalence of fatigue-related disorders affects educational outcomes, workforce productivity, healthcare utilization, and overall quality of life. Traditional single-factor prevention strategies are insufficient to address this multifaceted problem.

An exposome-based approach enables identification of high-risk exposure profiles and supports targeted interventions at multiple levels, including individual behavior, organizational practices, and policy frameworks. Integrating physical and digital exposure assessment into preventive medicine can improve early detection of fatigue risk and enhance prevention effectiveness [20].

An exposome-based understanding of chronic fatigue necessitates a fundamental shift in preventive strategies, moving from isolated interventions toward integrated, multi-level approaches. Because chronic fatigue emerges from the cumulative and synergistic effects of physical, digital, psychosocial, and behavioral exposures, prevention must address these domains simultaneously. This approach is particularly relevant when considering different age groups, such as automotive industry workers and schoolchildren, who experience distinct yet overlapping exposure profiles.

At the individual level, prevention focuses on enhancing adaptive capacity and recovery. For adult workers, this includes improving physical fitness, promoting adequate sleep, and developing skills for managing digital demands. Evidence indicates that interventions targeting sleep hygiene, stress management, and physical conditioning can significantly reduce fatigue severity and improve work capacity [21]. Among schoolchildren, individual-level prevention emphasizes balanced screen use, regular physical activity, and development of self-regulation skills, which are essential for mitigating cognitive fatigue and emotional strain.



At the organizational level, exposome-oriented prevention involves modifying environments and systems that generate excessive exposures. In the automotive industry, ergonomic redesign of workstations, optimization of work–rest schedules, and limitation of after-hours digital demands are key strategies. Studies show that organizations implementing integrated fatigue management programs experience reductions of 20–40% in fatigue-related complaints and occupational injuries [15,22]. In educational settings, schools play a critical role by regulating digital learning intensity, incorporating offline learning activities, and promoting healthy daily routines.

Preventive medicine serves as a central coordinating discipline in exposome-based fatigue prevention. By integrating exposure assessment, health surveillance, and targeted interventions, preventive medicine enables early identification of individuals and groups at risk of chronic fatigue. In occupational settings, regular health examinations should include assessment of cumulative physical and digital exposures, sleep quality, and fatigue-related symptoms.

Occupational health services are particularly important for automotive workers, as they provide a platform for ongoing monitoring and intervention. Early detection of fatigue-related changes in musculoskeletal, cardiovascular, and neurocognitive function allows timely preventive action. Evidence suggests that systematic fatigue screening combined with ergonomic and organizational interventions reduces progression to chronic fatigue and long-term disability [2,6].

In pediatric and school health services, preventive medicine focuses on monitoring cognitive performance, sleep patterns, and digital behavior. School-based health programs that integrate digital hygiene education and fatigue prevention have demonstrated improvements in attention, academic performance, and psychological well-being among students [24].

Digital hygiene represents a critical cross-cutting component of exposome-oriented prevention across age groups. Although digital exposure manifests differently in workers and schoolchildren, its cumulative impact on cognitive load, sleep, and recovery is a common pathway to fatigue. Establishing clear guidelines for digital device use, limiting unnecessary digital demands, and promoting conscious technology use are essential preventive measures.

For adult workers, digital hygiene includes setting boundaries around work-related digital communication outside working hours, reducing multitasking demands, and optimizing digital workflows to minimize cognitive overload. Research indicates that limiting after-hours digital connectivity improves sleep quality and reduces fatigue-related symptoms [2,5].

For schoolchildren, digital hygiene focuses on age-appropriate screen time limits, structured use of educational technologies, and restriction of screen exposure before bedtime. Public health guidelines emphasize the importance of parental involvement and school policies in shaping healthy digital habits [3,6,15].

A key contribution of the exposome approach is its emphasis on the life-course perspective. Chronic fatigue does not arise suddenly in adulthood but may be rooted in early-life exposures that shape resilience and vulnerability. Excessive digital load, sleep deprivation, and cognitive stress during childhood may impair development of regulatory systems, increasing susceptibility to occupational fatigue later in life.

Conversely, chronic fatigue in adult workers may influence family environments and social dynamics, indirectly affecting children's exposome through parental stress, reduced engagement, and altered routines. This bidirectional relationship underscores the



intergenerational nature of fatigue-related exposures and highlights the importance of early prevention.

From a public health standpoint, addressing fatigue across the life course can yield long-term benefits by enhancing resilience, reducing disease burden, and improving quality of life. Exposome-oriented prevention thus aligns with broader goals of sustainable health development and intergenerational equity.

The growing prevalence of chronic fatigue associated with complex exposome interactions has significant implications for public health policy. Traditional health policies often address physical workload, digital behavior, or mental health separately. However, the exposome perspective calls for integrated policies that recognize the interconnected nature of these exposures.

Public health surveillance systems should incorporate indicators of cumulative physical and digital load, sleep quality, and fatigue-related outcomes. Such data would enable identification of high-risk populations and evaluation of preventive interventions. Policy frameworks supporting healthy work environments, balanced digitalization of education, and protection of recovery time are essential for reducing population-level fatigue burden [27].

In both occupational and educational contexts, intersectoral collaboration is crucial. Health authorities must work alongside labor, education, and digital governance sectors to design coherent and effective prevention strategies.

**Conclusions:** Chronic fatigue represents a complex and increasingly prevalent health condition arising from the cumulative effects of diverse exposures across the life course. This review demonstrates that chronic fatigue should be understood not as an isolated clinical entity, but as a multidimensional outcome of a complex exposome encompassing physical, digital, psychosocial, and behavioral factors. Using the example of automotive industry workers and schoolchildren, the article illustrates how different exposure profiles converge to produce similar fatigue-related consequences affecting cognitive, somatic, and psychosocial health.

In automotive industry workers, chronic fatigue primarily results from sustained physical overexertion, occupational stress, and insufficient recovery, increasingly compounded by digital demands. In schoolchildren, excessive digital exposure, cognitive overload, sleep disruption, and educational pressure constitute the dominant components of the fatigue-related exposome. Despite these differences, both groups exhibit shared pathways of fatigue development, including autonomic imbalance, sleep disturbance, and impaired cognitive regulation.

The exposome-based approach offers significant advantages for preventive medicine by enabling comprehensive risk assessment and integrated intervention strategies. Addressing physical and digital exposures in isolation is insufficient; effective prevention requires coordinated action at individual, organizational, and policy levels. Preventive medicine, occupational health, and school health services play central roles in implementing exposome-oriented strategies, including exposure monitoring, health education, and environmental modification.

In conclusion, recognizing chronic fatigue as a product of a complex exposome provides a robust framework for advancing prevention across age groups. Exposome-oriented prevention has the potential to reduce fatigue-related health burden, improve cognitive and occupational functioning, and enhance quality of life throughout the life course. Integrating this perspective into public health practice and policy is essential for addressing the evolving challenges of modern work and education environments.



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