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Impact of wildfire smoke, heat stress and sleep deprivation on the brain health of wildland firefighters

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ABSTRACT

Wildland firefighters (WLFFs) face significant brain health risks due to prolonged exposure to smoke, extreme heat, dehydration, physical exertion and irregular sleep patterns. Here, the literature is presented as a narrative review on studies that inform our knowledge on WLFF brain health. The neurotoxic components of wildfire smoke, such as particulate matter, carbon monoxide and polycyclic aromatic hydrocarbons, can disrupt brain function by inducing oxidative stress, neuroinflammation and hypoxia, which can contribute to cognitive decline and increase the risk of neurodegenerative diseases. Chronic heat exposure can exacerbate these risks leading to impaired cognitive functions including attention, memory, and decision-making. Sleep deprivation and extended shifts can compound cognitive and mood impairments through elevated stress hormone levels and inflammatory cytokines. Psychological stressors in wildland firefighting, including exposure to traumatic events, increase vulnerability to post-traumatic stress, anxiety, depression and suicidal ideation. Protective strategies for WLFFs should include personal protective equipment, hydration protocols, extended recovery periods and mental health programs. Future research should focus on long-term studies to fully understand the cumulative effects of these occupational hazards on brain health and inform policy changes to safeguard WLFF well-being. This holistic approach is critical as fire seasons become longer and more intense due to climate change.

Keywords: brain health, cognitive, dehydration, dementia, heat, mental health, sleep, wildfire, wildfire smoke, wildland firefighters.

Introduction

Relevance of studying the effects of wildfire smoke, heat stress and other factors on brain health

The increasing frequency and intensity of wildfires globally, driven by climate change, have highlighted the health impacts of wildfire smoke and heat stress (Black *et al.* 2017; Liu *et al.* 2023). WLFFs, who confront these severe environmental hazards, face unique occupational risks that increase their vulnerability to neurological and cognitive health issues. These risks include inhalation of wildfire smoke containing hazardous air pollutants like particulate matter (PM), volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs) and carbon monoxide (CO), as well as prolonged exposure to extreme heat, physical exertion and psychological stress (Black *et al.* 2017; Liu *et al.* 2023). The significance of these studies is underscored by the growing body of evidence linking air pollution, heat and stress to neurological dysfunction, inflammation and potential long-term cognitive impairments (as reviewed in White 2024). By examining the effects of these hazards on brain health, research could reveal broader implications for at-risk populations, such as WLFFs, who are exposed to chronic environmental stressors (McGeehin and Mirabelli 2001; Black *et al.* 2017; Liu *et al.* 2023).

Overview of wildfires, and the composition of wildfire smoke

Wildfire smoke is a complex and variable mixture of gaseous and particulate pollutants whose composition depends significantly on the materials being burned, whether vegetation, buildings, or synthetic materials, particularly in the wildland–urban interface (WUI). The presence of multiple toxic substances in wildfire smoke raises concerns about both acute and chronic health impacts. Among these, fine particulate matter ($PM_{2.5}$) is one of the most hazardous components due to its ability to penetrate deep into the lungs and enter the bloodstream, exerting systemic effects. $PM_{2.5}$ exposure has been strongly linked to cardiovascular, respiratory and neurological diseases, including stroke and cognitive decline, with neurotoxic effects potentially mediated through oxidative stress and neuroinflammation (DeFlorio-Barker *et al.* 2019; Delgado-Saborit *et al.* 2021; Chen *et al.* 2024). Additionally, CO, which is a product of incomplete combustion, poses a significant risk by reducing blood oxygen-carrying capacity, resulting in hypoxia, dizziness, confusion, and in severe cases, unconsciousness or death. Chronic exposure to lower CO levels, such as that experienced by firefighters, may contribute to cumulative cognitive effects (Reisen and Brown 2009; Henn *et al.* 2019). Wildfire smoke also contains various VOCs, including benzene and formaldehyde, as well as PAHs. Both are potentially carcinogenic and also known to impair nervous system function. Prolonged exposure to VOCs has been associated with memory impairment, attention deficits and other cognitive dysfunctions (Dickinson *et al.* 2022). Furthermore, nitrogen dioxide (NO_2) and ozone (O_3) are common in wildfire smoke, acting as respiratory irritants with potential neurological consequences. NO_2 exposure has been linked to neuroinflammation, while O_3 exposure has been associated with oxidative brain tissue damage. WLFFs are particularly vulnerable to elevated levels of these gases, increasing their risk of harmful neurological effects (Chen *et al.* 2023; Sethi *et al.* 2024).

Neurotoxicants in wildfire smoke

The presence of neurotoxicants like $PM_{2.5}$, CO, and VOCs in wildfire smoke highlights the potential for these pollutants to impact brain health. Exposure to these substances can induce neuroinflammation, disrupt the blood-brain barrier (BBB), and potentially accelerate neurodegenerative processes (Wang *et al.* 2017) (Fig. 1). Due to the chronic and cumulative nature of exposure for WLFFs, understanding the specific neurological effects and potential long-term consequences is essential for developing protective and intervention strategies (Reisen *et al.* 2011; Kim *et al.* 2020; Scieszka *et al.* 2022).

Inhalation is the primary route of exposure for WLFFs, as they are continuously breathing in air contaminated with smoke, $PM_{2.5}$ and gases during fire control and suppression activities. In addition to inhalation, WLFFs may absorb neurotoxic substances through their skin. While dermal exposure is generally less significant than inhalation, it still poses a risk, especially in high-heat environments, where sweating increases skin permeability, facilitating the absorption of toxicants (Hwang *et al.* 2021).

Overview of thermal stress impact on the brain

Thermal stress arises when the body is exposed to extreme heat, disrupting its ability to regulate core temperature. This condition is particularly dangerous when environmental heat surpasses the body's capacity for cooling through natural processes such as sweating and vasodilation. Thermal stress is a significant occupational hazard for WLFFs, who work in intense heat for extended periods, often wearing protective gear that can restrict heat dissipation. The protective clothing and personal protective equipment (PPE)

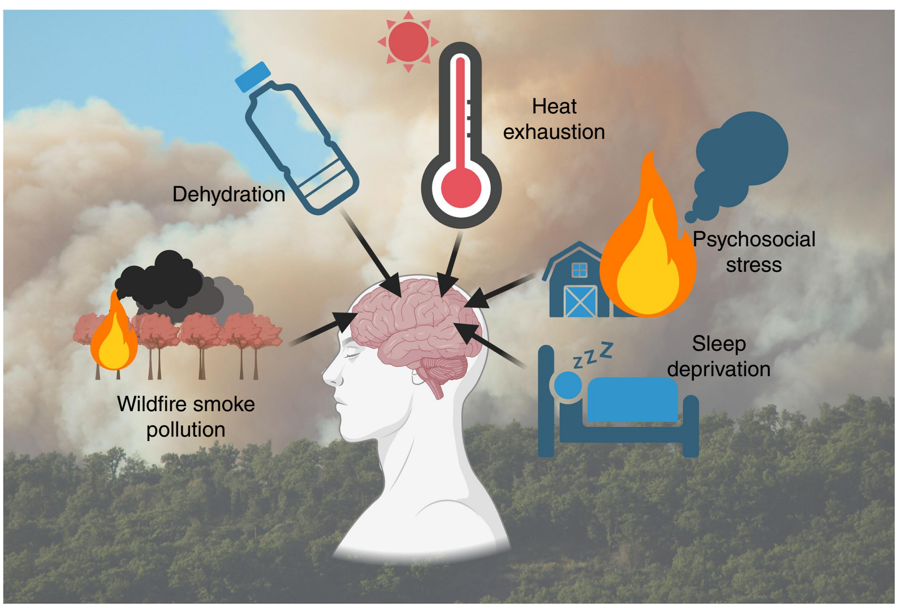

Fig. 1. Wildland firefighting can impact brain health through effects of wildfire smoke, dehydration, heat exhaustion, sleep deprivation and psychosocial stress. Created in https://BioRender.com.

can additionally cause thermal stress even in absence of high temperatures, especially during strong physical exertion (Ghiyasi *et al.* 2020). Factors like dehydration and physical exertion further intensify physiological strain (Wald 2019; Donnan *et al.* 2021; Ruby *et al.* 2023; Held *et al.* 2024).

When exposed to excessive heat, several physiological mechanisms may impair brain function, posing significant risks to cognitive and neurological health. Extreme heat exposure can disrupt brain homeostasis by altering neurotransmitter function, impairing synaptic signaling and disrupting cellular processes within the central nervous system (CNS). Elevated core temperatures also increase BBB permeability, allowing harmful substances such as inflammatory molecules and toxins to infiltrate the brain, potentially triggering neuroinflammation (Kiyatkin and Sharma 2009; Sharma *et al.* 2016). Heat stress is further linked to elevated levels of pro-inflammatory cytokines that can cross a compromised BBB, initiating inflammatory responses in brain tissue that may damage neurons and glial cells, resulting in impaired cognitive function. Concurrently, oxidative stress from excessive heat exposure generates reactive oxygen species (ROS), which damage cellular components such as DNA, proteins and lipids, contributing to neuronal degeneration (Leon and Helwig 2010; Audet *et al.* 2016). Cognitive impairments induced by extreme heat particularly affect executive functions like decision-making, attention and memory, posing risks to those working in high-temperature environments, such as wildland firefighters, who may experience cognitive fatigue, confusion, slower reaction times and diminished situational awareness. These effects not only endanger personal health but also increase the likelihood of operational errors as has been reported in studies on non-WLFF populations (Hancock and Vasmatzidis 2003; Ebi *et al.* 2021; Kuo *et al.* 2024). Prolonged exposure to high temperatures may further result in heatstroke, a severe condition characterized by core body temperatures exceeding 40°C (104°F), which leads to thermoregulatory failure and CNS dysfunction. Symptoms of heatstroke may include disorientation, seizures, loss of consciousness, and, in severe cases, brain damage or death (Leon and Bouchama 2015; Wang *et al.* 2024; White 2024).

Long-term consequences of thermal stress on brain health

The long-term effects of chronic thermal stress on brain health are an emerging area of concern, particularly for individuals such as WLFFs who are repeatedly exposed to high-heat environments. Chronic exposure to heat stress and recurring episodes of heat-related illnesses may lead to lasting alterations in brain function. Evidence suggests that persistent neuroinflammation and oxidative stress can contribute to neurodegenerative processes, raising the risk of cognitive decline and disorders such as dementia later in life, as reported in studies on mice and non-WLFF populations (Lee *et al.* 2015; Chauhan *et al.* 2021; Zhu *et al.* 2023). Furthermore, the interaction between thermal stress and other environmental hazards, such as smoke inhalation and physical exertion, may amplify these risks, emphasizing the importance of preventive measures to safeguard brain health in vulnerable populations (Martin *et al.* 2019; Bongioanni *et al.* 2021; White 2024).

Cognitive and psychological impacts on wildland firefighters

WLFFs are regularly exposed to various environmental stressors including smoke, heat, physical exertion and psychological strain. These exposures can lead to a range of cognitive and psychological impacts, both in the short and long term. The combination of neurotoxic exposures and the demanding nature of their work significantly elevates the risk for cognitive impairments and psychological disorders (Fig. 1).

WLFFs are at heightened risk of cognitive and psychological impairments due to prolonged exposure to heat, smoke and physically demanding conditions. Executive function deficits are commonly reported, manifesting as difficulties with decision-making, problem-solving and attention. The combination of extreme environmental exposure and physical exhaustion can impair cognitive flexibility, resulting in slower reaction times and compromised judgment in high-pressure situations (Williams-Bell *et al.* 2017; Lee *et al.* 2022; Thompson *et al.* 2023). Additionally, studies on both adults and children show that memory impairments are associated with long-term exposure to pollutants such as $PM_{2.5}$ and VOCs in wildfire smoke, with repeated hypoxia from CO exposure and neuroinflammation further disrupting brain circuits and impairing information retention and recall (Haghani *et al.* 2020; Jalaludin *et al.* 2022). Attention and concentration issues are also prevalent, particularly during prolonged shifts and extended heat exposure. Fatigue, combined with the cumulative effects of smoke inhalation, contributes to these deficits, increasing the risk of lapses in situational awareness (Wen and Burke 2022; Pauletti *et al.* 2024).

The psychological toll of firefighting is significant, with WLFFs frequently exposed to traumatic events such as life-threatening fires, evacuations, and destruction of property and natural landscapes. These experiences heighten the risk of developing post-traumatic stress disorder (PTSD), characterized by intrusive thoughts, nightmares, hyperarousal and emotional numbing, which may affect both professional performance and personal relationships (Psarros *et al.* 2018). Chronic stress is also common, contributing to anxiety and depression, with symptoms including hopelessness, fatigue, irritability and sleep disturbances, often compounded by exposure to scenes of destruction and loss (Lane 2024). Firefighter burnout is another major concern, resulting from long shifts, sleep deprivation and intense physical demands. Burnout symptoms, emotional exhaustion, depersonalization and reduced personal accomplishment, can, in extreme cases, progress into clinical depression (Maphis 2011).

Sleep disturbances are widespread among WLFFs, exacerbated by demanding work schedules, environmental stress and anxiety. Chronic sleep deprivation worsens cognitive issues such as attention deficits, memory impairments and mood disorders, while also increasing the long-term risk of anxiety, depression, and dementia (Aisbett *et al.* 2012; Vincent *et al.* 2018; Jeklin *et al.* 2020). In an effort to cope with the psychological burden of firefighting, some WLFFs may turn to substance use, including alcohol and drugs, further worsening mental health outcomes and heightening the risk of cognitive and psychological decline (Scott *et al.* 2024).

Empirical research investigating the effects of heat and dehydration on brain health in WLFFs

Effects of heat and dehydration on cognitive performance in WLFFs

The cognitive performance of WLFFs is significantly influenced by environmental stressors such as extreme heat and dehydration, which are prevalent during wildfire suppression efforts. WLFFs undertake physically demanding manual tasks (Phillips *et al.* 2012) in high temperatures that can reach between 45 and 50°C (Teague *et al.* 2010). These tasks are generally performed in personal protective clothing that can have high heat retaining properties (Barr *et al.* 2010). These conditions can lead to severe dehydration losses of up to 2–4% of body weight. To better understand these effects, researchers have conducted both experimental and observational studies exploring the impacts of heat and dehydration on cognitive performance. Previous studies have shown that high levels of physical activity and dehydration can lead to cognitive impairment (Gopinathan *et al.* 1988). In contrast, other studies have shown that such dehydration was not associated with changes in cognitive performance compared to non-dehydrated controls (Serwah and Marino 2006). However, it has been suggested that in these studies, a lack of cognitive change may have been due to the simplicity of the cognitive tasks being tested (Radakovic *et al.* 2007). Impairment of cognitive function may be more likely to occur when more complex cognitive tests are performed under these conditions (Radakovic *et al.* 2007; Morley *et al.* 2012).

Several key studies have investigated these factors in WLFFs, providing critical insights into how they affect brain function during high-stress, physically demanding tasks. Distinguishing between experimental and epidemiological study designs is crucial for interpreting these findings. An experimental study involves researchers deliberately altering a variable to examine its impact on a particular outcome. In contrast, an epidemiological study involves observing existing patterns and relationships between variables within a population without direct intervention. Consequently, researchers in epidemiological studies cannot control exposure factors as they would in experimental research, and these differences should be considered in assessing the two types of studies on WLFF health. Experimental research by Cvirn *et al.* (2019) and Williams-Bell *et al.* (2017) highlights how these stressors influence cognitive abilities, particularly in the context of wildland firefighting. Cvirn *et al.* (2019) examined the effects of temperature and dehydration on 73 volunteer firefighters (35.7 ± 13.7 years, mean age ± standard deviation) during a simulation of wildfire suppression under either control or hot conditions (18–20°C; or 33–35°C). Their findings revealed that dehydration significantly slowed reaction times (RTs) in hot conditions, with pronounced effects in the late afternoon. The study used the Psychomotor Vigilance Task (PVT), which measures reaction times and lapses in attention (Dorrian *et al.* 2004), and the Stroop task, a measure of executive function of response inhibition, which have previously been reported during studies on dehydration (Szinnai *et al.* 2005). Cvirn *et al.* (2019) found that when firefighters were exposed to hot conditions (33–35°C) and were dehydrated, their reaction times RTs on the PVT were significantly slower compared to when they were adequately hydrated. The mean RT increased substantially, with the most pronounced effects occurring in the late afternoon (17:50 hours compared to 13:50 hours ($P < 0.001$) and 15:50 hours ($P = 0.002$). Furthermore, the study revealed that dehydration impacted executive functions, particularly response inhibition as measured by the Stroop task, regardless of temperature. Although there can also be natural diurnal variations in cognitive function that may occur regardless of hydration and other factors (Munnilari *et al.* 2024), the findings in this study indicated that critical cognitive functions such as decision-making, situational awareness and response inhibition can be compromised when firefighters are both dehydrated and fatigued. These impairments pose significant safety risks in real-world wildland firefighting scenarios, where quick decision-making is essential to ensuring safety (Cvirn *et al.* 2019).

In another simulated study, Williams-Bell *et al.* (2017) explored the effects of continuous and intermittent heat exposure on cognitive performance during fireground tasks, focusing on the role of hydration. Interestingly, their findings indicated that maintaining euhydration played a protective role, stabilizing cognitive performance even in extreme temperatures. In this study, male volunteer firefighters completed tasks in both thermoneutral (CON) and hot (HOT, 45°C) environments. The authors applied The Cambridge Neuropsychological Test Automated Battery (CANTAB) cognitive testing battery for this study. CANTAB comprises of testing batteries that cover three different areas of cognition, including decision making, analytical thinking and problem solving, and situational awareness (Romero and Hayes 2010). Notably, Williams-Bell *et al.* (2017) found that cognitive performance remained stable in both conditions, which the study attributed to the maintenance of euhydration – adequate water intake that likely helped mitigate the potential cognitive declines associated with heat exposure. The ability to maintain euhydration can potentially play a protective role in sustaining cognitive stability during physically and mentally demanding tasks, such as those faced by wildland firefighters (Williams-Bell *et al.* 2017).

Beyond hydration, other environmental stressors further compound the risk of cognitive decline. Aisbett *et al.* (2012) published a review of combined impact of heat, smoke and sleep disruption on physical and cognitive performance in WLFFs. In particular, the review by Aisbett *et al.* (2012) highlighted that firefighters subjected to prolonged high temperatures during fire suppression tasks, when combined with insufficient sleep, exhibited substantial declines in attention, memory and motor coordination. These impairments significantly reduce a firefighter's ability to make quick decisions and perform critical tasks, increasing the risk of accidents or mistakes in high-pressure environments. The combination of extreme heat, fatigue and other environmental stressors such as smoke inhalation creates a cumulative risk, exacerbating the already demanding cognitive load WLFFs experience during wildfire suppression tasks (Aisbett *et al.* 2012).

Given these insights, it is crucial to implement preventative strategies to safeguard cognitive function in WLFFs. The findings emphasize the importance of implementing strategies that focus on hydration, rest and cooling mechanisms to protect cognitive function during extended firefighting efforts. There are well-established associations between heat stress, cognitive function and workplace incidents (Tawatsupa *et al.* 2013). WLFF mental functions can potentially deteriorate during dehydration and especially in conjunction with high temperatures and at late afternoon. Fire agencies should therefore be active in responding to these potential cognitive concerns during high temperatures and long shifts. This can be further exacerbated by the fact firefighters can arrive on shift already dehydrated (Ruby *et al.* 2003; Cuddy *et al.* 2008; Raines *et al.* 2012). An important implication of these findings is that dehydration late in a shift could impair ability to plan, co-ordinate and undertake life-saving exit strategies based on incoming cues from the environment and centralized information sent out regarding changing fire conditions. Maintaining cognitive performance in such extreme environments is essential to ensuring both physical and mental resilience in WLFFs. Key studies are summarized in Supplementary Table S1.

Impact of extended shifts and sleep deprivation

The impact of extended shifts and chronic sleep deprivation on WLFF cognitive performance is closely linked to the environmental and physical demands they face during wildfire suppression. Prolonged work shifts and chronic sleep deprivation are significant stressors affecting the brain health and cognitive performance of WLFFs. This section expands on these challenges, exploring the physiological and psychological impacts of disrupted sleep patterns on cognitive function (Supplementary Table S2). The combination of demanding physical tasks, exposure to extreme environmental conditions and irregular work schedules can result in suboptimal sleep and long-term cognitive impacts. Previous studies have shown that multiple days of sleep loss can lead to chronic sleep deprivation linked to impaired neurocognitive performance, together with compromised judgment, and poor hazard recognition (Harrison and Horne 2000; Van Dongen *et al.* 2003; Durmer and Dinges 2005). In a previous study by Haslam (1982), soldiers receiving either no sleep, 1.5 or 3 h sleep over successive 24-h periods revealed substantial decline in visual vigilance, reaction time and speed at which they responded to orders or numerical code substitution tasks. Numerous supporting studies have since corroborated the impact of sleep deprivation on cognitive function in the military and other situations (Rice and Schroeder 2019; Ritland *et al.* 2019; Buguet *et al.* 2023). Studies on WLFFs and other highly physically demanding work has shown that a disproportionate number of workplace injuries occur in these situations when compared to typical shift workers (Aisbett *et al.* 2012; Britton *et al.* 2013). Studies by Jeklin *et al.* (2020), Wolkow *et al.* (2016) and Aisbett *et al.* (2012), investigated detrimental effects of extended shifts and sleep restriction on cognitive performance, mood and inflammatory responses, underscoring the need for better recovery strategies and interventions to protect the mental and physical wellbeing of WLFFs.

Building on this, research by Jeklin *et al.* (2020) provides valuable data on the long-term cognitive effects of sustained sleep loss during wildfire suppression. Jeklin *et al.* (2020) conducted a cohort study that monitored the sleep and fatigue patterns of British Columbia Wildfire Service (BCWS) firefighters during a 17-day deployment. In this study, 30 firefighters worked 14 consecutive days on the fire line, followed by three rest days. Despite these rest periods, the findings revealed that firefighters averaged 6.6 h of sleep per night during fire days, compared to 6.8 h during rest days. Both figures fall below the recommended 7–9 h of sleep for adults, resulting in chronic sleep debt. The cognitive consequences of this sleep deprivation were again assessed using the PVT test. By Day 13 of the deployment, firefighter reaction times had slowed significantly, with a mean RT of 267.1 ms compared to 253.4 ms on Day 5 ($P = 0.025$). The data showed a clear trend toward declining cognitive performance as the deployment progressed (Jeklin *et al.* 2020).

To investigate the physiological mechanisms underlying these effects, Wolkow *et al.* (2016) explored the role of inflammatory responses and cortisol dysregulation associated with sleep deprivation. Their findings demonstrated that restricted sleep triggers inflammatory markers such as interleukin-6 (IL-6) and tumor necrosis factor-alpha (TNF-α), which are known to impair cognitive function and mood stability. This has important implications for wildfire firefighters, who often face extended shifts with limited recovery time, potentially heightening their vulnerability to cognitive deficits, mood disturbances and long-term neurological risks.

In particular, this study involved simulated wildfire suppression tasks, followed by either normal sleep (control group) or restricted sleep (sleep-restricted group) each night. In this study, participants completed 3 days of simulated wildfire suppression work with an 8-h (control condition; $n = 18$) or 4-h sleep break (sleep restriction; $n = 17$) each night. The mood of the participants was assessed daily using the Mood Scale II and Samn-Perelli fatigue scale. Firefighters also provided samples for measurement of salivary cortisol and pro-inflammatory cytokines. The results showed that the sleep-restricted group experienced heightened levels of fatigue, slower reaction times, and elevated levels of inflammatory markers such as IL-6 and TNF-α, cytokines that have been linked to cognitive decline and mood disturbances (Feng *et al.* 2023). This aligns with broader evidence suggesting that inflammatory responses can exacerbate cognitive fatigue during high-intensity tasks like wildfire suppression. Firefighters in the sleep-restricted group also reported increased feelings of fear and fatigue, which likely exacerbated the cognitive deficits observed during the fire suppression tasks. This highlights the direct relationship between sleep loss, inflammatory responses and impaired cognitive and emotional health in firefighters, although, as presented above, information obtained in such simulated studies as conducted here, should be treated with some caution for their translation to real-world wildland firefighting where many additional factors can affect outcomes (Wolkow *et al.* 2016).

Furthermore, the review by Aisbett *et al.* (2012) emphasized the cumulative burden on WLFFs, through highlighting the compounding effects of sleep deprivation, environmental stressors and physical exertion. As indicated above, studies have examined how sleep deprivation affects performance and health of WLFFs. This research revealed that WLFFs frequently obtain as little as 3–6 h of sleep during multi-day fire suppression activities, well below the required level to maintain optimal cognitive function. Moreover, as described above, the combination of sleep deprivation and the physical exertion required during fire suppression creates a feedback loop, where cognitive decline is exacerbated by ongoing fatigue and inflammatory responses.

One of the key physiological findings from the Wolkow *et al.* (2016) study was the relationship between sleep deprivation and cytokine release, particularly IL-6 and TNF-α. These cytokines are known to impair cognitive function by disrupting the hypothalamic-pituitary-adrenal (HPA) axis, which regulates cortisol levels in the body (Mikulska *et al.* 2021; Feng *et al.* 2023). Wolkow *et al.* (2015) also revealed that elevated cytokine levels, particularly under conditions of restricted sleep, are correlated with abnormal cortisol patterns. This dysregulation of the HPA axis can impair memory, mood and overall cognitive function. Exposure to either physical or psychological stresses can prompt inflammatory responses (Maier and Watkins 1998), which can subsequently activate the HPA axis, leading to cortisol release. Changes in immune and endocrine functions are linked to affective states (Mittwoch-Jaffe *et al.* 1995; Kemeny and Gruenewald 2000), suggesting that the activation of these physiological systems in response to stress, along with the release of cortisol and cytokines, establishes a bi-directional network with the brain (Maier and Watkins 1998; Maier 2003). The positive association between negative mood, inflammatory markers and cortisol levels with physical exertion and restricted sleep offers valuable insights for fire agencies into subjective fire-ground measures of physiological changes.

Chronic inflammation is a well-established factor in the development of neurodegenerative diseases such as Alzheimer's disease. For WLFFs, who endure repeated episodes of sleep disruption, inflammation, and extreme physical exertion over the course of a fire season, the cumulative impact on brain health may be significant. The findings by Wolkow *et al.* (2016) suggest that interventions aimed at reducing inflammation, improving sleep hygiene and providing adequate rest periods are crucial for mitigating the cognitive risks associated with sleep deprivation in this population. Additionally, the persistence of cognitive impairments observed in the study by Jeklin *et al.* (2020), even after a 3-day rest period, indicates that the current rest and recovery strategies for WLFFs may be insufficient for full cognitive and physiological recovery. Firefighters continued to report high levels of sleepiness and poor sleep quality during rest days, suggesting that more extended or structured rest periods may be necessary to allow for complete recovery. Given the complex interplay of heat exposure, dehydration and sleep deprivation, developing comprehensive strategies that address these combined stressors is vital for preserving the cognitive and physical well-being of WLFFs.

The role of smoke inhalation in cognitive decline

Smoke inhalation is a significant occupational hazard for WLFFs and has far-reaching consequences for brain health. While much of the research on smoke exposure in this population has traditionally focused on respiratory outcomes, there is a growing body of evidence pointing to the potential neurological effects of chronic exposure to wildfire smoke. The harmful components found in wildfire smoke, including PM, CO, and PAHs, can impair oxygen delivery to the brain, increase oxidative stress and inflammation, leading to both acute and long-term cognitive decline (Adetona *et al.* 2016).

CO binds to hemoglobin with a much greater affinity than oxygen, forming carboxyhemoglobin and reducing the oxygen-carrying capacity of the blood. This results in decreased oxygen delivery to the brain, leading to potential cognitive impairments. Bunnell and Horvarth (Bunnell and Horvath 1988) found that elevated levels of CO in wildfire smoke could impair several cognitive functions, including spatial processing, reaction time, and visual search tasks.

While the immediate effects of CO exposure might be subtle, repeated exposure during fire seasons poses the risk of cumulative cognitive deficits. Over time, chronic CO exposure could lead to significant impairments in cognitive function, particularly in tasks that require complex decision-making, attention and rapid response (Bunnell and Horvath 1988).

Moreover, individuals with compromised cardiovascular health, such as those with coronary artery disease, are at an even higher risk of experiencing cognitive decline due to CO exposure. Benignus and Coleman (2010) reported that CO interacts with pre-existing cardiovascular conditions, noting that WLFFs with underlying heart conditions may face more severe cognitive consequences than their healthier counterparts. This is particularly concerning, as firefighting is already a physically demanding job, and any exacerbation of cardiovascular strain through CO exposure could further deteriorate brain health.

Chronic exposure to PM has been linked to reduced cognitive function and an increased risk of neurodegenerative diseases, such as Alzheimer's and Parkinson's disease (Wang *et al.* 2021). PAHs, which are a class of organic compounds released during the combustion of organic material, are particularly abundant in wildfire smoke. Adetona *et al.* (2017) reported that firefighters exposed to PAHs during prescribed burns showed elevated levels of hydroxylated PAH metabolites in their urine, indicating significant internal exposure. This bioaccumulation of PAHs in the body is concerning because PAHs are known to generate reactive oxygen species (ROS) in the brain, which can lead to oxidative damage and inflammation (Tanaka *et al.* 2023). These oxidative processes can disrupt neuronal function and contribute to cognitive decline over time.

The effects of smoke inhalation on brain health are not limited to cognitive decline during active firefighting but may also have long-term implications. Chronic exposure to wildfire smoke may result in lasting damage to the brain's structure and function, increasing the likelihood of developing neurodegenerative diseases later in life. The cumulative impact of pollutants like CO, PM and PAHs can lead to persistent inflammation, impaired neurogenesis and the acceleration of brain aging (White 2024). This underscores the importance of further research into protective strategies that could mitigate neurological risks faced by WLFFs, such as improving air filtration technologies, developing effective PPE and implementing strategies to reduce overall smoke exposure. Key studies are summarized in Supplementary Table S3.

Psychosocial stress, PTSD, and suicide risk

Brain health and mental health are distinct, yet closely linked concepts, that when combined, shape cognitive and emotional well-being. Brain health generally refers to the brain's ability to function optimally in processes like memory, attention and decision-making, while mental health is usually associated with psychological and emotional stability (Eyre *et al.* 2023). Although mental health is influenced by social and environmental factors, it is also deeply connected to brain function through key biological mechanisms. Significantly, these mechanisms often interact in ways that create a reinforcing cycle, where deficits in one domain exacerbate vulnerabilities in the other. This interplay is particularly relevant in high-stress professions such as wildland firefighting. One significant link between brain and mental health is neuroinflammation (Dahoun *et al.* 2019). Environmental stressors such as heat, dehydration and smoke exposure can trigger inflammatory responses that disrupt neurotransmitter signaling and increase oxidative stress (Tost *et al.* 2015; Singh *et al.* 2022). Environmental stressors also impact mitochondrial function, reducing energy production in brain cells. These processes affect cognitive performance and mental health (Sun *et al.* 2023). In turn, psychological stressors such as anxiety, depression or post-traumatic stress can worsen these biological effects. Chronic mental stress promotes inflammation and hormonal dysregulation, which further impairs cognitive function, memory and decision-making (McEwen 2017). This bi-directional relationship is particularly concerning in populations like WLFFs, who frequently experience both environmental and psychological stressors. Chronic stress, anxiety and depression are also known to alter brain structure and function (Mariotti 2015), and prolonged stress can elevate cortisol levels, which may impair learning and memory functions leading to cognitive deficits (de Souza-Talarico *et al.* 2011). Additionally, conditions such as depression have been linked to decreased neurogenesis, reduced synaptic plasticity and impaired connectivity in key brain networks (Price and Duman 2020), further compromising cognitive performance. For populations such as wildland firefighters, these interconnected effects are especially critical.

A range of studies, such as those by Leduc *et al.* (2021), Smith (2024), Stanley *et al.* (2018), Zhang *et al.* (2022) and others, have shed light on the psychological toll that can affect WLFFs. Leduc *et al.* (2021) examined the psychosocial risk factors for WLFFs, identifying work demands, long shifts, and the unpredictable nature of firefighting as key contributors to elevated stress levels and burnout. To address these issues, Leduc *et al.* (2021) tested a psychosocial education intervention designed to increase WLFF awareness of workplace stressors while providing strategies for coping with psychological challenges. The intervention focused on critical areas such as civility, work-life balance and access to psychological support. These components were highlighted as essential for improving mental health outcomes in WLFFs. While interventions like this offer promise, they are often not enough to address the full extent of mental health risks faced by WLFFs.

Smith (2024) painted a more concerning picture of mental health in this population, focusing particularly on PTSD and suicide risk. The study revealed that WLFFs are disproportionately affected by suicidal thoughts and behaviors, with rates of suicide attempts higher than both the general population and their structural firefighter counterparts. PTSD symptoms, often triggered by the traumatic events associated with wildfire suppression (e.g. witnessing the destruction of homes and communities), were identified as a significant contributor to suicidal ideation. Stanley *et al.* (2018) corroborated these findings, also showing that WLFFs reported a higher risk of suicide than structural firefighters. This underscores how unresolved trauma, coupled with occupational stress, may create a compounding psychological burden that elevates suicide risk. This study pointed to 'thwarted belongingness,' or a sense of social isolation, as a key factor driving this elevated risk. The disconnection many firefighters feel from society, coupled with the intense demands of their job, exacerbates feelings of hopelessness and suicidality.

Zhang *et al.* (2022) explored the prevalence of PTSD in wildland firefighters in Australia following traumatic wildfire events and found that rates of probable PTSD were as high as 47.6%, three and a half years after a major wildfire. This long-term psychological impact underscores the lasting toll that wildfire exposure can have on firefighters. The persistence of these symptoms highlights that acute mental health responses can evolve into chronic conditions without sufficient intervention and support. Zhang's findings are consistent with earlier research by McFarlane (1986), who similarly reported high rates of psychiatric impairment and PTSD in WLFFs after major fire events. These studies highlight how chronic stress, trauma exposure and sleep deprivation can converge to create a 'perfect storm' of mental health risks, increasing the likelihood of suicide and long-term psychological decline (Zhang *et al.* 2022; Smith 2024).

The mental health toll on WLFFs is compounded by the continued stigma that can surround mental health in the firefighting community. Smith *et al.* (2022) reported that many wildland firefighters in an Australian study were reluctant to seek mental health support for fear of being perceived as 'weak' or jeopardizing their careers. This culture of silence around mental health creates barriers to accessing necessary resources, leaving many firefighters without the psychological support they need. As noted in the Smith study of volunteer firefighters who responded to the Black Summer bushfires in Australia, 4.5% of respondents reported probable PTSD, 4.6% experienced high levels of psychological distress and another 4.6% had seriously considered suicide in the year following the fires. These rates are significantly higher than those seen in the general population, further illustrating the intense psychological burden that WLFFs face. The reluctance to seek help exacerbates this burden, with many firefighters internalizing their struggles rather than reaching out for professional support (Smith *et al.* 2022).

Given the cumulative impact of environmental, occupational, and psychological stressors, addressing the mental health challenges faced by WLFFs requires multi-faceted strategies. The combination of sleep deprivation, chronic stress, and exposure to traumatic events places WLFFs at significant risk for mental health problems. While short-term interventions, such as those implemented by Leduc *et al.* (2021), can provide some relief, the long-term mental health needs of this population require more comprehensive strategies. These strategies should include regular mental health screenings, access to counseling services and peer support networks to mitigate the risks of PTSD, depression and suicide. Additionally, addressing the stigma surrounding mental health in firefighting culture is crucial for encouraging firefighters to seek the support they need without fear of judgment or career repercussions.

Stanley *et al.* (2018) emphasized the importance of fostering a supportive organizational culture that promotes social connection and belonging among firefighters. Given that 'thwarted belongingness' is a key driver of suicide risk, creating environments where firefighters feel supported by their peers and connected to their communities is essential. This could involve formal peer-support programs, open dialogs about mental health within firefighting teams and leadership initiatives prioritizing psychological well-being of crew. By combining proactive intervention strategies with cultural change, fire agencies may better protect the mental well-being of their workforce. Key studies are summarized in Supplementary Table S4.

The role of inflammation and immune response in brain health impacts

Beyond the cognitive and psychological effects of firefighting, WLFFs are also subject to physiological changes that can influence brain health. Wolkow *et al.* (2016) investigated the relationship between mood, cytokine levels, and cortisol in response to physical firefighting work and sleep restriction. This study found that positive mood changes, such as feelings of happiness and activation, were associated with lower levels of pro-inflammatory cytokines, including IL-6 and TNF-α. Conversely, negative mood states, such as fatigue and fear, were linked to increased levels of inflammatory cytokines (Wolkow *et al.* 2016).

The bi-directional communication between the brain and the immune system plays a critical role in how firefighters respond to stress. The release of cytokines and cortisol in response to physical and psychological stressors not only affects immune function but also influences mood and cognitive performance (Zhao *et al.* 2022). Chronic exposure to high levels of stress hormones and cytokines may contribute to cognitive impairments and mood disturbances observed in sleep-deprived WLFFs (Wolkow *et al.* 2016). Key studies are summarized in Supplementary Table S5.

Study limitations in research on Wildland Firefighter brain health

Research on the brain health of WLFFs is still developing, and several limitations affect the validity and applicability of current findings. These limitations include methodological issues, potential biases, confounding factors and a lack of comprehensive longitudinal data. Addressing these limitations is essential for understanding the true impact of wildfire exposure on neurological and cognitive health in this population.

Lack of longitudinal data

A major limitation in studies on WLFF brain health is the lack of long-term, longitudinal data. Most research focuses on short-term effects or cross-sectional assessments, which only provide a snapshot of cognitive and neurological status. This approach is inadequate for capturing the long-term consequences of repeated exposure to wildfire smoke, heat stress and physical exertion, especially since neurological conditions like cognitive decline, neuroinflammation and neurodegenerative diseases can develop over years. Without longitudinal studies tracking firefighters over multiple fire seasons and throughout their careers, it is challenging to assess the cumulative and progressive effects of occupational exposures (Adetona *et al.* 2016; Barbosa *et al.* 2024).

Potential biases in study design and recruitment

Several biases can affect outcomes in research on wildland firefighters' brain health. Selection bias is an issue where studies often recruit active firefighters, potentially excluding retired or former firefighters who may have left due to health issues, skewing findings toward healthier individuals and underestimating the true burden of cognitive and neurological disorders (Semmens *et al.* 2016). Recall bias can occur in studies that rely on self-reported data for exposure history (e.g. fires fought, hours of smoke exposure) and mental health symptoms, which can introduce recall bias if participants inaccurately report their exposures and health impacts (Moody *et al.* 2019).

Confounding Factors

Multiple confounding factors complicate the interpretation of findings in WLFF research. Pre-existing health conditions, where firefighters may have health issues unrelated to occupational exposures, like cardiovascular disease or genetic predispositions to neurological disorders, can confound results (Schulte and Chun 2009; Rajnoveanu *et al.* 2022). Lifestyle factors can also include cases where firefighters maintain high levels of physical fitness, which could have neuroprotective effects, confounding associations between occupational exposures and brain health. Conversely, stress-related substance use could worsen cognitive outcomes (Sidossis *et al.* 2023).

Limited control groups

Few studies include appropriate control groups for comparison. Without baseline comparisons to non-exposed populations or control groups of structural firefighters, it is difficult to isolate the specific impacts of wildfire exposure. Control groups that are used may not be sufficiently matched for factors such as age, fitness, or socioeconomic background, complicating results (Adetona *et al.* 2016; Pelletier *et al.* 2022).

By addressing these limitations, future research can potentially provide more accurate and comprehensive insights into the cognitive and neurological impacts of wildland firefighting and ultimately lead to better protective measures and interventions for WLFFs.

Conclusions and future directions

The cumulative findings from these studies underscore the significant health risks faced by WLFFs, particularly in terms

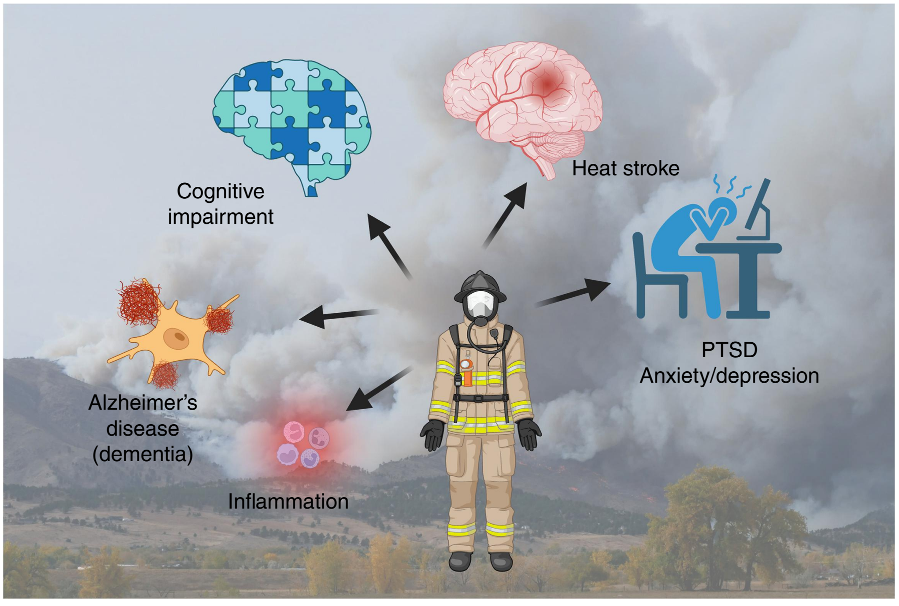

Fig. 2. The impacts of wildland firefighting can induce inflammation, cognitive impairment, heat stroke, and mental health changes as well as long term effects on dementia. Created in https://BioRender.com.

of their brain health. Heat stress, dehydration, smoke inhalation, chronic sleep deprivation, psychosocial stress and PTSD all contribute to cognitive impairments, mental fatigue and mental health disorders among this population (Fig. 2). These factors not only jeopardize individual well-being but also compromise safety during firefighting operations. The studies by Cvirn *et al.* (2019) and Williams-Bell *et al.* (2017) highlights the protective role of hydration in mitigating cognitive decline during prolonged firefighting tasks. Meanwhile, Jeklin *et al.* (2020) and Wolkow *et al.* (2016) provide evidence of the long-lasting effects of sleep deprivation and stress on cognitive function and immune response, suggesting that current recovery periods may be insufficient for full recovery. Leduc *et al.* (2021), Smith (2024) and Zhang *et al.* (2022) underscored the importance of addressing the psychosocial and mental health challenges faced by WLFFs, particularly with respect to PTSD and suicide risk. Additionally, smoke exposure, rich in neurotoxicants such as CO, PM, and PAHs, poses a serious risk to cognitive health, as chronic inhalation of these pollutants can lead to neuroinflammation, oxidative stress and a heightened risk of neurodegenerative diseases. These findings emphasize the need for comprehensive support strategies that address both the physical and mental health risks associated with prolonged firefighting efforts.

To protect the brain health of WLFFs, fire agencies should implement evidence-based strategies, including hydration protocols, extended recovery periods and comprehensive mental health programs. Regular mental health screenings, access to counseling services, and peer support programs are essential for mitigating the risks of PTSD and suicide. Additionally, interventions aimed at reducing stress and improving sleep quality could help alleviate the cognitive and physiological toll associated with this occupation. Enhanced PPE, specifically designed to reduce smoke inhalation and limit exposure to neurotoxicants like PM and CO is also critical. Further research is needed to explore the long-term effects of cumulative stressors on WLFF brain health, with a focus on identifying effective interventions that enhance cognitive resilience and mental well-being. As the frequency and intensity of wildland fires continue to rise, so too should the efforts to safeguard the neurological and mental health of those on the front lines.

Supplementary material

Supplementary material is available online.

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