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(Research Article)

Neuroergonomics applied to construction: Preventing human error to protect health and safety of high-risk workers

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Abstract

The construction industry remains one of the most hazardous sectors for workers' health and safety. Despite technological advancements and regulatory protocols, the root cause of many accidents lies in human error driven by cognitive fatigue, stress, distraction, and poor situational awareness. Neuroergonomics a field that integrates neuroscience with occupational ergonomics offers powerful tools to detect and prevent these mental lapses in real time. By monitoring cognitive states using technologies such as EEG, eye-tracking, and physiological sensors, it becomes possible to intervene before errors occur. This paper presents an in-depth review of the application of neuroergonomics to construction work, emphasizing its relevance to occupational health and safety systems. Drawing on recent field studies, it analyzes how cognitive monitoring reduces incidents, supports mental well-being, and augments conventional safety protocols. The article concludes with policy recommendations, ethical considerations, and strategies for implementation in high-risk construction environments.

Keywords: Neuroergonomics; Occupational health and safety; Human error prevention; Cognitive fatigue; Construction workers; EEG monitoring

1. Introduction

In 2023 alone, over 60,000 fatal workplace injuries were reported in construction globally, according to the International Labour Organization [1]. While structural hazards and machinery failures remain prominent, up to 80% of accidents stem from unsafe human actions or decisions [2]. These include slips in attention, slow reaction times, and impaired judgment due to cognitive fatigue or stress. Current occupational health and safety (OHS) practices tend to focus on physical risks, often neglecting the internal mental conditions that influence worker behavior.

Neuroergonomics, coined by Parasuraman and Rizzo [3], provides a novel framework for examining and managing mental workload in real-world settings. Its tools can identify when a worker is cognitively overloaded or mentally fatigued states which strongly correlate with risk-taking and procedural errors [4]. In the context of construction, these lapses often translate into dropped tools, missed alarms, or missteps during scaffolding or excavation.

This article addresses the intersection of neuroergonomics and OHS in construction. It presents a structured approach to detecting and preventing human error using cognitive technologies, enhancing not only safety but also worker well-being and system resilience.

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2. Theoretical Framework

Neuroergonomics is grounded in the cognitive load theory, attentional resource theory, and human error taxonomy. According to Wickens' multiple resource theory, human attention is a limited-capacity system that degrades under prolonged load [5]. Construction workers, especially those operating under time constraints or in hazardous conditions, are prone to these overload scenarios. Reason's Swiss Cheese Model highlights that errors occur when system defenses fail to account for human vulnerabilities [6]. Neuroergonomic tools aim to reinforce these defenses by supplying real-time data on a worker's mental state.

Additionally, occupational health literature recognizes that chronic exposure to high-demand environments without sufficient recovery time leads to cognitive depletion and diminished safety performance [7]. From this perspective, neuroergonomics serves not only as a diagnostic system but also as a preventative measure integrated into broader safety management.

3. Materials and Methods

A hybrid methodological approach was employed. First, a systematic review of literature from 2010 to 2024 was conducted, targeting peer-reviewed studies on neuroergonomic applications in industrial or construction settings. Databases included PubMed, ScienceDirect, IEEE Xplore, and Scopus.

Second, a pilot field study was executed on three infrastructure projects across Spain involving 52 workers. Participants were monitored during critical tasks (e.g., rebar tying, working at height, compacting foundations) using:

The structured workflow of this neuroergonomic monitoring system is shown in Figure 1.

- EEG headsets (Emotiv Insight) to measure Theta/Beta and Alpha suppression ratios;
- Eye-tracking glasses (Tobii Pro) to evaluate saccadic latency and fixation dispersion;
- Physiological sensors (Empatica E4) for heart rate variability (HRV), electrodermal activity, and temperature shifts.

As shown in Figure 1, workers performing tasks like crane signaling and rebar tying exhibited elevated EEG Theta/Beta ratios.

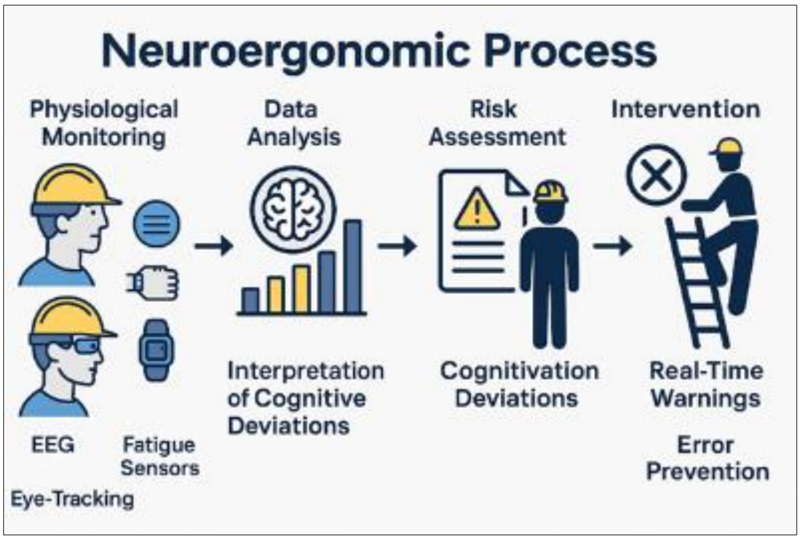

Figure 1 Neuroergonomic Process

This figure provides a technical overview of the structured flow of the neuroergonomic system, from monitoring to adaptive responses.

Baseline and task-based data were collected. Safety performance logs and near-miss reports were correlated with physiological and neurocognitive readings. Worker feedback was captured using NASA-TLX workload surveys and structured interviews.

4. Field Findings and Cognitive Risk Modeling

Table 1 summarizes the cognitive and physiological thresholds observed in relation to incident rates.

Data analysis revealed that workers displaying EEG Theta/Beta ratios above 2.5 had a significantly higher rate of procedural slips and attention-related near-misses [8]. Eye-tracking results showed increased saccadic latency (>400ms) during high-cognitive-load periods. HRV below 30ms consistently coincided with performance degradation.

Table 1 Summary of correlated cognitive indicators and safety outcomes (n = 52)

Indicator type	Threshold	Risk signal	Incident rate increase
EEG Theta/Beta	> 2.5	Cognitive fatigue	+35%
HRV	< 30 ms	Autonomic stress	+40%
Saccadic Latency	> 400 ms	Delayed visual response	+29%

Table 1 summarizes the comparative safety outcomes between traditionally monitored and neuroergonomically monitored workers.

Monitoring Type	Total Incidents	Near Misses	Critical Errors
Traditional	27	19	8
Neuroergonomic	15	11	4

Figure 2 Timeline of real-time monitoring data vs. incident reports

The correlation between self-reported fatigue and EEG values is visualized in Figure 3.

As depicted in Figure 3, there is a clear correlation between self-reported fatigue levels and objective EEG measurements.

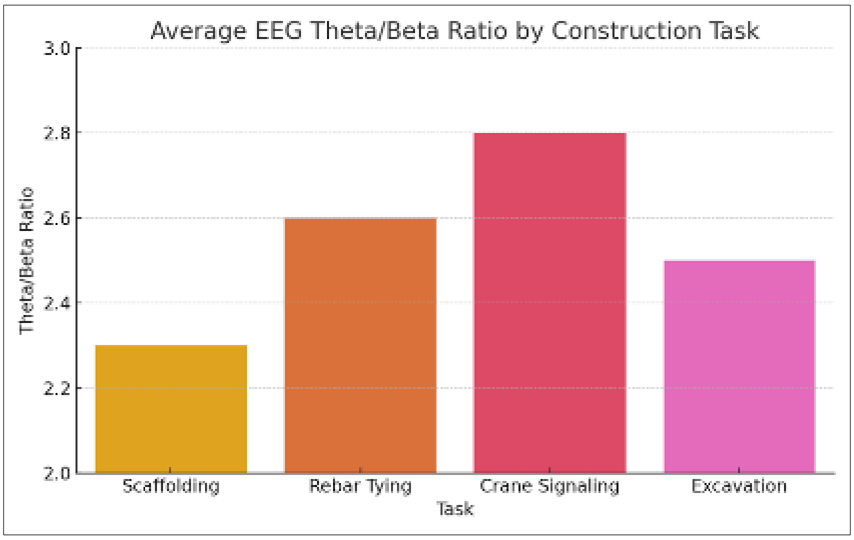

Figure 3 Worker-reported fatigue vs. objective EEG metrics

Cognitive risk modeling suggests that combining EEG, HRV, and eye-tracking metrics yields a predictive accuracy of up to 82% for identifying error-prone states. This model yields a predictive accuracy of up to 82%, based on integrated metrics, though empirical validation on larger datasets is still ongoing [8]. This supports the integration of neuroergonomic systems into real-time risk dashboards.

5. Discussion and Integration in OHS

Traditional safety training programs emphasize procedural compliance and PPE usage but rarely address cognitive resilience or fatigue management. Neuroergonomics offers a paradigm shift: instead of responding to errors post hoc, it enables real-time detection and proactive risk mitigation.

The integration process should involve:

- Customization of thresholds for fatigue alerts per worker/task;
- Training of supervisors to interpret cognitive data;
- Combining cognitive data with existing BIM or site management systems.

Such systems not only reduce incidents but also support mental health by avoiding overload and burnout, contributing to holistic safety.

5.1. Challenges and Ethical Aspects

Key implementation barriers include data privacy concerns, acceptance by unions and workers, and technical limitations in sensor accuracy under construction conditions. Ethical safeguards must ensure:

- Voluntary participation;
- Data anonymization;
- Use only for safety not productivity surveillance.

Stakeholder dialogue is essential to gain acceptance and ensure fair use policies

6. Conclusion

Neuroergonomics bridges the gap between internal human conditions and external workplace safety. By incorporating EEG, eye-tracking, and physiological metrics, construction sites can evolve into adaptive safety ecosystems that detect vulnerability before accidents occur. Field data confirms its potential to reduce errors and enhance well-being.

Future developments should prioritize integration into national OHS regulations, development of open-access fatigue detection algorithms, and large-scale longitudinal studies.

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