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Enhancing Construction Project Management through Cognitive Science and Neuroimaging: A Comprehensive Literature Review

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ABSTRACT

While substantial advances have been made in Cognitive Science and Neuroimaging, a notable gap remains in assessing cognitive status within the construction sector. This paper aims to demonstrate the considerable benefits of interdisciplinary approaches in enhancing project management effectiveness and outcomes by examining the complex interplay between cognitive processes, decision-making, and project management. Key findings indicate that cognitive status plays a critical role in the performance of construction workers, underscoring the necessity of prioritizing cognitive well-being in project strategies. Furthermore, the review highlights a deficiency in objective tools for evaluating cognitive status and proposes the adoption of neuroimaging technologies as a solution. By integrating neuroscientific insights with management practices, leaders can enhance training, team dynamics, and risk assessment, ultimately improving decision-making and productivity in construction project management.

Keywords: Decision Making, Literature Review, Neuroimaging, Cognitive Science, Construction Project Management

INTRODUCTION

The construction industry, heralded as one of the most significant sectors, is at a crossroads where ensuring the productivity improvement and efficiency of its workforce is paramount. This challenge is amplified by the sector's dynamic nature, necessitating a deep dive into the cognitive realms that govern construction workers' actions and decision-making processes. Recent cognitive science and neuroimaging strides have unveiled promising avenues to revolutionize construction project management. This study seeks to unravel the potential of integrating cognitive science insights with neuroimaging findings to refine leadership and management strategies within the construction domain. This literature review explores the intersection of cognitive processes, decision-making strategies, and their implications on construction project management, aiming to illuminate pathways toward optimized project outcomes and enhanced project management.

Construction project management encompasses many tasks that demand significant physical and mental effort from workers, leading to fatigue that adversely affects decision-making and productivity. The cognitive status of construction workers, including their awareness, reasoning, and decision-making capabilities, is a critical determinant of their effectiveness on the job (Chen et al., 2017; Clevenger et al., 2020; Lawani et al., 2023; Zhu & Mostafavi, 2017). Despite its recognized importance, the industry faces challenges in accurately assessing and enhancing these cognitive aspects due to the lack of practical tools and methodologies(Lohani et al., 2019; Wang et al., 2021). Recent advancements in cognitive science and neuroimaging offer promising avenues for addressing these gaps. Cognitive theories and models, such as those related to attention, perception, and memory, provide a framework for understanding the complexities of human behavior in high-risk environments (Ashcraft, 1989; Barnes et al., 2002; Reason, 1990). A systematic review of behavioral decision-making in projects reveals deviations from normative decision theories, which fail to account for psychological, emotional, cognitive, social, and cultural factors (Ahmad, 2018). Furthermore, neuroimaging technologies like functional Near-Infrared Spectroscopy (fNIRS) present new opportunities for directly measuring cognitive states and assessing mental workload, potentially overcoming the limitations of traditional assessment methods (Glimcher & Fehr, 2013; Wallis & Miller, 2003). These findings encourage leaders to foster environments that stimulate creative collaboration and strategic thinking, thereby improving decision-making processes.

In the construction industry, professionals view cognitive approaches as alternatives to traditional behavioral methods while it comes down to improving productivity and safety. This perspective focuses on the cognitive processes enabling engineers to anticipate and address challenges across various stages of the construction process. Understanding cognitive strategies using personal, material, and social resources to resolve problems contributes to more effective decision-making and planning (Fonseca et al., 2019). Team members become more present, mindful, and adept at seizing opportunities, enhancing both individual and project outcomes when project goals align with team members' personal values and identities (Mgbere et al., 2023). Literature highlights distinct decision-making behaviors between project managers and team members, but encourages further exploration (Nowińska & Pedersen, 2024). Although cognition, the ability to process information, apply knowledge, and adapt preferences, is increasingly recognized as crucial in management science, its application in construction engineering management remains underexplored (Xue et al., 2011).

Lastly, the review presents the application of cognitive psychology and neuroscience in elucidating decision-making processes, which can significantly assist leaders in understanding the mental limitations and biases that impact project decisions. By integrating neuroscientific insights with traditional management practices, leaders can enhance their strategies for training, team dynamics, and risk assessment, ultimately leading to more informed, and efficient construction project management.

The primary objectives of this comprehensive literature review are as follows:

- *To Explore Cognitive Processes in Construction:* To investigate the cognitive status of construction workers and how it impacts their performance, and decision-making abilities on-site.
- *To Examine the Role of Cognitive Analysis and Modeling:* To assess the applications and benefits of cognitive analysis and modeling frameworks in understanding and improving construction project management.
- *To Identify the Influence of Neuroimaging on Decision-Making:* To evaluate how neuroimaging technologies, particularly fNIRS, contribute to understanding the neural basis of decision-making and creativity in construction project management.
- *To Assess the Application of Cognitive Systems Engineering (CSE):* To determine how CSE and resilience engineering principles can be applied to enhance efficiency in construction project management.
- *To Bridge the Leadership and Management Gap in Construction Project Management:* To offer insights into how leadership and management in construction projects can benefit from cognitive science and neuroimaging research findings.

RESEARCH METHOD

This study employs a systemic literature review methodology, systematically collecting and analyzing scholarly articles, journal publications, and empirical studies that intersect cognitive science, neuroimaging, and construction project management. The systemic review method was chosen particularly for synthesizing qualitative data since it employs a rigorous and transparent process for literature search and screening for thematic analysis. The selection criteria for the literature included relevance to cognitive processes affecting construction workers, the application of cognitive modeling and neuroimaging in understanding these processes, and the implications for leadership, and decision-making in construction projects. The databases used in the study included PubMed, Scopus, and Web of Science. The keywords used in the search were related to cognitive science, neuroimaging, construction, decision-making, and project management. The study's objectives guided the review process, ensuring a focused examination of the literature to extract pertinent findings and theoretical insights. Through a thematic analysis, the collected literature was categorized according to the key themes identified, facilitating a comprehensive synthesis of the current state of research at the nexus of cognitive science, neuroimaging, and construction project management.

RESULTS

The comprehensive literature review is presented below which is based on thematic analysis. First the literature is arranged into similar topics using keywords and then regrouped based on their analysis and findings. The following Table 1 provides a succinct overview of the topics and their corresponding authors or citations, encapsulating the breadth of research across cognitive analysis, construction project management, and advances in neuroimaging and decision-making.

Table 1

Overview of Topics with Keywords and their correspond literatures

Topics with Keywords	Literatures
Cognitive Status and Performance in Construction	Chen et al., 2017; Clevenger et al., 2020; Leung et al., 2017; Mitropoulus & Menarian, 2012; Wang et al., 2019; Zhu & Mostafavi, 2018
Challenges in Assessing Cognitive Status in Construction	Hwang et al., 2018; Lohani et al., 2019; Wang et al., 2021; Wu et al., 2021; Zhang et al., 2019;
Priming Effects and Cognitive Functions	Dijksterhuis & van Knippenberg, 1998; Fitzsimons, et al., 2008; Friedman & Förster, 2000; Kay, et al., 2004; Slepian et al., 2010; Slepian et al., 2015

Cognitive Theories in Decision-Making and Perception	Epstein et al., 1996; Evans, 2008; Evans & Stanovich 2013; Keren & Schul, 2009; Todd & Gigerenzer, 2000; Tversky & Kahneman, 1974; Tversky et al., 1982; Von Neumann & Morgenstern, 1947; Vranas, 2000
The Role of Attention and Visualization in Cognition	Castle & Buckler, 2009; Duval, 2011; Fabrikant et al., 2010; Hegarty et al., 2010; Hegarty et al., 2016; Padilla et al., 2017; Schmidt 1995; Schirillo & Stone, 2005; Stone et al., 2003; Stone et al., 1997
Human Factors Analysis in Construction	Chi et al., 2012; Hinze et al., 2005; Shappel & Wiegmann, 2000
Cognitive Theories and Models in High-Risk Sectors	Ashcraft, 1989; Barnes et al., 2002; Reason, 1990; Flower & Hayes, 1981; Farrow, 1991; Koda 1988
Human Information Processing and Cognitive Load in Construction	Kines, 2003; Mohan & Duarte, 2006; Nakayasu et al., 2010; Wickens et al., 2021
Enhancing Construction Safety through Cognitive Systems Engineering	Jackson & Harel, 2017; Vicente, 1999; Saurin et al., 2005
Stress and Mental Strain in the Construction Sector	Alonso et al., 2015; Abbe et al., 2011; Jebelli, 2019; Campbell, 2006; Haynes & Love, 2004; Castaldo, 2015; Bernston & Cacioppo, 2004; Choi et al., 2015; Seo et al., 2010
Advances in Neuroimaging and Decision-Making	Gold & Shadlen, 2007; Romo & Salinas, 2003; Sajda et al., 2009; Smith & Nichols, 2018
The Role of Brain Imaging in Cognitive Studies	Bassett & Gazzaniga, 2011; Banville & Falk, 2016; Johnson & Haan, 2015; Kisi & Sulbaran, 2022; Sulbaran & Kisi, 2024; Sulbaran & Kisi, 2022, Funahashi, 2017; Koren et al., 2020; Williams et al., 2023
Functional Near-Infrared Spectroscopy (fNIRS) in Cognitive Function Analysis	Glimcher & Fehr, 2013; Wallis & Miller, 2003; Wanniarachchi et al., 2020; Tak & Ye, 2013; Hall et al., 2013; Homae, 2014; Kozel et al., 2009; Sasai et al., 2011
Contributions of Cognitive Psychology and Neuroscience to Decision-Making	Coltheart, 2015; Eysenck & Keane, 2020; Ferrari & Quaresima, 2012; Kupis & Uddin, 2023; Shealy & Hu 2017; Uddin, 2021

Once Table 1 is created, the next step was to use a thematic analysis and reorganize them to realign with the study's objectives. For example, Table 2 shows a short version of how the contents of the literature were organized under specific themes, with each entry comprising a synthesized topic drawn from the literature review, followed by key references that support the topic. This structure is designed to offer clarity and facilitate the reader's understanding of the research landscape concerning cognition, decision-making, neuroimaging, and their applications in construction project management and beyond.

Table 2

Themes from Key References

Theme	Synthesized Topic	Key References
Cognitive Processes in Construction	Exploration of cognitive status including awareness, reasoning, and decision-making abilities in construction workers and its impact on safety and productivity.	Chen et al., 2017; Clevenger et al., 2020; Wang et al., 2021; Zhu & Mostafavi, 2017
Role of Cognitive Analysis and Modeling	Investigation into cognitive analysis and modeling techniques such as COGNET for understanding human-computer interaction and decision-making processes in construction.	Kunz et al., 2004; Todd & Gigerenzer, 2000; Tversky et al., 1982; Tversky & Kahneman, 1974; Von Neumann & Morgenstern, 1947
Impact of Neuroimaging on Decision-Making	Assessment of how neuroimaging technologies like fNIRS contribute to understanding the neural basis of decision-making processes.	Gold & Shadlen, 2007; Heekeren et al., 2008; Romo & Salinas, 2003; Sajda et al., 2009; Smith & Nichols, 2018
Application of Cognitive Systems Engineering	Application of Cognitive Systems Engineering principles to improve safety management and task allocation in construction, emphasizing a holistic view of worker-system interaction.	Hollnagel and D Woods, 1999; Lillrank 1995; Rasmussen, 1990; Rasmussen et al., 1994; Saurin et al., 2005; Vicente, 1999
Gap in Leadership and Management	Identification of leadership and management practices gap in integrating cognitive science and neuroimaging findings into construction project management.	Glimcher & Fehr, 2013; Jebelli, 2019; Shi et al., 2020; Wallis & Miller, 2003

DISCUSSION

The following section discusses the findings of comprehensive literature review organized by the study's main objective.

Cognitive Processes in Construction Project Management

The performance of construction workers is deeply influenced by their cognitive status, encompassing elements like awareness, reasoning, and decision-making abilities. Zhu and Mostafavi (2017) underscored the significance of this connection for the success of construction projects. Further explorations into cognitive status by Chen et al. (2017) and Clevenger et al. (2020) reveal its intricate components, such as perception, judgment, and memory, and their critical impact on occupational safety, productivity, and incident rates due to decreased vigilance (Leung et al., 2017; Mitropoulos & Memarian, 2012; D. Wang et al., 2019). Despite its acknowledged importance, the construction sector needs more effective methodologies for objectively evaluating cognitive status. Traditional psychological assessments for mental fatigue and stress suffer from limitations tied to self-reporting, introducing biases and practical difficulties in the hectic atmosphere of construction sites (Hwang et al., 2018; Lohani et al., 2019; F. Wang et al., 2021; Zhang et al., 2019).

The industry is known for its demanding conditions, significantly straining workers mentally and contributing to heightened stress levels. This stress, exacerbated by heavy workloads, prolonged hours, and limited family time, can lead to more frequent errors and unsafe practices. In response, research has ventured into physiological indicators such as cortisol, glucocorticoids, ECG, and EEG for a direct assessment of stress levels (Abbe et al., 2011; Alonso et al., 2015; Berntson & Cacioppo, 2004; Castaldo et al., 2015; Choi et al., 2015). However, these methodologies need help in real-world applications due to their technical complexity and cost. The motion sensitivity of EEG necessitates a stable laboratory setting for precise measurements, as noted by Jebelli (Jebelli, 2019). As an innovative solution, Shi et al. (Shi et al., 2020) introduced fNIRS, offering a neurophysiological method for assessing stress that may sidestep the limitations of conventional approaches.

Role of Cognitive Analysis and Modeling

In cognitive analysis and modeling, the study of decision-making under risk has been primarily divided between two theoretical approaches. One approach focuses on a rational, mathematical framework for modeling decisions, while the other advocates for the influence of intuition and heuristics. This division highlights the multifaceted nature of decision-making, recognizing the human capacity to employ both analytical and intuitive methods (Epstein et al., 1996; Evans, 2008; Evans & Stanovich, 2013; Keren & Schul, 2009; Kunz et al., 2004; Todd & Gigerenzer, 2000; Tversky & Kahneman, 1974; Von Neumann & Morgenstern, 1947; Vranas, 2000).

Attention and concentration are Central to cognitive performance, vital information processing resources, problem-solving, and decision-making. The capacity to selectively concentrate on pertinent stimuli while filtering out distractions is fundamental for mastering complex tasks and learning efficiently (Castle & Buckler, 2009; Duval, 2011; Schmidt, 1995). Additionally, the role of visualizations in shaping attention is significant, as evidenced by research showing how prominent graphical information can alter behaviors and perceptions (Fabrikant et al., 2010; Hegarty et al., 2010, 2016; Padilla et al., 2016; Schirillo & Stone, 2005; Stone et al., 1997, 2003).

Furthermore, cognitive theories encompassing human memory, attention, and situational awareness have broad applications in high-risk fields like nuclear energy, transportation, and mining. These theories support the development of cognitive models to decipher the intricate dynamics of human error and decision-making processes. Such models, anchored in classical psychological approaches, facilitate a more profound comprehension of cognitive functions across diverse activities, including writing and second-language acquisition (Ashcraft, 1989; Barnes et al., 2002; Farrow, 1991; Flower & Hayes, 1981; Koda, 1988; Reason, 1990). This breadth of application underscores the significance of cognitive analysis and modeling in enhancing understanding and performance within complex, risk-laden environments.

Influence of Neuroimaging on Decision-Making

Integrating neuroimaging technology with decision-making research has revolutionized our comprehension of the brain's pivotal role in expedited decision-making activities. Progress in signal processing and neuroimaging, as delineated by Sajda et al. (2009) and Smith & Nichols (2018), has illuminated the critical cortical networks that underpin rapid decision-making. This furthers the seminal research in perceptual decision-making and electrophysiology conducted by Heekeren et al. (2008), Gold and Shadlen (2007), and Romo and Salinas (2003).

Advancements in brain imaging technologies have profoundly influenced cognitive neuropsychology by facilitating the precise delineation of cognitive functionalities and brain activities (Kisi & Sulbaran, 2022; Sulbaran & Kisi, 2022). These methodologies have unveiled the specific activation patterns within various brain regions, notably illustrating the prefrontal cortex's engagement in decision-making and arithmetic operations (Funahashi, 2017; Koren et al., 2020). Despite the inherent challenges in brain research (Bassett & Gazzaniga, 2011), findings demonstrate a notable correlation between brain activity and cognitive exertion, highlighting the complex interplay between neural activation and cognitive processes (Banville & Falk, 2016; Johnson & de Haan, 2015).

Functional Near-Infrared Spectroscopy has emerged as a groundbreaking neuroimaging tool. By tracking cerebral hemodynamic responses, fNIRS provides profound insights into the brain activity (Glimcher & Fehr, 2013; Wallis & Miller, 2003; Wanniarachchi et al., 2020). Its superior temporal resolution enables an intricate analysis of the brain's functional connectivity, offering distinct advantages over conventional imaging modalities such as fMRI (Hall et al., 2013; Homae et al., 2011; Kozel et al., 2009; Tak & Ye, 2014).

Cognitive psychology delves into the formation of individual preferences and the impact of cognitive constraints on decision-making across varied sectors, including finance and healthcare, enriching disciplines such as engineering and project management with a nuanced understanding of decision-making mechanisms (Shealy & Hu, 2017). Additionally, cognitive neuroscience aims to elucidate the operational frameworks of cognitive systems and their linkage to behavior, emphasizing the significance of neuroimaging in uncovering brain activity patterns and identifying deficiencies (Coltheart, 2015; Eysenck & Keane, 2020). This multidisciplinary approach sheds light on the neural and cognitive mechanisms influencing decision-making and paves the way for integrating these insights into practical applications, enhancing the efficacy of leadership and management within complex project environments.

Application of Cognitive Systems Engineering

Cognitive Systems Engineering (CSE) introduces an innovative approach to enhance safety within the construction sector by focusing on the intricate socio-technical systems where workers operate. This methodology underlines the critical role of understanding how organizational, managerial, and team dynamics significantly affect worker interactions and safety practices. Drawing from empirical studies and accident causation theories across diverse industries, CSE provides a robust framework for creating safety models specifically designed to address the distinct challenges faced by the construction industry (Saurin et al., 2005; Vicente, 1999).

Furthermore, CSE presents a paradigm shift in safety management by treating man-machine systems not as separable entities but as integrated cognitive systems. This perspective views these systems as adaptive, utilizing knowledge about themselves and their environments in planning and adjusting actions. This approach acknowledges the complex settings of organizational environments and regards humans as proactive entities seeking goals rather than merely responding to stimuli (Rasmussen et al., 1994).

Models developed by researchers elucidate the cognitive stages and processes involved in interacting with external stimuli, stressing the importance of cognitive resources like attention, working memory, and long-term memory in ensuring safety within mining and construction settings (Hollnagel & Woods 1999; Nakayasu et al., 2010). These models emphasize the necessity of balancing cognitive demands with worker capabilities, demonstrating how cognitive load can affect safety and performance on construction sites (Kines, 2003; Mohan & Duarte, 2006).

The synthesis of neuroimaging, cognitive psychology, and interdisciplinary research creates a comprehensive understanding of the decision-making complexities. This collaborative framework reveals the neural and cognitive mechanisms that underpin decision-making, offering valuable insights for improving mental performance and decreasing cognitive load across various applications (Ferrari & Quaresima, 2012; Uddin, 2021). Such a holistic approach to decision-making science promises to advance our comprehension and optimization of decision processes in many contexts.

Despite its origins in sectors like aviation and healthcare, the principles of CSE are well-suited for construction project management, particularly given its dynamic and complex nature. CSE's high-level guidelines enable the transference of best practices from other fields into the construction environment, paving the way for novel management strategies in construction (Hollnagel et al., 2006; Lillrank, 1995). By positioning humans as intentional goal-seekers and emphasizing the role of context in human actions, CSE aligns with broader socio-technical system design principles, confirming its relevance and applicability across various high-risk domains beyond its initial scopes (Hollnagel et al., 2006; Rasmussen et al., 1994).

Leadership and Management Gaps in Construction Project Management

Construction projects are inherently complex, characterized by a variety of tasks and a wide range of crew expertise levels. This complexity often complicates the process of allocating tasks effectively. The demanding nature of construction work can lead to substantial physical and mental fatigue among workers, negatively affecting both individual well-being and overall project performance (Abdelhamid & Everett, 2002; Chen et al., 2016). Physical fatigue, exacerbated by extended working hours and crowded work environments, directly diminishes productivity and increases safety risks on construction sites (Hanna et al., 2008; O'Neill & Panuwatwanich, 2013). Concurrently, the mental demands placed on workers can impair cognitive functions, reducing alertness, concentration, and the capacity to recognize hazards or assimilate new information effectively (Simon et al., 2011; Zhao et al., 2011).

The dual challenge of managing both physical and mental fatigue highlights the necessity of accurately assessing workloads to optimize task distribution, thereby protecting worker health and boosting operational safety and efficiency (Mitropoulos & Memarian, 2012; Newnam et al., 2006). However, despite the extensive exploration of cognitive processes, modeling, and the application of neuroimaging in enhancing decision-making, safety, and operational efficiency, there remains a noticeable gap in the application of these insights to leadership and management practices within the construction sector. For example, while CSE offers promising avenues for improving task allocation and safety management, discussions on how these methods can inform leadership strategies to cultivate an environment that values cognitive health and adaptive work systems are scarce (Rasmussen et al., 1994; Zachary & Ryder, 1997). Similarly, the potential of neuroimaging technologies like fNIRS to deepen our understanding of cognitive functions and decision-making processes is well recognized, yet there is a lack of guidance on how leaders can employ these tools to enhance project management and team dynamics (Glimcher & Fehr, 2013; Wallis & Miller, 2003). This identified gap presents an opportunity for future research to develop and integrate leadership models and management practices informed by the latest findings in cognitive science and neuroimaging. By doing so, leaders in the construction project management can effectively leverage these insights to improve project outcomes and worker well-being.

CONCLUSIONS

This article comprehensively reviews the intersection between cognitive science, neuroimaging, and construction project management. Exploring cognitive processes in construction, along with the role of cognitive analysis and modeling, has laid the groundwork for a deeper understanding of the industry's cognitive challenges and opportunities. Neuroimaging's impact on decision-making further elucidates the potential for technological advancements to enhance our comprehension of cognitive functions in complex project environments.

Cognitive Systems Engineering applications emerge as transformative approaches, advocating for an integrated understanding of worker-system interactions to improve safety and efficiency. However, a discernible gap in leadership and management practices highlights the need for the construction sector to incorporate insights more effectively from cognitive science and neuroimaging into strategic decision-making and organizational culture.

Addressing this gap offers a significant opportunity to enhance construction project outcomes through a more informed and nuanced approach to leadership and management. The construction project management can achieve better leadership and management for excellent safety, productivity, and innovation by fostering an environment that prioritizes cognitive well-being and leverages the latest in cognitive research and technology. Ultimately, this review underscores the potential of a multidisciplinary approach to construction project management, where cognitive science and neuroimaging contribute to advancing the field. More specifically, the path forward would be to perform neuroimaging using such as magnetoencephalography (MEG), Functional near-infrared spectroscopy (fNIRS), and electroencephalography (EEG) while performing construction project management task and understand the brain activity and how workforce training would impact decisions and brain activity.

LIMITATIONS

The study used systematic review method for comprehensive literature analysis. However, the study did not include all the journal articles, conference proceedings, and book chapters due to limitation to access of those articles as well as limitation to the scope of this study objectives. This study used five research objectives to provide a comprehensive synthesis in which the research team found difficulties in searching and managing articles. The future study should be more aligned to a specific research question to narrow down the literature search to be able to conduct more detailed thematic analysis and present discussion. The future study could explore narrative literature review and meta-analysis to synthesize diverse fields and answer specific hypotheses.

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