A REVIEW OF THE POTENTIAL IMPACT OF HOSPITAL EVACUATION ROUTE DESIGNS ON BRAINWAVE ACTIVITY AND WAYFINDING COGNITION PERFORMANCE DURING FIRE EVACUATION

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Abstract
In hospital buildings, fires are a significant risk, and occupants' failure to evacuate can result in death. Therefore, efficient hospital fire evacuation is important. Hospital evacuation routes are among the most challenging to design due to complex indoor environments and restricted circulation. Additionally, not every hospital user has spatial familiarity due to the restricted public access, making it difficult to navigate unfamiliar evacuation routes. Human wayfinding, which involves wayfinding cognition performance, has a big impact on how effectively one can carry out navigational tasks. To ensure safe evacuation, aspects of hospital physical design, in particular evacuation routes, must be improved. However, when outlining the ideal evacuation route design, hospital building guidelines rarely take wayfinding cognition aspects into account. A neuroscientific understanding of the relationship between hospital evacuation route designs and wayfinding cognition is timely given the emergence of neuroarchitecture research which applies neuroscientific methodologies in architectural studies for more accurate assessment of human behaviour. This article proposes a neuroarchitecture framework outlining a clear relationship between these aspects through critical review of the literature whereby potential applications of EEG brainwaves are also highlighted. Findings can promote hospital evacuation route designs that optimize wayfinding cognition performance to ensure occupants' safety.

Keywords: electroencephalogram (EEG), evacuation route design, fire evacuation, hospital, wayfinding cognition.

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INTRODUCTION

Hospitals are particularly vulnerable to fires. In England, hospitals ranked second in terms of fire rates per 1000 structures with 264 cases per year (UK Home Office, 2019), while in Türkiye, there were 20 hospital fires that occurred between March and December 2020 alone (European Commission Joint Research Centre, 2021). Hospital fires especially risk causing catastrophic loss of lives as vulnerable groups and the disabled frequent hospitals (Othman et al., 2023). The 2021 hospital fire in Iraq was one of the more recent tragedies that cost 82 lives and wounded 100 others (Wood et al., 2021). Similarly, since August 2020, hospital fires have claimed the lives of over 120 Indians (Barnagarwala, 2020), and in 2016, six people lost their lives in the deadliest hospital fire in Malaysia (Muhammad Salleh et al., 2020).

Unlike other building typologies, the constant presence of flammable consumables, prolonged electrical consumption, oxygen-rich environment, and complex indoor design places hospitals at a unique risk to fire (Wood, Hailwood and Koutelos, 2021). Medical equipment, electronic equipment, kitchen equipment, laundry washers and dryers, trash or debris, smoking materials, and especially poor electrical wiring and lighting are some of the main causes of hospital fires (Pan American Health Organization (PAHO), 2018). Due to the prevalence of such incidences in hospital settings, extra care must be taken to maintain hospital fire safety.

In terms of human factors during emergency evacuations, the nature and scale of the emergency, the characteristics of the hazard or the affected area, the information provided to the public, evacuee inherent behaviours and tendencies, as well as the planning and implementation of evacuation guidelines may impact the evacuation process (Wang et al., 2021). Evacuee behaviour, in particular, their associated physical, cognitive, motivational, and social factors, and the necessity of their integration into evacuation planning and modelling were critically addressed by Wang et al. (2021) and Hofinger et al. (2014). From these comprehensive reviews, it is clear that while there are various evacuation contexts and scenarios, there is a lack of consensus in the literature about the specific human behaviour or tendencies that occur during fire evacuation. Overall, this has been predominantly due to the lack of empirical data.

Nonetheless, what is quite certain is that higher-order human brain processes such as problem-solving abilities, logical thinking, and wayfinding cognition play a greater and more critical role than fight-or-flight reactions (i.e., panic) during emergencies (Daylamani-Zad et al., 2022; Kuligowski, 2016). Recent research on the autonomic nervous system function in humans has revealed that adrenaline-induced fight-or-flight responses significantly improve short-term cognitive abilities by inducing sympathetic activity in the prefrontal cortex and exerting tonic inhibition of limbic system activities, both of which improve cognition (Stogios et al., 2021).

PROBLEM STATEMENT

As hospital fires are common, the mortality rate remains at a high as lives continue to be threatened when fire suppression and prevention systems fail. In order to prevent casualties in the event of a hospital fire, reliable mitigation measures are required. As hospital access and internal circulations are often more complex and restricted than other typologies, they pose a unique difficulty to design. Therefore, designing hospital evacuation routes remain a challenging feat for designers. Additionally, navigating evacuation routes in hospitals can be challenging as it is difficult for the public to achieve spatial awareness in a space they do not frequently visit. This is because familiarity affects occupants' utilisation of fire evacuation routes. As a result, evacuating a hospital during a fire is considered a wayfinding task. Designing hospital evacuation routes that optimise wayfinding cognition and enhances evacuation in unfamiliar situation and environments should be a primary approach as wayfinding cognition is an important component of wayfinding. However, building guidelines for hospitals rarely take wayfinding cognition into account when outlining optimum evacuation route designs, instead relying heavily on physical performance metrics. Most fire simulation research tends to inaccurately simulate or ignore human wayfinding cognition due to the lack of corroborating evidence of wayfinding cognition during fire evacuation. Recent developments in neuroarchitecture research have adopted neuroscientific principles in architectural studies for a more precise neurophysiological understanding of human behaviour. However, our current understanding of brain activity and human cognitive function during a fire evacuation is still limited, despite recent developments in brain research. The majority of studies on human wayfinding, particularly when evacuating from a fire, are qualitative. Furthermore, neuroimaging techniques-based quantitative studies of the brain activities that define cognition and evacuation wayfinding performance have not yet been published. Hence, a neuroarchitecture framework highlighting the relationship and impact of hospital evacuation route design, brainwave activity and evacuation wayfinding performance is especially novel and timely as an important reference point that will prove beneficial for future studies. Moreover, the potential brainwave activity that could represent cognitive activity during fire evacuation is also highlighted as the potential ways to optimize wayfinding performance during hospital fire evacuation to contribute to better evacuation route designs.

AIM AND OBJECTIVES

This paper aims to construct a neuroarchitecture framework that encompasses the neurophysiological relationship between hospital evacuation route designs and wayfinding cognition as a human behavioural response to a fire situation to provide better understanding of human experience within the indoor environment. The main objectives are to draw attention to the significance of thoughtfully designed hospital evacuation routes and the critical function of wayfinding cognition during hospital fire evacuation, and also to highlight theories of human behaviour in fire (HBiF), indoor wayfinding, and cognitive performance which will help explain how wayfinding cognition performance during fire is affected by hospital evacuation route design.

METHODOLOGY

As a conceptual study, this paper adopts critical review of literatures to achieve its objectives, similar to other recent high-impact reviews by Jamshidi et al. (2020) and Muhammad Salleh et al. (2020) that were utilised in this paper. Four electronic databases such as Web of Science, Scopus, Medline via Pubmed, and pre-prints in Medrxiv, indexing journals encompassing safety science, neuroscience, and architectural fields were searched with the following keywords – hospital fire, neuroarchitecture, indoor wayfinding, wayfinding cognition, fire evacuation, spatial cognition electroencephalogram, and neural efficiency (Fig.1). Publications that address human behaviour and the neurophysiological impact of hospital evacuation route design on wayfinding cognition performance during fire up to the 15th of February 2023 were principally reviewed.

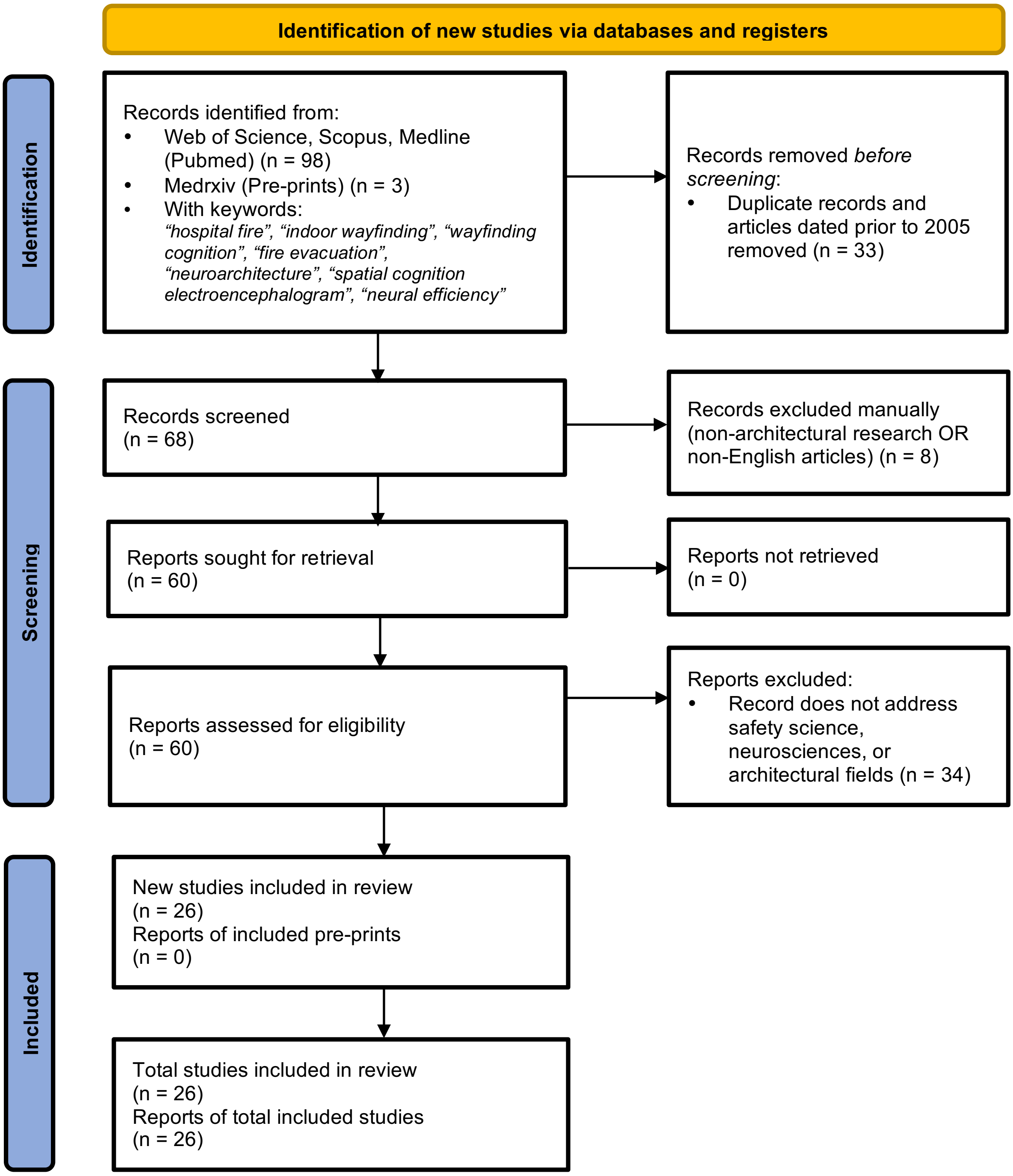

Figure 1: Article selection methodology as per Moher et al. (2009) and PRISMA 2020 guideline by Page et al. (2020).

In order to achieve the first objective, commonly utilised guidelines such as the United States NFPA Standards, British Standards, Malaysia's Uniform Building By-Laws, and Malaysian Standards were reviewed, however, the most widely acknowledged guideline for fire safety systems in healthcare facilities is by the World Health Organization (WHO) (PAHO, 2018). The recommendations in other guidelines do not include criteria that solely apply to healthcare buildings. However, noteworthy suggestions were still included to ensure a more thorough synthesis and discussion. A thorough review of articles on human cognition and wayfinding performance during fire were included, paying particular emphasis on healthcare facilities. According to Choudhary et al. (2018), such separation is important to effectively achieve Objective 1 as hospitals have unique risk to fire, alongside a specific nature of occupants, and medico-legal issues that are explicit and incomparable with those of other building typologies.

Objective 2 was achieved through a neuroarchitecture approach as conducted by Erkan (2018) and Huang et al. (2021). The basic premise was that human behaviour and cognitive performance in indoor wayfinding have a neuroscientific basis. In order to create the proposed framework and accomplish Objective 2, popular and widely accepted neuropsychological, neuroanatomical and neurophysiological theories of human indoor wayfinding, brainwave activity during cognitive activities and wayfinding behaviour during fire situations were adopted. Prior and out-of-date, but significant notions and theories were briefly acknowledged and considered but ultimately dropped due to redundancy.

Conclusively, 98 peer-reviewed articles and 3 pre-prints were gathered. Among them 68 papers were included after preliminary screening, however, only 60 articles and no pre-prints were kept following a full-text inspection. Duplicate articles, conference proceedings with journal reproductions, and ones that did not fit the inclusion criteria are among the excluded articles. Further, only the most recent studies were cited in the case of studies with identical themes or conclusions. In particular, 26 publications pertaining studies on fire evacuation and evacuation route designs, 13 articles on indoor wayfinding, and 13 articles involving health sciences, neuroarchitecture and neurosciences were included in this paper (Fig.1).

LITERATURE REVIEW AND FINDINGS

Significance of Efficient Evacuation Routes in Hospital Fire Systems

Malaysia's Uniform Building By-Laws, British Standards, and the United States NFPA Standards contain guidelines for fire standards, requirements and regulations for all building typologies including for hospitals (Othman et al., 2023). Healthcare facilities, however, present unique difficulties in terms of medico-legal guardrails and fire risks that have significant influence on building design considerations (Muhammad Salleh et al., 2020; PAHO, 2018; Choudhary et al., 2018). Due to its thoroughness, comprehensiveness and primary focus on hospitals, the WHO guideline for hospital fire systems has become the standard for hospital fire safety design worldwide. The guideline divided hospital fire systems into three key categories: suppression, prevention, and evacuation (Table 1) (PAHO, 2018). In designing the prevention measures, the need to minimise the three elements that make up the "fire triangle" – fuel, heat, and oxygen must be considered (Othman et al., 2023). Combustible materials are prohibited for both structural (such as floors, walls, and roofs) and non-structural (such as doors, windows, and fixtures) parts of a hospital. Combustible storage areas require fittings that are made of fire-retardant materials or be placed well away from heat sources. In order to prevent fires from spreading, evacuation methods must also be incorporated into prevention systems (PAHO, 2018).

Table 1: Hospital Fire Systems

Fire Systems	
Prevention System	● Considerations during the planning stage ● Considerations during the design and construction stage ● Sufficient exit
Suppression System	● Active fire alarm systems (smoke detector, heat detector, gas detector, alarms) ● Fire suppression systems (sprinklers) ● Scheduled preventative maintenance
Evacuation System	● Evacuation routes ● Relocation of occupants and information tracking ● Personnel and emergency services ● Transport equipment

In order to avoid or reduce property damage and also prevent fatalities, suppression systems are present to detect and put out fires. Key elements include alarms, smoke and heat detectors, sprinklers, extinguishers, water hose reels, and ventilation systems. Hospital fire suppression systems are the first line of defence against fires and must be triggered rapidly, making them an extremely essential component, which also causes them to be costly, particularly ventilation systems. However, scheduled preventative maintenance is vital since such systems are mechanical and electrical in nature, causing them to be susceptible to deterioration and degradation (PAHO, 2018).

The evacuation system pertains to the escape of occupants to a safe outdoor location or a transitional area. This involves staff training to impart familiarity with evacuation routes and hospital access to emergency services such as phone lines and broadband. Each floor must have enough transport tools such as blankets, backboards and Sked Stretchers, also methods to move, relocate and track patient notes. The foundation of the evacuation system is the evacuation routes that function to direct all services to and from crisis zones and ensure the safe evacuation of occupants by leading them in the direction of an exit. All rooms larger than 230 m^2, aside from patient sleeping spaces must have at least two independent evacuation routes that are at least 2.4 m wide, with exit doors that are at a minimum of 1.25 m wide (PAHO, 2018). However, as patients may have limitations in mobilising, a hospital's primary aim is to keep patients from being evacuated until it is absolutely necessary (Othman et al., 2023). Therefore, a fundamental endeavour for hospital fire safety should be to ensure that well-designed and fully effective fire prevention and suppression system are in place.

Unfortunately, prevention and suppression system do not always work as intended as it is not fail-proof. Globally, due to financial restrictions, out-of-date building designs, and negligence, inadequate maintenance of fire suppression systems are widespread and can endanger lives. In their study in China, Olanrewaju et al. (2018) noted that hospital fire suppression system failures were alarmingly frequent. Likewise, negligence was partly to blame for the six fires that occurred at the Sultanah Aminah Hospital in Malaysia between 2010 and 2020 (Muhammad Salleh et al., 2020). Furthermore, hospital fires can take hours to put out because of the size and complexity of hospital structures. As an example, despite having 334 firefighters dispatched, the fire at the Hospital Barros Luco in Chile, which treats 10,000 people daily, took 5 hours to put out (PAHO, 2018). The potential risk of occupant injury and death was dramatically increased by the ongoing fire. As a result, efficient hospital fire evacuation routes can reduce this risk and should be adjusted for reducing risks of casualties during a fire (Muhammad Salleh et al., 2020). Additionally, case studies on hospital fires in the Americas indicated that the primary determinant of casualty rates was the failure of occupant evacuation during a fire – highlighting the need for reliable hospital fire safety systems that include the appropriate evacuation route designs (PAHO, 2018).

Importance of Human Wayfinding Cognition in Hospital Fire Evacuation

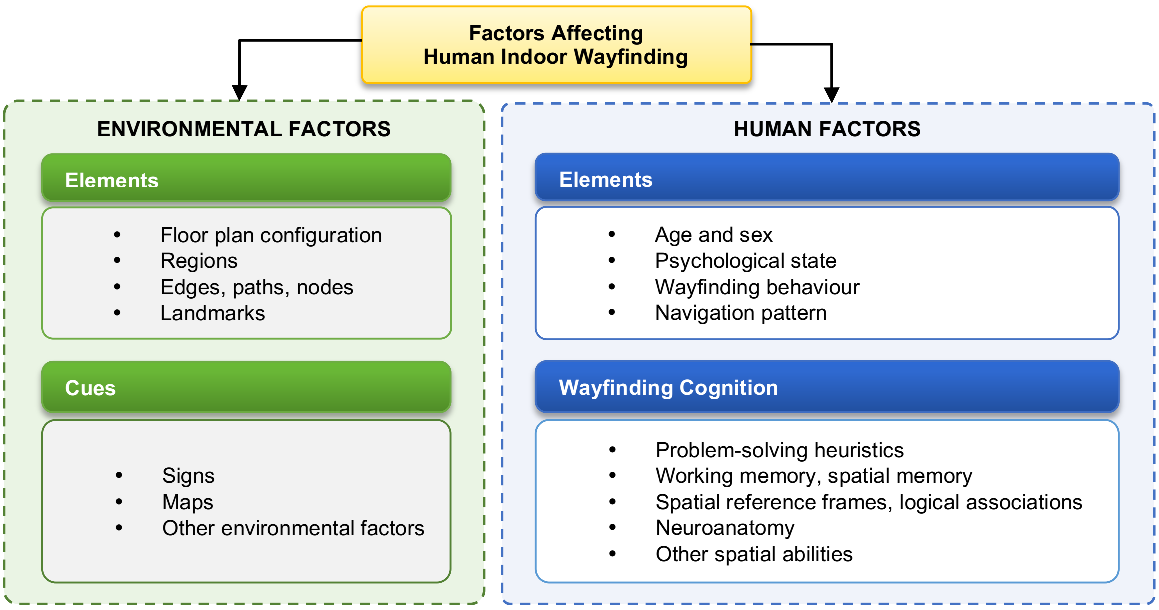

Figure 2: Factors that affect human wayfinding in indoor environment.

Hospital access and indoor circulation are complex and are often designed to be restrictive as a measure to protect patient's rights and dignity, making the evacuation routes challenging to design among all building typologies (Muhammad Salleh et al., 2020; Choudhary et al., 2018). Complicating matters, not every member of the public who enters a hospital is able to achieve familiarity and spatial awareness (Kinsey et al., 2019). Moreover, as modernisation brings along higher prevalence of non-communicable diseases such as heart disease, diabetes, and cancer, which are currently among the major health burdens of healthcare systems worldwide (Zaiki et al., 2022; Zaiki & Wong, 2021), hospital overcrowding is becoming increasingly common and is approaching critical breaking point, especially in developing countries (Darraj et al., 2023; Daw & Mahamat, 2023). This puts the public at greater risk in the event of a fire occurring in hospitals. Thus, for a safe evacuation, occupants' indoor wayfinding is essential in navigating unknown and unfamiliar hospital fire evacuation routes.

The process of choosing and determining a path towards a destination of unknown location is known as indoor wayfinding (i.e., locating the hospital exit while not knowing the exact location) (Othman et al., 2023). Gibson's Theory of Affordances was used in earlier human wayfinding studies to explain how physical settings affected human responses which included behaviour and wayfinding

(Maier et al., 2009; Brown & Blessing, 2005; Shaari et al., 2021). However, this hypothesis falls short of explaining indoor wayfinding because it presumes that people passively react to their surroundings, but indoor wayfinding is a complex human behaviour influenced by more than just affordance (Fig. 2) (Jamshidi et al., 2020; Dalton et al., 2019; Slone et al., 2015; Vilar et al., 2015). Recent scholars however contend that wayfinding cognition makes up an important component of indoor wayfinding as it extensively incorporates spatial cognition, logic, and problem-solving heuristics (Huang et al., 2021; Jamshidi et al., 2020; Othman et al., 2023). This becomes even more pertinent in the setting of a hospital fire as occupant's unfamiliarity with fire evacuation routes is taken into account, lessening the direct impact of environmental elements on indoor wayfinding will lose its effectiveness (Kinsey et al., 2019; Erkan, 2018).

Kuligowski's theory of human behaviour in fire and MacGregor's progress-monitoring theory of indoor wayfinding

Kuligowski's Theory of Human Behaviour in Fire eventually proposes a Protective Action Decision Model (PADM) for human decision-making processes with the goal of understanding human behavioural responses during a fire (Kuligowski et al., 2017). The PADM also suggests that cues from the environment have an impact on cognitive processes, including pre-decisional (e.g., risk identification and information perception) and decisional processes (Kuligowski et al., 2017). According to Kuligowski's theory, a person will choose the optimum course of action based on how they perceive and evaluate environmental stimuli (Kuligowski et al., 2017). These protective measures include moving towards safety and deciding to either evacuate right away or to stay put in a safe location, after evaluating and determining which is more beneficial (Kuligowski et al., 2017). Additionally, Kuligowski et al. (2017) emphasise how familiarity with exits (Sime, 1983), exit routes, and distinctive exit designs that emphasise safety have a significant effect on the protective actions performed (Kuligowski et al., 2017; Nilsson, 2009).

Furthermore, MacGregor's Progress-Monitoring Theory, which views interior navigation as a problem-solving task, is a generally acknowledged theory in indoor wayfinding studies and by extension, explains wayfinding cognition as well (Jamshidi & Pati, 2021; MacGregor et al., 2001). The theory can be explained in two components: (1) using hill climbing heuristics to discover one's route, and (2) self-monitoring to track one's progress in heading towards their destination. The hill climbing heuristics indicates a wayfinder like a hill climber, who is a problem-solver as their decision on choosing a route depends on how likely it would lead to the quickest advancement towards their goal. The navigational plan will be abandoned, and a new route will be devised if the progress is deemed inefficient (MacGregor et al., 2001). Thus, during indoor wayfinding, the perception of one's environment and cognitive processes take place and better wayfinding cognition performance is what will lead to better wayfinding behaviour (Jamshidi et al., 2020).

This is essential for hospital fire evacuation as it will overcome the problem of unfamiliarity in the environment as wayfinding cognition performance will heavily influence occupants' evacuation performance or how well they evacuate. As the physical aspect of the indoor environment can be altered to influence human cognitive processes, performance, and subsequent behaviour (Othman et al., 2023; Shaari et al., 2020a; 2020b; 2021), the environmental elements that favourably affect such wayfinding cognition can be constructed to enhance indoor wayfinding performance. Therefore, designers should incorporate a better grasp of human wayfinding cognition to facilitate more efficient evacuation in order to design an effective hospital evacuation route.

The Neurophysiological Relationship Between Hospital Evacuation Route Designs and Wayfinding Cognition During Fire Evacuation

The principles of neuroarchitecture

Observations, interviews, and questionnaires are commonly used in architectural research methodologies to analyse human behaviour (Othman et al., 2023). Although commonly adopted, these techniques are biased, subjective, and frequently lack the objective proof to support participants' responses (Vijayan & Embi, 2019). As a result, data's reproducibility, generalisability, and significance are often jeopardised. Therefore, in order to better understand how people behave in response to their environment, neuroscientific methodologies are being adopted into architectural studies as part of an emerging transdisciplinary field known as neuroarchitecture (Eberhard, 2008).

Comprehension of the fundamentals in neuroscience such as the basic terminologies is necessary in order to implement neuroscientific ideas. The brain emits electrical signals sent by neurons, which are specialised cells. The nervous system in the human body controls all organs with neurones and is the central command centre for bodily functions (Rosen & Halgren, 2022). The nervous system is made up of nerves, the spinal cord, the brain, and all sensory organs (eyes, ears, nose, tongue, and skin receptors). Neurophysiology is described as the neural mechanisms involved in the nervous system functions, and neuroanatomy describes where these processes take place (Vijayan & Embi, 2019). Thus, the essential framework for neuroarchitecture research involves the study of the nervous system activities and the subsequent behaviour in response to the environment from a neurophysiological and neuroanatomical perspective (Fig. 3) (Eberhard, 2008).

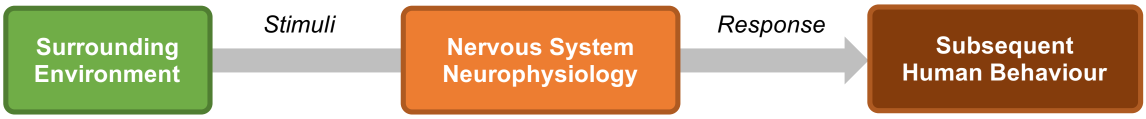

Figure 3: The neuroarchitecture framework for the influence of surrounding environments on human behaviour.

Neuroarchitecture studies are particularly focused on brain activity due to its significance in determining human perception, cognition and what influences behaviour (Othman et al., 2023). The electroencephalogram (EEG), computer tomography (CT), and functional magnetic resonance imaging (fMRI) are the three main neuroimaging techniques used to examine brain activity. The EEG however, is the simplest, cheapest, and most portable method, making it the most popular in recent neuroarchitecture studies (Karandinou & Turner, 2017). Due to its superior temporal resolution in comparison to CT and fMRI scans, it is also more precise in measuring split-second neural activity.

An EEG correctly identifies the precise brain region involved by measuring the electrical activity coming from neuronal activity linked to brain activities. There are four main frequency bands that make up brain EEG activity (brainwaves which are: Delta waves (ranging from 0.5Hz - 4Hz), Theta waves (ranging from 4Hz - 8Hz), Alpha waves (ranging from 8Hz - 13Hz), and Beta waves (ranging from 13Hz - 30Hz) (Anoor et al., 2020; Erkan, 2018). Higher brainwave frequencies typically indicate more active or intense brain activity. Delta waves are commonly interpreted to represent unconsciousness, Theta waves represent the brain in a meditative or semi-conscious state, Alpha waves are frequently encountered in alert but calm states, whereas Beta waves indicate strong or intense mental activities (Azzazzy et al., 2021). Therefore, wayfinding cognition during fire can be accurately explored and investigated by identifying the presence of this particular set of brainwave patterns.

The neural efficiency hypothesis and the regions of the brain involved in cognitive performance

Human cognition has been the subject of psychological research since the 19th century. However, it was only until the late 20th century that the neurophysiological knowledge of human cognition began to thrive, which was a result of the development of more advanced and accurate neuroscientific investigative techniques. The Neural Efficiency Hypothesis, first proposed in 1992 is part of current neurophysiological interpretation and view that explains human cognitive performance (Li & Smith, 2021; Anoor et al., 2020; Neubauer & Fink, 2009). According to the hypothesis, the brain’s productivity, and efficiency – rather than how hard it works – determines how intelligent one is. In order to emphasise “efficiency” as a key component, proponents of this hypothesis contend that in addition to working quickly, it is crucial to attenuate task-irrelevant activities (or eliminate “noise”) because the brain region that is responsible for completing the task ensures that resources are used as efficiently as possible during complex cognitive activities (Neubauer & Fink, 2009). The synchronisation of EEG Alpha waves and desynchronisation of EEG Beta waves during cognitive tasks can be used to describe this measure of brain efficiency (Anoor et al., 2020).

The Parieto-Frontal Integration Theory was developed by Jung and Haier (2007) to better understand the neuroanatomy of brain cognition. The hypothesis contends that when doing cognitive activities, the parietal and frontal portions of the brain are more active. It was developed based on the analysis of various brain imaging data. Additionally, a recent review by Friedman and Robbins (2022) noted that the prefrontal cortex, which is located in the frontal region of the brain, is responsible for cognition, emphasising its crucial role in determining the various aspects of cognitive function. This indicates that the parietal lobe and prefrontal cortex of the brain are the regions that are specifically in charge of perception and cognition, respectively. This occurs upon the reception and processing of external stimuli. In these brain regions, the synchronisation of Alpha waves and desynchronisation of Beta waves would indicate extremely effective cognitive performance (Anoor et al., 2020; Neubauer & Fink, 2009). Such productive neural activity in the parietal lobe and prefrontal cortex of the brain during a fire evacuation may enhance wayfinding cognition performance, which will ultimately enhance occupant wayfinding and evacuation performance.

Influence of hospital evacuation route designs on wayfinding cognition during fire evacuation: A neuroarchitecture framework

Despite recent efforts to enhance our understanding of the neurophysiology behind human wayfinding cognition in order to build indoor environments that favourably affect occupants' indoor navigation (Huang et al., 2021; Kuligowski et al., 2017, Kuligowski, 2016) in the context of fires, let alone hospital fires, such research is still scarce (Huang et al., 2021; Jamshidi et al., 2020). In order to recognise features and aspects of hospital indoor environment that could be adapted to accommodate occupant wayfinding, designers must have a thorough grasp of the neurophysiology of wayfinding cognition and how hospital evacuation route designs can affect it (Othman et al., 2023).

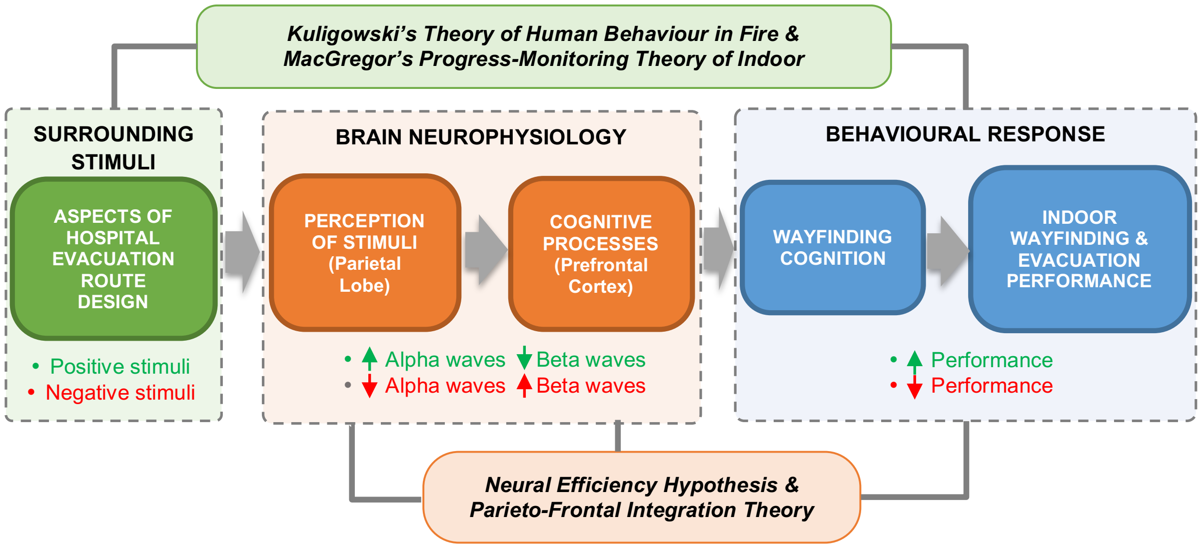

Figure 4: A neuroarchitecture framework showing the impact of hospital evacuation route design on brain neurophysiology and the subsequent behavioural response (wayfinding cognition).

The neuroarchitecture framework for the influence of hospital evacuation route designs on brain activity and wayfinding cognition has been outlined above by combining the tenets from Kuligowki's Theory of Human Behaviour in Fire, MacGregor's Progress-Monitoring Theory of indoor wayfinding, the Neural Efficiency Hypothesis, and the Parieto-Frontal Integration Theory of cognitive function (Fig. 4). This unique approach, in contrast to previous neuroarchitecture studies, emphasises the neurophysiological and neuroanatomical elements of wayfinding during hospital fire evacuation to provide a clearer understanding of the relevant brain activity and mechanisms and how they influence evacuation behaviour (Othman et al., 2023). This will allow for better understanding of human behaviour in fire, simultaneously allowing us to develop future neuroarchitecture studies that are more neuroscientific accurate and for it to be possible to optimise human evacuation wayfinding performance.

DISCUSSION

Aspects of hospital evacuation route designs influence human neurophysiology through physical stimuli, similar to most built environment elements (Fig. 4) (Natapov et al., 2022; Azzazzy et al., 2021; Erkan, 2018). This can involve visual, auditory, or tactile stimuli, additionally also involving smell. The significance of environmental stimuli and context is emphasised in Kuligowski's Theory of Human Behaviour in Fire because of the considerable impact it has on decisions made to move towards safety (Nilsson, 2009; Sime, 1983). Common examples include using designs that are typically linked with safety and utilising design features that help in indicating direction (Kuligowski et al., 2017). Similar to Kuligowski's Theory, MacGregor's Progress-Monitoring Theory of indoor wayfinding states that a wayfinder will choose a route based on the perceived likelihood of leading to the quickest and safest exit at key intersections, starting points, turns, and corridors. This may be the result of better visibility brought on by elements like transparent walls, or landmarks that indicate towards an exit, like staircases (Natapov et al., 2022). As a result, additional elements that are frequently linked to safe exits, such as colour, visual signage, and architectural features, may also affect the choice of routes (Kalantari et al., 2022). The design of these features and elements must also be clear and unambiguous, as any confusing indicators can prompt occupants to re-evaluate their routes and possibly cause confusion. Wayfinding for hospital fire evacuation is detrimental as confusion may result in wrong turns towards the actual exit, thus, placing occupants at risk (Othman et al., 2023).

The Neural Efficiency Hypothesis and the Parieto-Frontal Integration Theory of cognitive function, which delves deeper into the framework, content that for the parietal lobe and prefrontal cortex to respond to physical stimuli effectively, the stimulus must be consistent and not overwhelming (Li & Smith, 2021). Therefore, it is necessary to include frequent but simple indicators of a safe exit in the design of hospital evacuation routes. This can be done by using clear signage and by avoiding making too many complicated turns. Furthermore, since the prefrontal cortex must work harder to perform wayfinding cognition, which requires intense cognitive processes like deductive risk assessment, distance estimation, and spatial cognition to orient oneself in a complex hospital environment, having confusing stimuli from the hospital evacuation route could also be seen as cortical “noise” (Friedman & Robbins, 2022; Kalantari et al., 2022). These unwelcomed interruptions in cognitive function could be detrimental in emergency scenarios like fires where split-second decision-making is essential for a safe evacuation, which is why such interferences must be avoided in fire evacuation route designs.

Research findings must adequately characterise both positive and negative environmental stimuli in terms of neurophysiology in order for neuroarchitecture to become practical for building design (Eberhard, 2008; Othman et al., 2023). Although many architectural studies have noted how the physical environment affects human behaviour, it is the accompanying neurophysiological features that reliably demonstrate human behavioural responses in built environment settings. Therefore, positive stimuli can be identified by the synchronisation of Alpha waves and the desynchronisation of Beta waves at the parietal lobe and prefrontal cortex, and vice versa (Fig. 4).

Making decisions and solving problems are crucial mental processes in evacuation or emergency situations (Daylamani-Zad et al., 2022). Additionally, according to Kuligowski's Theory of Human Behaviour in Fire, the cognitive processes that result from environmental perception have a significant impact on human responses and evacuation performance (Kuligowski, 2016). Similarly, MacGregor's Progress Monitoring Theory of Indoor Wayfinding supports the notion that wayfinding is primarily a problem-solving task (i.e., a cognitively taxing process) in architectural theories related to wayfinding and navigation (Macgregor et al., 2001). This indicates that wayfinding in emergency situations relies on cognitive performance. We can therefore optimise and subsequently improve evacuation wayfinding performance by comprehending the cognitive process (type of wave bands, pattern of wave power, and the origin of the activity). However, there haven't been many studies that have looked into brainwave activity in emergency situations, which could lead to different results than when the brain is put through a task with less urgency. Studies on the built environment that used the EEG to comprehend human cognition in various situations were compiled by Naghibi Rad (2019). Recently, we have outlined and critically reviewed a number of additional studies that demonstrate how different levels of cognitive performance in various indoor contexts are represented by brainwave, wave pattern, and activity location (Othman et al., 2023).

We previously argued that the Alpha and Theta waves are the brainwaves that are most indicative of improved cognitive function (Othman et al., 2023). According to earlier characterisations, Alpha waves typically appear when one is alert, while Theta waves signify a relaxed reaction to a situation (Anoor et al., 2020). When confronted with a crowd, finally finishing a task, or running into obstacles while navigating, Beta waves are thought to be produced. These situations involve intense feelings of joy, focus, and cognition (Karandinou & Turner, 2017). Only one study (Banaei et al., 2017) had significant Delta activity, which was present when temperatures increased, and participants started to feel sleepy or drowsy during the task. This suggests that Delta activation can also be used to measure poor cognitive performance. In contrast to Beta bands, which are linked to feelings of overwhelmingness, Delta bands are linked to feelings of extreme non-interactivity.

As a result, we can conclude that evaluating the relative power ratios between the wave band patterns (Alpha/Theta vs. Beta/Theta) and the source of the activity will enable us to gauge cognitive performance and enhance wayfinding performance (Othman et al., 2023). We can hypothesise that similar methodologies can be used for studies of evacuation wayfinding performance based on earlier studies that track brain activity during indoor human behaviour. Evacuation wayfinding performance can be improved by implementing EEG brainwave features because it has been concluded that cognitive performance and wayfinding performance are related (Othman et al., 2023).

This would improve wayfinding cognition and evacuation performance during a hospital fire. As a result, neuroimaging techniques become essential for neuroarchitecture studies as tools like the EEG is the most ideal for gathering such information (Karandinou & Turner, 2017). This knowhow forms the framework’s central component (Fig. 4) and ought to be used in future neuroarchitecture studies on human evacuation behaviour in complex situations such as hospital fires.

CONCLUSIONS

As healthcare systems across the world become critically burdened by the increasing prevalence of diseases, hospitals continue to be an important public building in many countries. This puts many civilian lives at great risk in the event of a hospital fire. Given the significance of hospital fire evacuation routes as a reliable system that protects the lives of vulnerable hospital patients, it is imperative that their design ensures efficient egress during a fire. While hospital evacuation routes are undoubtedly challenging to design due to the issues discussed earlier, special considerations must be taken to ensure that various physical design elements can optimize human wayfinding cognition performance, its associated neurophysiology, and subsequent evacuation performance. Better methods are required to simulate the actual stimuli experienced during a fire without endangering study participants' safety for future neuroarchitecture research. This involves simulating the visual and auditory stimuli of real hospital environments during a fire using virtual reality (VR) technology. To accurately replicate the heat and odour of an actual fire, controlled fires and artificial smoke may also be used in rigorous research settings. Furthermore, rather than being studied separately, the impact of various physical design elements on wayfinding cognition should be examined collectively in the form of design configurations. This method enables a more precise assessment of brain activity during fire evacuation, despite the fact that such study designs are difficult (a common limitation even in recent high-impact neuroarchitecture studies). The information gathered will also be more useful for designing better evacuation routes and enabling more accurate fire simulation studies. Nonetheless, the current absence of hospital fire safety guidelines in many parts of the world that emphasise or incorporate elements of wayfinding cognition in evacuation route design remains glaring and must be addressed. This knowledge gap is largely attributable to a lack of awareness and insufficient study of the topic. The neuroarchitecture framework put forth here establishes, as a first step, a distinct neurophysiological and neuroanatomical connection between hospital evacuation route designs, wayfinding cognition, and subsequent evacuation performance. Moreover, the potential application of brainwave characteristics to optimize hospital fire evacuation route designs seem promising as they have been adopted in various other studies to accurately characterize human cognition. It is hoped that as a new framework, it will serve as an essential basis for upcoming studies on indoor evacuation wayfinding with potential applications in building designs for disaster response, such as fires and earthquakes, or in other complex building typologies, like airports and offices.

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