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INTEGRATING VIRTUAL REALITY AND EYE-TRACKING TO ASSESS THE RESTORATIVE POTENTIAL OF DYNAMIC VISUAL CONDITIONS

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Abstract

As interest in the physiological impacts of indoor environments grows, increasing attention is oriented toward how lighting conditions shape gaze and internal states. While broader and more flexible gaze patterns have been linked to improved physiological regulation, particularly in clinical contexts, the specific influence of dynamic lighting conditions on gaze behaviour in everyday interior environments remains underexplored. As a result, design strategies often rely on static assumptions about visual engagement, overlooking the potential of dynamic stimuli to support well-being. This study presents a narrative review synthesising recent findings on how dynamic environmental stimuli, including lighting variation and visual saliency, mediate gaze behaviour and influence cognitive and emotional outcomes. The review integrates evidence from vision science, environmental psychology, and lighting research to highlight emerging relationships between dynamic conditions, attention, mood, and recovery. The findings aim to inform adaptive lighting strategies that enhance occupant well-being and attentional engagement in interior environments.

Keywords: Dynamic Visual Conditions, Gaze Behaviour, Lighting Environments, Cognitive Load, Emotional States

1 Introduction

Research on gaze behaviour has demonstrated that viewing open scenes, such as abstract paintings or landscapes, elicits faster eye movements as people spend more time trying make sense of the scene (Dupont et al., 2017). These rapid eye movement patterns have been recognised and used in therapies like Eye Movement Desensitization and Reprocessing (EMDR), effectively addressing conditions such as post-traumatic stress disorder and depression through affective distractions (Davidson and Parker, 2001). While modulating eye movement patterns through external stimuli is a well-operationalised therapeutic strategy (Klainin-Yobas et al., 2015), the influence of dynamic visual conditions in everyday built environments is yet to be fully explored. Adults spend approximately 90% of their time indoors (Andersen, 2015), often in urban environments with limited access to daylight and nature (Cox et al., 2017). Dynamic visual stimuli, such as varying light levels, movement, and natural views, have been shown to positively impact well-being and cognitive functioning (Ko et al., 2022; Rodriguez et al., 2021). Understanding how these dynamic conditions influence gaze behaviour and emotional responses can provide valuable insights for modulating lighting in indoor environments to promote well-being, particularly those where natural stimuli are limited, such as hospitals.

Advances in visualisation technologies and eye-tracking systems present new opportunities to explore how naturalistic and simulated dynamic visual conditions influence eye movement speed and mediate internal states in people. Studies have examined eye movement patterns in response to static visual and lighting conditions from windows, highlighting the interplay between lighting, visual content, and gaze behavior (Batool et al., 2021; Sarey Khanie et al., 2013). While these findings underscore the potential of advanced visualisation tools for examining restorative potential, the specific impact of dynamic visual conditions on eye movement patterns and their role in fostering positive mental states remain largely unexplored.

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This paper presents a narrative review of existing research on dynamic visual conditions, gaze behaviour, and psychological well-being, addressing the question of how dynamic lighting and visual stimuli influence eye movement patterns and, by extension, cognitive and emotional states. By synthesising findings from vision science, environmental psychology, and lighting research, the review aims to clarify the extent to which dynamic visual conditions can be harnessed to promote restorative experiences in indoor settings. Rather than introducing new empirical data, this paper integrates current knowledge to identify patterns, reveal gaps, and propose future directions for research and evidence-based design.

2 Methodology

To support a structured yet flexible review process, this study adopts a narrative approach, focusing on thematically relevant and methodologically sound studies. Given the interdisciplinary nature of research on dynamic visual conditions, gaze behaviour, and psychological well-being in interior environments, this approach enables the integration of varied methods and perspectives without requiring uniformity in study design or outcomes (Popay et al., 2006).

The literature search was conducted using the Scopus database between December 2024 and April 2025, limited to peer-reviewed articles and conference proceedings published in English until 2025. Search terms were applied to the title, abstract, and keyword fields using advanced search functions. Boolean operators (AND, OR) and wildcard characters (e.g., relax*, depress*, calm*) were used to capture variations in terminology and ensure comprehensive coverage. The search strategy was structured around three conceptual domains: (1) gaze behaviour, (2) dynamic visual and lighting conditions, including visual saliency and spatial understanding, and (3) psychological, cognitive, and mental health outcomes (Table 1). References were managed and assessed using Covidence.

Table 1 – Search Terms Used for Narrative Review

Conceptual Domain	Keywords / Wildcards	Rationale
Gaze Behaviour	"eye movement*", “eye behavio*”, gaze, “gaze behavio*”, "visual attention", saccade*, fixation*	To capture terminology commonly used in eye-tracking, attentional processing, and visual perception research.
Dynamic Visual and Lighting Conditions, including Visual Saliency and Spatial Understanding	"dynamic light*", "light* variation*", "chang* light*", "dynamic visual*", "daylight change*", light*, Saliency, “scene understanding”	To cover both perceived motion and temporal variation relevant to lighting and visual dynamism; to capture terminology related to spatial saliency and understanding.
Psychological and Cognitive Outcomes	"mental health", emotion*, affect*, mood, stress*, relax*, anxi*, depress*, arous*, comfort*, calm*, restorat*, cogniti*, "mental* fatigue*", focus*, attenti*, alert*, "rate of recovery", glare, perform*, productiv*	To encompass a broad range of emotional, cognitive, and recovery-related terms relevant to occupant well-being and attentional performance.

The initial search yielded 1241 studies for screening. In the second round, studies focusing on deep learning model development, computer vision callibration, branding, and diagnostic applications of eye-tracking (e.g., autism spectrum disorder) were removed. To maintain focus on visual engagement and cognitive responses within interior environments, studies centered on outdoor and movement contexts, such as sports and driving or pedestrian behaviour were excluded, leaving 1083 studies deemed irrelevant. This left 158 studies for further review. In the third round, 97 studies addressing incidental media content, isolated pupillary responses, or vision without environmental considerations were excluded, leaving 61 studies for detailed analysis. Following full-text review, a final set of 22 was selected, with this smaller number reflecting a focus on studies that explored mediating effects between dynamic visual conditions, gaze behaviour, and psychological outcomes. These studies were divided into primary (core) and secondary evidence. Primary evidence (n = 4) comprised empirical studies that directly linked dynamic lighting or ephemeral visual features, gaze behaviour, and psychological outcomes. Secondary evidence (n = 18) included empirical studies addressing closely related concepts (e.g., saliency) that contextualised and supported interpretation of the core evidence (Table 2).

Table 2 – Overview of the Evidence Base

Evidence Base	Authors
Primary (n = 4)	Gómez-Sirvent et al. (2024); Kang et al. (2024); Li et al. (2024); Wu et al. (2023)
Secondary (n= 18)	Açık et al. (2010); Berggren et al. (2012); Chen et al. (2022); Dombrowe et al. (2010); Huang et al. (2014); Jarodzka et al. (2010); Jiang et al. (2024); Kim et al. (2022); Laco et al. (2021); Liu et al. (2016); Raptis et al. (2018); Sarey Khanie et al. (2017); Schmidt et al. (2011); Schmidt-Weigand et al. (2010); Thurman et al. (2021); Waldin et al. (2017); Wang et al. (2018); Wykowska and Schubö (2012)

3 Results

Lighting conditions influence gaze behaviour in complex ways, with implications for attentional performance, emotional regulation, and visual comfort. These effects are shaped by several interacting factors: broad-scale environmental lighting conditions, fine-scale dynamic features, people's internal cognitive and emotional states, and their task demands and levels of expertise.

3.1 Environmental Lighting Conditions: Effects on Gaze

Several studies have shown that gradual light variations promote positive outcomes. Li et al. (2024) found that when interior lighting varied gently over time, people's gaze became more exploratory, and they reported greater comfort. Similarly, Kang et al. (2024) showed that gradual brightness changes helped people maintain attention during tasks, suggesting that the rhythm and pacing of lighting changes is important. At a spatial scale, Gómez-Sirvent et al. (2024) showed that windows allowing natural light to shift across the day helped stabilise gaze and promoted a sense of calm. In parallel, Wu et al. (2023) found that when indoor lighting produced smooth transitions, people felt greater restoration, suggesting that indoor lighting consistency supports attentional and emotional wellbeing.

However, not all light changes are beneficial, particularly when variation is abrupt, unpredictable, or poorly calibrated. Jiang et al. (2024) showed that when dynamic lighting in signage was poorly tuned, it distracted attention from important information, reducing the effectiveness of visual communication. In addressing similar unpredictable lighting conditions in built environments, especially those that cause glare, Sarey Khanie et al. (2017) advocated for the use of eye-tracking as a more meaningful method to assess visual discomfort, rather than relying solely on traditional lighting metrics.

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While gaze under unpredictable lighting can primarily impact cognitive performance and cause visual discomfort, emerging evidence also suggests that discomfort in lighting environments can manifest physically, influencing posture and head orientation. Kim et al. (2022) found that uncomfortable lighting in virtual environments caused people to tilt or turn their heads to reduce glare, suggesting that lighting quality can influence bodily orientation, forcing compensatory movements that could add physical strain. Similarly, Huang and Menozzi (2014) showed that sudden glaring conditions disrupted peripheral vision and impaired task performance, underscoring the risks of uncontrolled lighting peaks.

Together, these findings suggest that gradual and coherent lighting variation supports stable gaze patterns, enhances attentional focus, and promotes emotional comfort. In contrast, abrupt, unpredictable, or poorly calibrated lighting changes can disrupt visual engagement, impair cognitive performance, contribute to visual discomfort, and lead to posture adjustments as people try to reduce discomfort or glare.

3.2 Fine-Scale Dynamic Visual Features: Effects on Gaze

At finer spatial and temporal scales, brief and localised changes in visual conditions, such as flicker, brightness shifts, and contrast, were found to strongly influence gaze behaviour. However, these effects are highly time- and context-dependent.

Waldin et al. (2017) showed that peripheral flicker, even when not consciously perceived, could subtly guide gaze during search tasks. This highlights how localised, dynamic light can guide attention without distracting observers. Similarly, Wang et al. (2018) found that when small areas near a person's line of sight became brighter, it caused their pupils to narrow automatically. This suggests that even minor changes in luminance can involuntarily influence visual attention. Thurman et al. (2021) built on this idea by showing that natural patterns of brightness outdoors, such as the change between the horizon and the sky, helped stabilise both gaze direction and pupil size. Together, these studies suggest that gradual changes in light can help stabilise gaze behaviour and support more natural visual engagement.

Yet, subtle or fine-scale lighting changes may not always be effective in maintaining attention. Dombrowe et al. (2010) showed that although bright or colourful areas first captured attention, this effect quickly faded as observers shifted their focus to different tasks. Similarly, Schmidt et al. (2011) showed that brightness illusions could trigger quick but inaccurate reactions based on misleading visual cues. This highlights that while quick lighting changes can prompt attention, stable lighting conditions are necessary to support consistent gaze behaviour.

Across these studies, small lighting changes stand out as powerful but brief influences on gaze behaviour. When carefully callibrated, they can help guide attention and make visual exploration feel more natural. However, if these changes are too distracting, they can destabilise gaze patterns, increasing visual load, and reducing the effectiveness of spatial or visual cues. For lighting research, this underscores the importance of understanding how small-scale dynamic effects, such as flickers, can influence attention, making their control as critical as achieving suitable overall lighting conditions.

3.3 Internal States: Effects on Gaze

While most studies within the evidence base focus on how lighting influences gaze behaviour, internal factors such as cognitive load, mood, and emotional states also play a critical role. Studies showed that gaze behaviour is not just a reaction to what is visible; rather, it is shaped by what the observer is thinking, feeling, or trying to do. This means that even a well-designed lighting environment can be experienced differently depending on an occupant’s cognitive or emotional state.

Wu et al. (2023) found that uneven spatial luminance distributions increased visual effort and made gaze patterns less stable, with participants showing more scattered fixations. This suggests that lighting environments requiring frequent visual adaptation may increase visual strain rather than support attention recovery. Beyond spatial factors, temporal variation in lighting can also affect gaze behaviour and cognitive effort. Liu et al. (2016) found that changes in light levels, including those designed to mimic natural variation, can confuse gaze behaviour, making it difficult to recognise signs of mental strain. This highlights the need to match dynamic lighting conditions closely to the task, as too much fluctuation at the wrong time can disrupt concentration and affect the monitoring of workload. Similarly, Berggren et al. (2012) found that cognitive load made gaze patterns less efficient during emotionally charged visual tasks, especially for people with high levels of anxiety. This suggests that stress and emotional sensitivity can influence how lighting is experienced, either positively or negatively, depending on the occupant's state.

While stress can narrow and disrupt visual attention, positive emotional states appear to widen it. Laco et al. (2021) found that observers in a positive mood showed wider gaze patterns during search tasks, suggesting that environments that support positive emotions, such as through daylight or a quality spatial atmosphere, could encourage more exploratory gaze behaviour and may help support a more comfortable visual experience. Chen et al. (2022) introduced a trait-based perspective, showing that individuals with stronger connections to nature spent more time looking at natural elements, even when viewing a virtual environment that combined buildings and trees. This suggests that lighting that incorporates natural qualities could influence people differently depending on their personal connection to nature. Wykowska and Schubö (2012) demonstrated that action intentions, such as planning to reach or point at an object, can modulate early stages of visual attention. Even simple planned movements influence where and how gaze is directed, suggesting that lighting should be designed to support not only passive viewing but also active behaviours, such as navigating, reaching, and decision-making.

These studies show that internal cognitive and emotional states systematically shape gaze behaviour and how lighting environments are perceived and experienced. While baseline internal states influence where and how people look, it remains less clear whether lighting conditions can actively shift or stabilise these internal states in ways that are detectable through gaze patterns.

3.4 Expertise and Task Demands: Effects on Gaze

Gaze behaviour is shaped not only by environmental conditions but also by individuals’ expertise and the demands placed on them by the tasks they undertake. Research shows that people do not explore visual environments uniformly: where and how they move their gaze depends strongly on what they know, what they are trying to do, and how complex the scene is. This highlights that people’s experience cannot be predicted solely from spatial or lighting conditions but must also acknowledge how different they interact visually with a scene.

Expertise significantly shapes visual exploration. Jarodzka et al. (2010) demonstrated that experts interpreting dynamic visual scenes displayed more efficient and goal-directed gaze patterns compared to novices, who tended to fixate more randomly. Similarly, Açık et al. (2010) showed that individuals whose gaze behaviour aligned more closely with salient features to performed better in memory tasks. Furthermore, the study revealed that age-related experience influenced gaze behaviour, with younger observers focusing on visual saliency, while older observers relying more on semantic understanding to direct their attention. This suggests that experienced individuals may prioritize meaningful cues over mere visual contrast, and spaces designed to rely solely on visual salience may fail to support more expert navigation or engagement.

Task demands also shape how people visually interact with their environment. Schmidt-Weigand et al. (2010) demonstrated that the pacing of dynamic visualisations influenced gaze behaviour, with slower information delivery encouraging broader visual exploration, and faster information delivery pushing observers to reading accompanying text. In built spaces, rapid lighting changes or over-stimulating scenes could narrow attention, while more gradual transitions may promote broader engagement with the environment. Raptis et al. (2018) showed that in a visually rich mixed-reality environment, participants completing a search task who explored more extensively performed better and felt more immersed, while participants with narrower exploration areas found it harder to engage.

Together, these studies highlight that environments requiring active exploration are sensitive to variations in gaze behaviour driven by task demands, and that the ability to maintain engagement depends on how visual information aligns with individuals’ goals and expertise. Lighting research should account for not only visual salience but also the influence of individuals’ expertise, task demands, and cognitive strategies on gaze patterns.

4 Discussion

This narrative review explored how dynamic lighting and visual conditions at multiple scales influence gaze behaviour and associated cognitive and emotional outcomes. The findings highlight four main themes: the role of broad environmental lighting conditions, the impact of fine-scale visual dynamics, the influence of internal cognitive and emotional states, and the moderating effects of individual expertise and task demands.

With respect to environmental lighting conditions and gaze, a clear pattern emerging from the reviewed studies is that gradual, predictable lighting variation supports more exploratory gaze behaviour and fosters emotional comfort, whereas abrupt changes tend to disrupt attention and induce visual discomfort. These findings align with emerging evidence that dynamic environmental transitions play a critical role in occupant wellbeing. In this context, recent work by Aries et al. (2024) illustrates how dynamic artificial lighting, designed to replicate twilight conditions, may induce comparable psychological and health benefits, highlighting opportunities to extend naturalistic strategies to controlled interior environments. However, the positive effects of dynamic lighting depend critically on the quality of its modulation. Recent studies (Kim et al., 2022; Huang and Menozzi, 2014), consistent with earlier observations by Rea et al. (1985), demonstrate that poorly calibrated lighting, particularly when it induces glare, can cause visual discomfort and prompt compensatory posture adjustments, such as occupants turning away from sources of discomfort. This highlights that visual discomfort under unstable lighting is not only a perceptual burden but can also impose physical strain. Future research should focus on understanding how the temporal characteristics of dynamic lighting, such as pacing and modulation patterns, can be optimised to better support gaze behaviour, reduce physical strain, and enhance occupant comfort.

As for fine-scale dynamic visual features and gaze, this narrative review highlights that brief and localised visual changes, such as flicker and small shifts in brightness, can influence gaze behaviour in ways that are highly dependent on timing and environmental conditions. This is consistent with empirical studies showing that even subtle differences in spatial structure can guide visual exploration. Batool et al. (2021) found that fine-grained attributes of urban views, such as coherence and complexity, affected how people explored scenes and which environments they preferred. Similarly, Dupont et al. (2016) demonstrated that low-level visual saliency, such as local contrast, strongly predicts gaze allocation when viewing natural landscapes, highlighting how fine-scale spatial structures shape visual exploration independently of internal emotional states. These findings suggest that fine-scale visual structure, when carefully organised, can support natural gaze behaviour and promote positive environmental experiences. However, fine-scale dynamic variations, such as excessive flicker or abrupt brightness shifts, may also overload visual processing, increase cognitive demand, and disrupt the coherence of a space. Future research should establish practical thresholds for fine-scale dynamic lighting interventions, including acceptable flicker rates and spatial luminance distributions, to support comfortable visual engagement.

Regarding internal cognitive and emotional states and gaze, while environmental conditions influence visual engagement, individual factors such as cognitive load, mood, and emotional state also play an important role. Evidence suggests that high cognitive demands or negative emotional conditions tend to narrow visual attention, leading to longer fixations and reduced exploratory gaze patterns, whereas positive emotional states are associated with broader and more flexible visual exploration. Environmental complexity can influence gaze behaviour independently of internal states (Dupont et al., 2017), but emotional conditions are also likely to affect how people engage visually with their surroundings. Some studies presented here (e.g., Laco et al., 2009) have explored how cognitive and emotional states modulate gaze behaviour; however, there is still limited research linking these internal states to dynamic lighting conditions. More work should incorporate real-time monitoring strategies, such as gaze tracking, physiological measures, and self-reported assessments, to better understand how lighting environments interact with occupants' internal states.

In addition to environmental and internal factors, expertise and task demands are significant determinants of gaze behaviour. Experienced individuals tend to display more efficient gaze patterns, concentrating on task-relevant stimuli, whereas novices are more likely to explore environments more broadly, often fixating on salient but less relevant features. On the other hand, task demands also shape gaze patterns, as environments that require active exploration are sensitive to how visual information aligns with occupants' goals and cognitive resources. This is in line with Sarey Khanie et al. (2013), who showed that window views in office settings attracted gaze primarily when individuals were not engaged in visually demanding tasks, highlighting how environmental features are more likely to capture gaze when cognitive load is reduced. These findings suggest that dynamic lighting and view elements may have stronger effects on gaze behaviour when task demands are low. Future research should investigate how adaptive lighting and view systems can be designed not only to support focused attention but also to provide opportunities for positive distraction and cognitive restoration, depending on occupants' task demands and mental states.

5 Conclusion

This narrative review synthesised current research on the impact of dynamic visual and lighting conditions on gaze behaviour, cognitive performance, and emotional outcomes. A narrative synthesis was necessary to integrate findings from diverse methodologies and emerging areas of research, providing a comprehensive understanding of how dynamic environmental features interact with internal cognitive and emotional processes. Evidence indicates that both gradual, predictable lighting changes and well-integrated fine-scale visual dynamics support broader visual exploration and positive emotional states, whereas abrupt, poorly calibrated, or overly distracting variations often induce discomfort and reduce attentional engagement. Internal factors such as cognitive load, emotional state, expertise, and task demands further modulate these effects, highlighting the need for adaptable, occupant-responsive lighting strategies.

Several limitations must be noted. Much of the current evidence is based on short-term experimental studies in controlled environments, limiting ecological validity. Further, most studies have focused on relatively homogeneous populations, leaving gaps in understanding across different user groups and real-world settings. Future research should prioritise investigating dynamic lighting and view elements in complex, naturalistic environments, examining long-term impacts on attention and emotional regulation, and including more diverse populations. Greater attention is needed to how lighting systems can respond flexibly to variations in cognitive load, emotional states, and expertise, supporting both focused task performance and opportunities for cognitive restoration.

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