Attention map as a way of representing visual patterns based on brightness contrast in a three-dimensional video game environment

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Abstract. This paper investigates the use of saliency maps to represent visual perception patterns driven by luminance contrast in three-dimensional virtual environments. The primary objective was to evaluate the effectiveness of a modified Itti–Koch–Niebur algorithm in analyzing player navigation and its applicability to video game level design. The study focused on bottom-up attention mechanisms, examining how subtle lighting cues can subconsciously guide movement, enhance immersion, and reduce perceptual overload.
An experiment was conducted with participants in a custom forest environment developed in the Unity engine. A logging system recorded camera position and rotation every 0.5 seconds, enabling reconstruction of the player's field of view and generation of saliency maps. The analysis calculated the angle between the vertical screen axis and the geometric center of the highest-contrast region identified by the algorithm. Three navigation techniques were tested: static point lights, volumetric light beams (god rays), and a breadcrumb system, each at three intensity levels.
Results indicate that saliency maps were most effective in the static point-light condition. The god rays condition revealed detection limitations, while the breadcrumb method required morphological analysis, uncovering recurring behavioral patterns. Overall, saliency maps proved valuable for designing intuitive virtual environments.

Keywords: video game · environment · visual cues · attention maps

1 Introduction

The primary objective of this article is to conduct an in-depth analysis and verification of the effectiveness of using attention maps as an instrument for

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representing visual attention patterns of users in interactive three-dimensional environments, with particular emphasis on luminance contrast as a navigational determinant. The study is situated within the broader context of perceptual psychology and video game level design, where lighting manipulation is employed to subconsciously guide player movement, reduce sensory overload, and enhance immersion. The central aim is to provide a practical explanation of the correlation between algorithmically determined areas of interest and the actual movement direction of experimental participants. A key methodological component is the use of an angular measure calculated between the vertical axis of the screen and the geometric center of the attention point, enabling an objective mathematical assessment of the extent to which a player's gaze is attracted by predefined lighting cues.

The study focuses on attention mechanisms based on automatic responses to sensory stimuli such as light intensity, color, and spatial orientation. It isolates the luminance parameter, examining how different lighting techniques—point light, god rays, and a breadcrumb system—influence the structure of attention maps generated from gameplay screenshots. The analysis investigates human interaction with virtual space mediated by algorithmic saliency models, specifically a modified Itti–Koch–Niebur model simulating receptive fields of the human visual system.

More broadly, the research provides level designers with empirically grounded diagnostic tools for optimizing visual level structure and designing more intuitive exploration paths. The findings demonstrate that attention maps constitute a valuable method for representing visual attention patterns when applied with consideration of three-dimensional rendering constraints and the physiological foundations of visual attention.

2 Related Works

The analysis of the theoretical foundations of the use of attention maps in three-dimensional video game environments requires, first and foremost, defining human attention as a complex mechanism of stimulus selection. Attention is a process that enables the extraction of key information from the multitude of data reaching the organism, which is of fundamental importance for orientation within virtual space [11, 15].

A fundamental theoretical pillar in visual attention research is the distinction between gaze-guidance mechanisms categorized as bottom-up (BU) and top-down (TD) processes. The bottom-up mechanism is characterized by automaticity and is driven directly by external stimuli such as luminance contrast, color, or motion, operating independently of prior experience [1, 5, 2]. In contrast, top-down processes are determined by the observer's internal intentions, expectations, and task-specific knowledge. In studies of navigation in video games, particular emphasis is placed on the BU component, as it largely governs eye movements in response to lighting conditions deliberately designed by developers. The TD component, however, remains an inseparable element of cognitive

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processing, both in everyday perception and during the execution of complex in-game tasks [10, 6].

The Itti–Koch–Niebur algorithm constitutes a paradigmatic representation of bottom-up (BU) attention control mechanisms, which are characterized by automaticity and are directly determined by the physical properties of stimuli, such as luminance contrast, color, and orientation. The selection of this particular algorithm for the analysis of attention maps in video games is justified by its capacity to precisely identify regions of visual saliency based on fundamental image parameters. In environments devoid of color, this capability enables the effective isolation and examination of the influence of light intensity alone on player behavior.

The architecture of the Itti–Koch–Niebur model is based on multi-layered processing of the input image, resulting in the generation of a final saliency map [7]. In its practical application to the study of luminance contrast in 3D games, the algorithm interpolates image representations at different scales to a common resolution and subsequently computes pixel-by-pixel differences between them [12]. This procedure allows for the extraction of regions with the highest luminance contrast, which the model identifies as potential centers of visual attention.

The use of luminance contrast as a navigational tool enables the creation of deep immersion while simultaneously reducing the risk of sensory overload caused by excessive information. Research indicates that simple light sources attract attention significantly more strongly than complex textures or intricate object geometry, making lighting a primary medium in the level design process [14]. In development practice, various lighting techniques are employed to structure visual hierarchy and guide player movement in a subtle and intuitive manner.

An important component of the comparative analysis involves studies on gaze-guidance patterns during vehicle driving, which have provided methodological inspiration for data representation and visualization [4, 9]. Player movement within the designed virtual environment exhibits constraints analogous to driving a car, where directional changes are controlled via mouse input and forward–backward motion is restricted to a single axis. The use of graphs correlated with degrees of the driver's viewing angle enables the refinement of an original method for presenting the effectiveness of attention maps in relation to the movement direction of experimental participants.

Another theoretical pillar is the analysis of level design patterns that stimulate curiosity-driven exploration [16]. Empirical studies on linear and non-linear player guidance methods have demonstrated that appropriately structured environments are highly effective in subconsciously shaping user decision-making. In this context, visual attention is examined through the reconstruction of gameplay paths and the analysis of movement trajectories, confirming the validity of using spatial data to assess the role of design in directing players' gaze in video games.

The interdisciplinary character of attention maps has also been confirmed in studies on pedestrian movement in open urban spaces conducted by researchers

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at University College London [3]. These analyses demonstrated that attention maps can function as effective predictive tools, enabling the identification of visually salient obstacles that pedestrians naturally avoid. Although these studies focused on urban planning, their findings highlight the broader applicability of attention maps as analytical instruments for predicting human behavior in spatial environments.

A further important reference point is the work of Wolfgang Einhäuser and Peter König, who investigated the influence of luminance contrast on overt visual attention [13]. Although their findings did not establish a clear correlation between increased contrast and participant attention, certain limitations—such as neutral scenes lacking explicit cues and a small sample size—suggest the need for further, more targeted research. These discrepancies provide strong justification for continued investigation into the effectiveness of attention maps in the context of intentional luminance-based navigation in 3D games.

3 Methodology

3.1 Lighting Techniques

The experiment was conducted in a custom-designed three-dimensional video game environment, previously prepared by the research team [8], built in the Unity engine, intentionally stripped of color and extraneous geometric stimuli, such as complex shapes or shadows, to avoid interference with the perception of the tested factor. Within this controlled environment, three primary navigational lighting techniques were implemented, each presented at three intensity levels, resulting in nine unique test levels. The methodology assumed that participants would subconsciously navigate toward areas of highest luminance contrast to locate a hidden portal.

The first technique analyzed was point light, a source emitting light with uniform intensity in all directions. During the experiment, intensity values of 150, 500, and 2000 units were tested to evaluate the effectiveness of attention maps in relation to point-based clusters of brightness with varying gaze-attracting potential. This method was selected due to its common use in level design, where it subtly highlights objects or paths important to the player.

The second technique involved god rays, or volumetric light, which in reality results from sunlight scattering through airborne particles such as dust or fog. Methodologically, Unity's particle system was used to create animated, elongated structures simulating light filtering through tree canopies. Unlike point lights, contrast was controlled via the alpha (transparency) parameter, set at 85, 170, and 255. Small, non-guiding flashes were introduced as distractors to test whether the primary cue remained the dominant area of interest for both the algorithm and players.

The final technique examined was the breadcrumb system, which, unlike the previous methods that rely on a single dominant cue, consisted of a sequence of bright objects along a planned path. Existing mushroom models were used

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as contrast carriers to avoid novelty effects that could divert attention. Lighting methodology combined emission maps with local point lights and HDR color intensity. By systematically increasing the brightness of successive elements across three intensity variants, the study assessed whether attention maps could accurately represent player movement patterns along trajectories defined by the sequence of luminance-enhanced points.

3.2 Tools and Process

The data collection process for the lighting techniques described above was closely integrated with the procedure for generating attention maps. During gameplay, the player's camera position and rotation were recorded at 0.5-second intervals, producing data in JSON format. This sampling frequency allowed precise reconstruction of each participant's perceptual path without the need for resource-intensive real-time screenshots, which could have negatively impacted gameplay fluidity and the authenticity of player behavior.

The next stage involved the automatic generation of a series of images representing the player's viewpoint based on the previously recorded data. Key selection filters were applied at this stage: the algorithm ignored periods of inactivity to prevent skewing results due to accidental pauses and excluded screenshots from the final segment of the path, where proximity to the portal and associated lighting effects could distort attention map readings. The prepared visual data were then analyzed in Python using a modified Itti–Koch–Niebur (IKN) model. This algorithm was chosen for its ability to decompose images into fundamental parameters, with priority given to light intensity, aligning perfectly with the experiment's focus on luminance contrast. The tool precisely identified regions of highest luminance, which served as potential visual attention foci. The final output was an attention map, where the brightest point was determined using OpenCV's minMaxLoc function, providing a basis for further geometric calculations.

To objectify the results, a trigonometry-based framework was applied to calculate the angular deviation between the vertical screen axis and the identified point of interest. This process required accounting for the camera's field of view (FOV) to accurately project pixel coordinates into angular space. The methodology transformed raw visual data into measurable statistical indicators, such as mean angle, median, and standard deviation, enabling quantitative comparison of the effectiveness of different lighting techniques. These angular values served as a universal metric for navigational efficiency, allowing a robust assessment of player behavior across conditions. The visualization of the calculated angles is shown in Fig. 1.

4 Results

A total of 58 individuals participated in the study, with males comprising approximately 78% of the group and females 22%. The majority of participants

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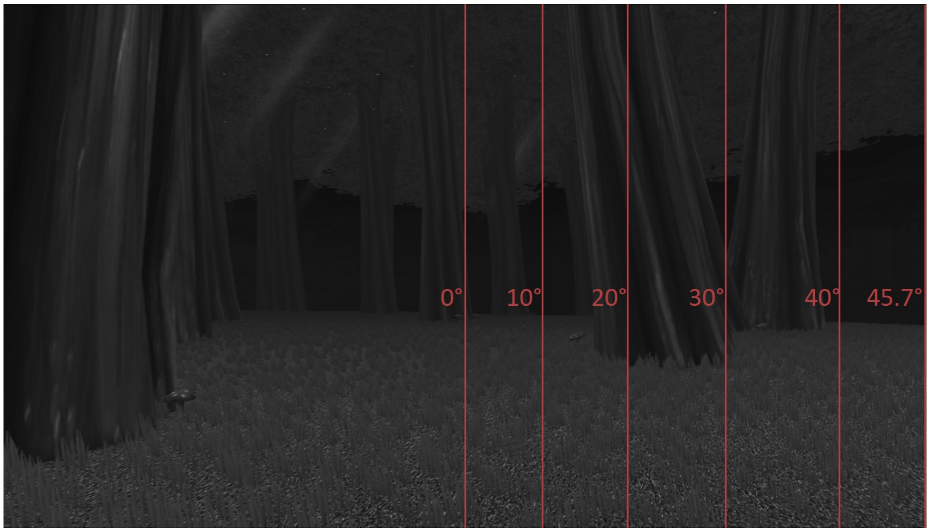

Fig. 1: Visualization of angles measured from the center of the screen.

were young adults aged 18–25, representing over 79% of the sample. The participant group showed a wide range of engagement with video games, but overall was highly familiar with gaming. The largest proportion (about 42%) played 10–20 hours per week demonstrating that the majority were well-acquainted with gaming environments.

The analysis of the results allows for clear conclusions regarding the effectiveness of attention maps as a tool for quantifying perception patterns in virtual environments. The primary research goal was to verify whether algorithmically generated maps, based on the Itti–Koch–Niebur model, can serve as a reliable representation of players' behavior while navigating 3D spaces using luminance contrast. The key analytical measure was the angular deviation between the vertical axis of the screen and the identified point of interest, providing a universal and clear way to represent telemetry data. The experimental results confirmed that attention maps most effectively reflect cognitive processes when visual cues are static and clearly isolated from the background.

The attached screenshots show example attention map results along with the marked point of actual player attention. Three images are presented one for each lighting technique tested: point light Fig. 2, god rays Fig. 3, and the breadcrumbs Fig. 4. This visualization allows for a direct comparison of the effectiveness of different light-based navigation methods and an assessment of the extent to which the areas highlighted by the maps correspond to the participants' actual gaze paths.

In the analytical phase, the angle of deviation was considered the most important statistical parameter. This parameter, expressed in degrees, served as a universal measure of the precision with which the participant moved toward

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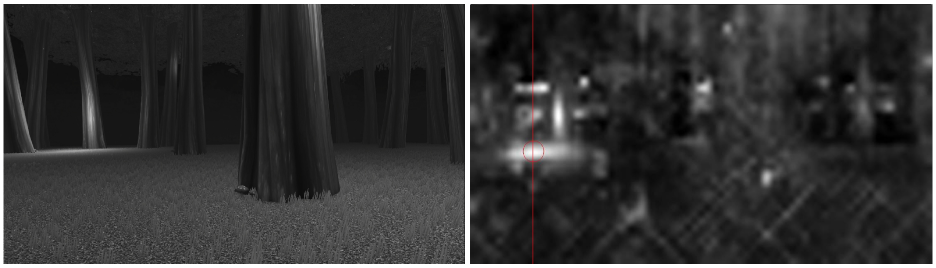

Fig. 2: Point Light Variant. On the left, a screenshot from the player's perspective. On the right, the generated attention map with the detected point of highest visual attention.

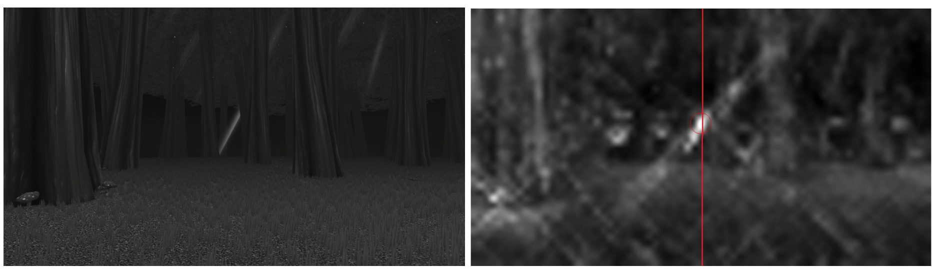

Fig. 3: God Rays Variant. On the left, a screenshot from the player's perspective. On the right, the generated attention map with the detected point of highest visual attention.

Fig. 4: Breadcrumbs Variant. On the left, a screenshot from the player's perspective. On the right, the generated attention map with the detected point of highest visual attention.

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the target; the lower its average value, the higher the navigational efficiency attributed to a given lighting technique. All results were collected and presented in Table. 1. Another important metric analyzed was the number of screenshots generated, which in the experimental methodology served as a parameter representing the level's difficulty and completion time. High values of this metric, when considered alongside angular data, allowed the researchers to identify specific behaviors, such as wandering while searching for cues or deliberate exploration of the environment.

Light			
Point Light	Average Number of Screenshots	Average Angle	Average Median Angle
Level I	30	18.6	14.6
Level II	17	12.0	7.5
Level III	14	12.8	7.2
God Rays	Average Number of Screenshots	Average Angle	Average Median Angle
Level I	31	26.7	28.7
Level II	20	16.4	13.8
Level III	18	12.0	10.0
Breadcrumbs	Average Number of Screenshots	Average Angle	Average Median Angle
Level I	25	19.8	16.2
Level II	25	18.6	17.2
Level III	22	22.5	21.4

Table 1: Summary analysis of lighting methods (point light, god rays, breadcrumbs) across intensity levels based on the average number of screenshots, average angle, and median angle.

The analysis of lighting techniques in the context of attention maps confirmed the usefulness of algorithmic representation of perceptual patterns in virtual environments. The precision with which participants followed contrast-based cues was reflected in angle measurements and the dynamics of the generated graphs, and the effectiveness of the tool was closely linked to the type and intensity of lighting, providing practical guidance for designing intuitive levels in 3D games.

In the context of the point light technique, the analysis results were the clearest and most unambiguous. A strong correlation was observed between increased light intensity and navigation efficiency; the lowest-intensity variant was identified as the most challenging, reflected in the highest average deviation angles and longer paths traveled by participants what can we see in the Fig. 5. Attention maps effectively captured instances of participant wandering, visible in the graphs as a lack of stable direction during the initial phase of the trial. Notably, at extremely high intensities, a specific limitation of the algorithm was observed: the point of maximum contrast was located at the edges of the light source rather than its center, generating artifacts in the form of apparent deviations in the player's trajectory on the graphs, despite correct movement toward the target.

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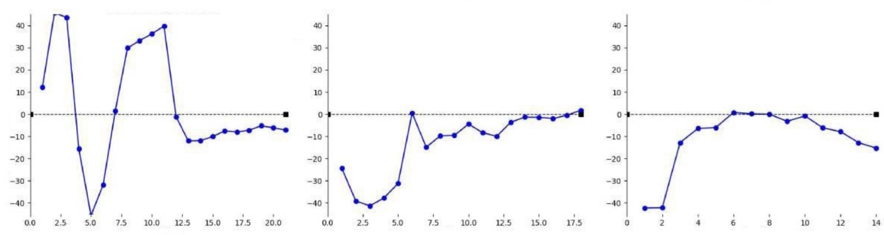

Fig. 5: Graph of angles for a single participant for maps with three intensity levels of the point light pattern. The graph shows the participant's progress and faster identification of the pattern as its intensity increases. The graph shows the sequence of screenshots on the X-axis. The Y-axis shows the angle measured from the center of the screen.

The effectiveness of the god rays method largely depended on its technical implementation, especially the animation. Flickering volumetric light introduced noise into the attention maps, as screenshots taken during invisible phases inflated average angles. The lowest-intensity variant performed poorly, showing inconsistent gaze trajectories, while higher-intensity variants produced stable results, confirming that with proper settings, this technique effectively guides player attention.

The most complex analytical challenge was the "breadcrumbs" technique, where traditional statistical measures, such as the arithmetic mean of angles, proved insufficient for assessing effectiveness. Since players moved along a path defined by a sequence of points, the attention maps generated series of readings that, from a purely statistical perspective, could suggest wandering. The key to confirming the effectiveness of this method was the visual analysis of the graphs, which revealed the presence of nearly identical, repeating geometric patterns across different participants as presented in Fig. 6. Characteristic curves on the graphs precisely reflected the moments of passing each successive cue, providing evidence that attention maps can faithfully visualize navigation along complex intermediate paths.

The final synthesis of the data indicates that attention maps constitute a highly effective analytical tool, provided the specifics of the experimental environment are taken into account. The experiment demonstrated that this tool enables not only a quantitative comparison of level difficulty through the analysis of the number of screenshots but also a qualitative assessment of navigational intuitiveness using angle graphs. Despite certain limitations related to animation or light saturation, the system provides unique insights into the relationship between luminance contrast and the subconscious guidance of player movement, making it a valuable instrument for optimizing visual experiences in interactive media.

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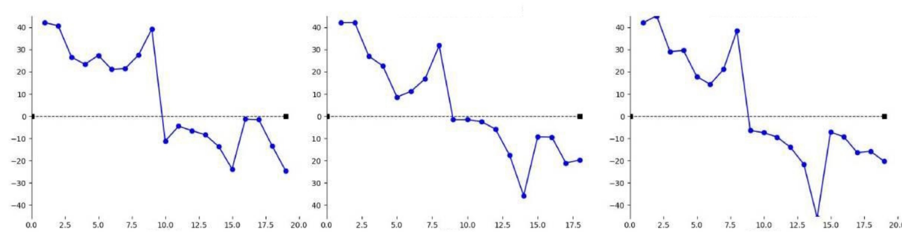

Fig. 6: Angle graphs of three different users for the same level of glowing objects at the first intensity level. The graphs are very similar, indicating that the users behaved in a comparable manner throughout the level. The graph shows the sequence of screenshots on the X-axis. The Y-axis shows the angle measured from the center of the screen.

5 Discussion

The conclusions drawn from the conducted research support the thesis that attention maps constitute a highly effective and reliable tool for representing human perceptual patterns in three-dimensional video game environments, particularly in the context of bottom-up attention stimulated by luminance contrast. The experiment demonstrated that algorithmic identification of areas of interest using a modified Itti–Koch–Niebur model corresponds with actual player behavior, enabling level designers to objectively assess the intuitiveness of constructed spaces. A key methodological achievement was the application of the angular deviation between the vertical screen axis and the point of interest as a universal metric, allowing for a clear and mathematically precise visualization of cognitive processes occurring during navigation.

The analysis of the point light technique provided the most unambiguous evidence of a correlation between stimulus intensity and spatial orientation accuracy. As luminance increased, mean angular deviation values systematically decreased, indicating improved target localization and reduced wandering. However, a significant technical limitation was identified: at extremely high brightness levels, the attention map algorithm tended to detect the edges of the light source rather than its center, generating artifacts in the form of apparent trajectory shifts. This suggests that the effectiveness of attention maps depends critically on appropriate lighting parameter calibration.

In the case of god rays, results highlighted the importance of temporal stimulus stability for reliable attention map generation. Animated, fading beams introduced informational noise, potentially distorting measurements unless synchronized with data acquisition. Despite these limitations, higher-contrast variants proved effective in guiding attention.

The most distinctive findings concerned the breadcrumb technique, where averaged statistics were insufficient to describe movement dynamics. Instead, recurring geometric patterns in angular graphs across participants confirmed

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that attention maps can successfully capture complex navigational processes when combined with trajectory visualization.

Overall, attention maps enable both quantitative comparison of level difficulty and qualitative behavioral analysis, offering designers measurable data for optimizing immersion and intuitive navigation in 3D environments.

6 Conclusions

The study demonstrates that attention maps are a reliable tool for representing human visual attention patterns in 3D video game environments, particularly for bottom-up attention driven by luminance contrast. The modified Itti–Koch–Niebur model accurately identified areas of interest corresponding to actual player behavior, allowing objective evaluation of level intuitiveness.

Point lights showed the clearest effect, with higher luminance reducing angular deviation and improving target localization, though extreme brightness caused peripheral artifacts. God rays were effective if temporal stability was maintained, while breadcrumbs highlighted the importance of repeated geometric patterns in representing complex navigational behavior.

Overall, attention maps provide both quantitative and qualitative insight into player behavior, enabling designers to optimize immersion and intuitive navigation in 3D game spaces.

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