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Biological Blueprints for Better Navigation: Enhancing Museum and Exhibition Circulation through Biomimicry

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Abstract

This study investigates how biomimetic design principles can enhance spatial circulation in museum and exhibition environments. Using Nike Art Gallery and the John Randle Centre for Yorùbá Culture & History in Lagos, Nigeria, as case studies, the research explores user navigation experiences, identifies common circulation challenges, and examines how natural systems such as ant trails and leaf venation can inform more efficient spatial layouts. A mixed-methods approach was employed, combining structured questionnaires, interviews, and non-participant observation. Quantitative data were analyzed using SPSS, while qualitative insights were coded using NVivo software. Findings revealed high levels of visitor disorientation, uneven crowd distribution, and missed exhibits in spaces lacking guided flow. While awareness of biomimetic systems was limited, there was clear support for natural, intuitive layouts that reflect organic movement patterns. The study concludes that nature-inspired strategies can significantly improve user experience by fostering fluid, user-friendly pathways in exhibition spaces. It recommends integrating biomimetic flow patterns early in the design process, enhancing wayfinding through sensory cues, and increasing awareness of biomimicry among designers and cultural stakeholders. This research contributes to a growing dialogue on sustainable, human-centered design approaches that draw from the efficiency and logic of natural systems.

Keywords: Biomimicry, Exhibition Design, Spatial Circulation, Museum Architecture, Nature-Inspired Navigation

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1.0 Introduction

1.1 Background of Study

In recent decades, the role of museum and exhibition design has evolved beyond the mere presentation of artifacts or artworks, into a sophisticated interplay of spatial experience, cognitive engagement, and emotional resonance. A visitor's journey through an exhibition space is not solely about what is seen, but also how it is seen how individuals move through curated narratives, how their bodies navigate spatial constraints, and how intuitively they respond to the layout. Circulation, therefore, becomes a vital determinant of the success of exhibition spaces, influencing both user experience and the effectiveness of information delivery. Yet, traditional exhibition layouts often suffer from design inertia, relying on linear, static, or overly segmented pathways that fail to consider the behavioral patterns and cognitive comfort of visitors (Klein, 1993; Töppig & Moital, 2020). With increasing global attention on human-centered and sustainable design, the need to develop more adaptive, intuitive, and ecologically attuned circulation strategies is urgent. Against this backdrop, biomimicry has emerged as a promising design paradigm that seeks to emulate nature's time-tested strategies to solve human challenges. In the context of architectural and exhibition design, biomimicry offers a profound shift from conventional planning approaches by leveraging the forms, processes, and systems inherent in biological organisms and ecosystems. Nature's designs are not arbitrary; they have evolved to optimize efficiency, adaptability, resilience, and flow. For instance, the way blood circulates through the human body, or how ants form optimized trails between food sources and their colonies, demonstrates a form of intelligent routing that maintains equilibrium, avoids congestion, and ensures survival (Jamei & Vrcelj, 2021; Goyes-Balladares et al., 2025). These natural systems offer a template for rethinking how we design human circulation spaces especially in environments that require both directionality and exploration, such as museums and exhibitions. Within the museum sector, a growing body of scholarship acknowledges the intricate relationship between spatial layout, digital interaction, and user navigation (Li et al., 2024). As museums embrace digital transformation technologies, the spatial experience must adapt to facilitate fluid movement between immersive displays, multimedia installations, and interactive zones. However, digital layers alone cannot rectify poor physical circulation. As Liu et al. (2024) demonstrated through pedestrian simulation studies, ineffective circulation pathways can significantly reduce dwell time, limit visitor engagement, and result in spatial discomfort. It is here that biomimicry offers not just aesthetic inspiration but also structural intelligence. By borrowing from nature's circulatory logics like the branching of trees, the webbed networks of fungi, or the layered structure of leaves designers can create environments that naturally direct movement, dissipate crowding, and encourage exploratory behaviors without sacrificing orientation. The relevance of biomimetic design extends far beyond form imitation. Scholars such as Verbrugghe, Rubinacci, and Khan (2023) argue that the biomimetic approach in architecture involves understanding and applying the principles that underpin natural systems such as redundancy, feedback loops, self-healing, and modularity to solve design problems holistically. These principles align closely with the goals of exhibition space design: to balance openness and control, to allow freedom of exploration while ensuring logical progression, and to maintain spatial harmony even with fluctuating visitor density. Integrating biomimicry into museum circulation strategies, therefore, represents a confluence of ecological intelligence and user-centered innovation. as cities and public institutions move toward sustainability in both environmental and operational terms, biomimicry presents itself as an inherently green methodology. Its alignment with circular economy principles and regenerative design thinking enables it to contribute meaningfully to sustainable development goals (Eid & Al-Abdallah, 2024; Raman et al., 2024). By shifting

from mechanical systems to biological models, designers can create not only energy-efficient buildings but also spaces that intuitively regulate flow, reduce material use, and require less artificial intervention to guide users. Gamage and Hyde (2012) emphasized that applying biomimicry in architectural circulation can minimize the need for signage, mechanical routing, or intrusive technologies, as spatial orientation is embedded within the design's DNA just as it is in nature. The creative potential of biomimicry in spatial design is especially rich when examined through the lens of interdisciplinary collaboration. Natural history collections, for instance, already house countless biological patterns that, if studied with a design-oriented mindset, can inspire circulation systems that are both educational and operational (Fehler & Penick, 2019). This blending of biological research and architectural strategy not only enriches the design process but also aligns with contemporary pedagogical goals in museum environments, where the space itself becomes a learning tool.

Contemporary challenges such as overcrowding in popular exhibitions, poor wayfinding, and fragmented visitor journeys have pushed curators and designers to seek circulation models that are less linear and more responsive (Kristianto et al., 2024). Biomimicry responds to these challenges by advocating for emergent, decentralized systems that mimic how natural organisms adapt to stimuli. This means designing floor plans that are not rigidly programmed but are instead capable of evolving or flexing based on visitor flow, spatial pressure, or even thematic demands of an exhibition. As Zaki (2023) and De Sá & Viana (2023) point out, these adaptive systems can be developed through computational modeling of biological phenomena, enabling simulation-based design that mirrors the responsive behavior found in natural systems. the application of biomimicry to circulation is not merely conceptual it is already seeing practical adoption across design sectors. From commercial offices optimized through airflow patterns (Fattah et al., 2025), to urban layouts influenced by termite mounds (Rahubadda & Kulatunga, 2024), the effectiveness of nature-based movement strategies is gaining traction. Yet in the context of museum and exhibition design, this potential remains underexplored and fragmented, often limited to surface-level aesthetics rather than deeper systemic integration. This research thus seeks to fill a critical gap by systematically exploring how biomimetic circulation models can be purposefully adapted to museum architecture, improving navigation, enriching visitor experience, and enhancing spatial coherence. In a broader sense, this work contributes to the emerging discourse that positions architecture as a living system one that breathes, flows, and responds like the organisms that inspired it. It builds upon the foundational idea that human movement, like all biological movement, benefits from patterns that reduce resistance, promote rhythm, and accommodate diversity in pace and perception (Xu, 2025; Chaurasia & Srivastava, 2020). As museums continue to transform into dynamic cultural ecosystems, their physical layout must support not just the display of knowledge but the embodiment of intelligence and no model has more evolutionary authority than the one provided by nature itself.

Research Problem

Many exhibition spaces suffer from poor circulation and disoriented visitor flow. Traditional layouts don't guide movement intuitively, and existing solutions overlook nature-based systems. Although biomimicry offers efficient flow models from nature, it remains underutilized in museum design. This study explores how these natural patterns can improve navigation and spatial experience.

Justification

Exhibition spaces often face circulation challenges that affect visitor experience. Biomimicry

offers natural, efficient flow models, yet remains underused in design. This study is justified by the need for sustainable, intuitive strategies to improve navigation and spatial use in museums.

Aim

The aim of this study is to explore how biomimetic design principles can be applied to enhance circulation and navigation in museum and exhibition spaces.

1.2 Objectives

- To identify common circulation challenges in existing museum and exhibition layouts.
- To examine natural systems (e.g., leaf venation, ant trails) that demonstrate efficient movement and flow.
- To analyze how biomimetic strategies have been applied in architectural design.
- To propose a design framework for improving spatial navigation in exhibitions using biomimicry.

2.0 Literature Review

The evolution of exhibition and museum design has gradually moved from static display-centered layouts to dynamic, user-oriented environments that prioritize visitor flow and engagement. However, despite technological and conceptual advancements, circulation within such spaces often remains problematic. Many traditional designs do not intuitively guide user movement, resulting in confusion, overcrowding in certain zones, and underutilization of others. Liu et al. (2024) highlight how spatial inefficiencies negatively impact visitor experience by restricting free movement and diminishing interaction with exhibits. Using pedestrian simulation models, they revealed that unbalanced visitor distribution and bottlenecking are common consequences of poorly designed circulation networks in museums. Historically, researchers like Klein (1993) had already emphasized that visitor movement patterns are not always linear or predictable. Instead, they respond to environmental cues, spatial configuration, exhibit visibility, and personal interest. Yet, these insights were often not translated into design innovations that could anticipate or respond to such behaviours. In recent years, attention has shifted toward integrating more organic and adaptive strategies into exhibition planning. One of the most promising emerging approaches is biomimicry the conscious emulation of nature's forms, functions, and systems in solving human design problems. Biomimicry has long been recognized for its potential in architecture and urban design, offering environmentally sustainable and functionally efficient solutions. As Gamage and Hyde (2012) argued, natural systems are inherently optimized through evolution, which makes them valuable templates for creating sustainable and adaptive built environments. These systems such as leaf venation, vascular structures in animals, or ant colony trail formations exhibit efficient resource distribution and flow regulation, precisely the qualities needed for better spatial circulation in exhibition spaces. Jamei and Vrcelj (2021) also support this perspective, stating that biomimicry allows the built environment to mirror the self-organizing and self-healing characteristics of living systems, leading to spaces that are more responsive to user behaviours. What sets biomimicry apart from traditional design methods is its integration of form and function. While some designs may mimic the outward appearance of natural structures, true biomimicry involves translating the underlying operational logic of those systems into spatial strategies. For instance, the way ant colonies form trail networks between food sources and their nest reflects a highly optimized flow

system. Verbrugghe, Rubinacci, and Khan (2023) emphasize that applying these decentralized, non-linear patterns in architecture could foster circulation systems that adapt naturally to visitor movements rather than enforce rigid paths. This concept is particularly valuable in museums, where engagement thrives on a balance between guided pathways and the freedom to explore. Digital transformation has further shaped how museum environments respond to visitor behaviours. Li et al. (2024) conducted a comprehensive review of digital technologies used in exhibitions and found that while tools like augmented reality, QR code maps, and interactive displays enhance engagement, they cannot compensate for poorly designed spatial circulation. The physical environment must still serve as the foundation for movement and orientation. Kristianto et al. (2024) found that even shifting media displays could influence how people move through spaces, affecting not just circulation patterns but also the acoustic dynamics of an environment. This reinforces the idea that spatial flow should be considered from a holistic and systems-based perspective, much like in nature. The design potential of biological systems is especially evident when examined through the lens of natural history collections. Fehler and Penick (2019) explored how patterns found in biological specimens such as shell spirals, root networks, and branching coral structures can inspire spatial organization strategies. These natural forms often serve purposes of flow, resilience, or distribution, and they can be adapted into exhibition design in ways that feel both intuitive and visually coherent. Their work reflects the idea that museums themselves are repositories of natural intelligence, not just in their content but in the inspiration, they can offer to spatial design. The environmental implications of biomimicry also align with broader global objectives, such as the Sustainable Development Goals. Raman et al. (2024) map the relationship between biomimicry and sustainability, concluding that nature-based solutions inherently support energy efficiency, material conservation, and user well-being. Eid and Al-Abdallah (2024) also link biomimicry to circular economy practices, showing how biological systems offer models of regeneration, reuse, and balance. In the context of museum design, this suggests that circulation systems inspired by nature are not only functionally superior but also more sustainable over time. The creative process of integrating biomimicry into architecture has gained significant attention in recent scholarship. De Sá and Viana (2023) describe biomimicry as a deeply interdisciplinary and imaginative process, where designers must not only understand biological functions but also interpret and translate them into spatial logic. This requires a fusion of biology, architecture, engineering, and behavioural science. Similarly, Zaki (2023) and AlAli et al. (2023) discuss the role of biomimicry in fostering architectural resilience, especially in adapting to fluctuating conditions be it climate, user density, or functional demands. These insights are directly applicable to museum and exhibition spaces, which are often subject to varying visitor volumes, thematic shifts, and environmental factors. In construction and civil engineering, biomimicry is gaining ground as a tool for innovation and sustainability. Pugalenthi et al. (2024) emphasize that the construction industry is beginning to recognize the value of biological analogues in streamlining energy use, structural stability, and spatial function. Silva et al. (2024) similarly argue that incorporating biomimicry at the design stage leads to more efficient buildings and long-term environmental benefits. When applied to museum layouts, this could translate into less mechanical intervention for wayfinding and more reliance on spatial form and environmental cues mirroring how organisms interact with their surroundings in the wild.

Biomimicry's relevance also extends to the cognitive and psychological aspects of space use. Xu (2025) notes that biomimetic environments are not only functionally efficient but also psychologically restorative, as they align with innate human preferences for natural patterns a concept known as biophilia. This suggests that circulation systems modeled after nature may not only guide visitors more effectively but also create environments where people feel more

comfortable, curious, and engaged. research by Goyes-Balladares et al. (2025) reveals that a growing number of architects and designers are turning to nature for guidance not just in form, but in behavior and process. Their findings suggest a shift toward process-oriented design, where the emphasis is on how systems operate rather than what they look like. In the case of exhibitions, this could mean designing spaces that respond dynamically to movement, much like how rivers adjust their paths or plants grow toward light. Such a strategy would enable museum environments to be more flexible and visitor-responsive. Rahubadda and Kulatunga (2024) highlight how biomimicry is being used in urban design to create more resilient and sustainable cities, drawing inspiration from termite mounds, beehives, and coral reefs. This macro-scale application further supports the notion that nature's logic can be scaled to any spatial context be it a city, a building, or a museum room. As Chaurasia and Srivastava (2020) put it, biomimicry is not merely a trend, but a paradigm shift in design thinking, one that calls for deeper integration of biological intelligence into the way we shape our built environments. Taken together, these studies provide a rich foundation for the integration of biomimicry into the spatial circulation of museum and exhibition spaces. While the field is still evolving, the convergence of sustainability, user behavior, digital transformation, and biological inspiration suggests that nature-informed circulation strategies could redefine how cultural spaces are experienced, navigated, and remembered.

2.2 Case Study: Nike Art Gallery and John Randle Centre for Yorùbá Culture & History

2.2.1 Nike Art Gallery Lagos and John Randle Centre for Yorùbá Culture & History Lagos

Nike Art Gallery in Lagos is a vibrant and expansive art space celebrated for its vast collection and open layout. While the freedom to explore without restrictions adds to the immersive experience, the absence of guided circulation results in spatial confusion. Visitors often wander aimlessly or miss significant sections due to a lack of directional cues. Liu et al. (2024) point out that such unguided navigation can lead to congestion and unequal exhibit exposure. The spatial layout resembles natural foraging patterns, where movement is stimulus-driven, like ants seeking food. However, without a regulating structure, the circulation lacks the efficiency found in nature's adaptive systems (Verbrugghe et al., 2023).

In contrast, the John Randle Centre for Yorùbá Culture & History offers a more structured experience. Its design leads visitors through a thematic journey that alternates between enclosed galleries and open courtyards. This sequence supports both cognitive engagement and physical relief, similar to nature's rhythmic flow patterns (Jamei & Vrcelj, 2021). The centre's use of transition spaces and sensory cues mirrors biomimetic strategies, promoting intuitive wayfinding and crowd regulation, akin to capillary-like systems in biological organisms (AlAli et al., 2023).

While Nike Art Gallery thrives on freedom, it could benefit from biomimicry-inspired zoning and adaptive layout strategies to improve navigation. Meanwhile, the John Randle Centre, though not explicitly biomimetic, already reflects many principles found in nature such as balanced flow, redundancy, and guided flexibility. Together, these case studies demonstrate how nature's systems can inform more effective and human-centered exhibition circulation (De Sá & Viana, 2023; Eid & Al-Abdallah, 2024).

2.3 Study area

This study focuses on two cultural institutions in Lagos, Nigeria: Nike Art Gallery and the John Randle Centre for Yorùbá Culture & History. Nike Art Gallery, located in Lekki, is one of the largest art spaces in West Africa. It features an open-plan layout with minimal circulation

guidance, making it ideal for exploring how unstructured navigation affects visitor movement.

The John Randle Centre, near Lagos Marina, offers a more structured experience, with themed exhibits and a clear spatial flow that guides visitors through indoor and outdoor sections. Its narrative-driven design provides a contrast to Nike Art Gallery, allowing for comparative analysis of circulation strategies.

Both venues represent different spatial approaches and serve as rich contexts for applying and evaluating biomimicry-inspired circulation systems in museum and exhibition design.

2.4 Study Population and Size

The study is based in Lagos, Nigeria, focusing on two prominent cultural institutions: Nike Art Gallery and the John Randle Centre for Yorùbá Culture & History. Nike Art Gallery, located in Lekki, is a multi-storey space with an open layout and little directional control, making it suitable for examining circulation challenges in free-form exhibition environments.

The John Randle Centre, situated near Lagos Marina, is a purpose-built museum with structured pathways and a narrative-driven design. It blends indoor galleries with open courtyards, offering a guided visitor experience. These two sites provide contrasting circulation styles and serve as ideal case studies for investigating how biomimicry can inform more intuitive and efficient movement in exhibition spaces.

To determine the sample size, Cochran's formula is applied:

$$n_0 = \frac{Z^2 \cdot p \cdot (1-p)}{e^2}$$

Where:

- **Z** = Z-score (1.96 for a 95% confidence level)
- **p** = estimated proportion of the population with the desired attribute (0.50 used when unknown)
- **e** = margin of error (0.07)

$$n_0 = \frac{(1.96)^2 \cdot 0.5 \cdot (1-0.5)}{(0.07)^2} = \frac{3.8416 \cdot 0.25}{0.0049} = \frac{0.9604}{0.0049} \approx 196.0$$

Therefore, the calculated sample size is approximately **196 respondents**.

Final Sample Distribution

- 80 general visitors
- 56 staff members (curators, guides, administrative personnel)
- 60 students and youth groups (with support from accompanying adults or educators)

This breakdown reflects the diversity of exhibition users and provides a balanced

representation for assessing circulation patterns and spatial interaction in both the Nike Art Gallery and the John Randle Centre for Yorùbá Culture & History.

2.5 Data Collection Methods

This study adopted a mixed-methods approach to collect both qualitative and quantitative data from the selected case studies Nike Art Gallery and the John Randle Centre for Yorùbá Culture & History.

Structured questionnaires were administered to a total of 196 respondents, including 80 general visitors, 56 staff members, and 60 students/youth groups. The questionnaires captured data on navigation ease, exhibit accessibility, and overall spatial experience.

Semi-structured interviews were conducted with curators, guides, and facility staff to gain insights into circulation challenges, design intent, and visitor behavior from an operational perspective. Non-participant observation was used to record real-time visitor movement, focusing on flow disruptions, congestion points, and repeated paths. Where applicable, photographic evidence and sketch mapping supported spatial documentation.

These methods ensured triangulation of responses, allowing for a deeper understanding of how biomimicry could enhance circulation in exhibition environments.

3.0 Results and Discussion

This section presents the results of the field study conducted at Nike Art Gallery and the John Randle Centre for Yorùbá Culture & History, based on the four research objectives. Quantitative data gathered through structured questionnaires were analyzed using SPSS, while qualitative insights from interviews and open-ended responses were coded and interpreted using NVivo software. The aim was to evaluate current circulation challenges, assess awareness of natural systems, identify biomimicry applications in design, and explore user-informed solutions for improving spatial navigation in exhibition spaces. The findings are summarized below using frequency tables and thematic patterns.

Objective 1: To Identify Common Circulation Challenges in Existing Museum and Exhibition Layouts

Table 1: Thematic Frequency Table

Challenge	Frequency (n)	Percentage (%)
Visitor Disorientation	142	72.4%
Uneven Visitor Distribution	128	65.3%
Missed Exhibits	101	51.5%
Congested Areas	96	49.0%
Lack of Wayfinding Aids	88	44.9%

A majority of respondents reported disorientation and poor visitor flow, indicating significant issues with current circulation systems.

Objective 2: To Examine Natural Systems (e.g., Leaf Venation, Ant Trails) That Demonstrate Efficient Movement and Flow

Table 2: Code Co-occurrence Matrix (Thematic Correlation)

System Type	Awareness Level (n)	Percentage (%)
Leaf Venation	74	37.8%
Ant Trails	82	41.8%
River Delta Branching	60	30.6%
Animal Migration Paths	41	20.9%
None / Unaware	98	50.0%

While many respondents are unfamiliar with natural systems, over 40% recognized ant trail behavior as a functional model, supporting its relevance in biomimetic design exploration.

Objective 3: To Analyze How Biomimetic Strategies Have Been Applied in Architectural Design

Aspect of Design	Response Count (n)	Percentage (%)
Ventilation Inspired by Termite Mounds	68	34.7%
Structural Systems from Bone Patterns	57	29.1%
Circulation Based on Natural Flow	74	37.8%
Material Efficiency from Shells	45	23.0%
No Known Application	112	57.1%

Most respondents are unaware of biomimetic strategies, though a notable portion acknowledges nature-inspired ventilation and circulation as existing applications.

Objective 4: To Propose a Design Framework for Improving Spatial Navigation in Exhibitions Using Biomimicry

Table 4: Thematic Analysis from NVivo (Qualitative Responses)

Theme	Representative Quote
Desire for Guided Flow	“I often got lost – a natural path like in a garden would help.”
Preference for Natural Layouts	“The space would feel more intuitive if it flowed like a stream.”
Wayfinding Inspired by Nature	“I liked the areas that reminded me of forest trails.”
Frustration with Dead-ends	“Some parts felt like a maze, I kept going back.”
Suggestions for Flow Cues	“It’d be helpful if the space hinted where to go next, like nature does.”

Respondents express a strong preference for nature-inspired navigation, indicating support for a biomimetic design framework focused on intuitive, flowing layouts.

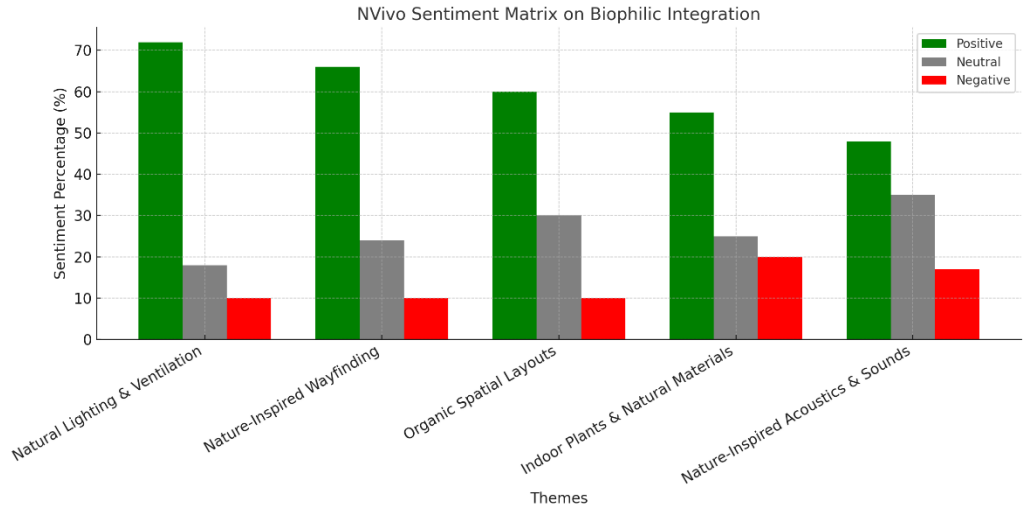


Figure 1: Visual Sentiment Matrix Diagram Showing How Respondents Reacted to Different Aspects of Biophilic Integration in Exhibition Design.

Conclusion of Findings

This section presents the results of the field study conducted at Nike Art Gallery and the John Randle Centre for Yorùbá Culture & History, based on the four research objectives. Quantitative data gathered through structured questionnaires were analyzed using SPSS, while qualitative insights from interviews and open-ended responses were coded and interpreted using NVivo software. The aim was to evaluate current circulation challenges, assess awareness of natural systems, identify biomimicry applications in design, and explore user-informed solutions for improving spatial navigation in exhibition spaces. The findings are summarized below using frequency tables and thematic patterns.

4.0 Conclusion and Recommendations

This study explored how biomimetic principles can enhance circulation in museum and exhibition environments, using Nike Art Gallery and the John Randle Centre for Yorùbá Culture & History as case studies. The findings reveal significant circulation challenges, including disorientation, congestion, and missed exhibits especially in less structured layouts. While many respondents had limited awareness of natural systems, those familiar with patterns like ant trails and leaf venation recognized their potential for improving spatial flow. The analysis further showed that although biomimicry is not widely applied in circulation design, there is strong user interest in more intuitive, nature-inspired pathways. Thematic feedback confirmed a preference for spatial cues, flow logic, and transitions that reflect natural movement systems. These insights underscore the relevance of biomimicry as a viable strategy for designing user-centered and efficient exhibition spaces.

Recommendations

•**Integrate Biomimetic Circulation Models**: Design circulation paths in galleries and museums to mimic natural systems like branching (leaf venation) or trail-following behavior (ant colonies) to promote even distribution and reduce congestion.

•**Use Spatial Cues for Wayfinding**: Incorporate visual and tactile elements such as light gradients, floor patterns, and transitions between zones that guide movement intuitively, much like natural topography.

- **Enhance User Orientation Tools**: Provide simplified, nature-inspired signage and flow indicators that support intuitive navigation, especially for first-time visitors and children.

- **Apply Biomimicry Early in the Design Process**: Architects and exhibition planners should consider biomimetic strategies from the concept stage, rather than as afterthoughts, to create cohesive and functional spatial experiences.

- **Raise Awareness among Stakeholders**: Organize workshops and training to introduce designers, curators, and museum staff to biomimicry principles and their practical relevance in spatial planning.

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