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Integrating technological, cognitive and semantic dimensions in exit sign systems: A systematic literature review and bibliometric analysis

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Abstract

Exit signs are fundamental components of modern safety systems, guiding occupants to safety during emergencies. This study conducts a Systematic Literature Review (SLR) integrated with bibliometric analysis to examine the evolution of sign system research, emphasizing technological innovation, cognitive interpretation, and semantic design. Using data retrieved from the Scopus database and following PRISMA 2020 guidelines, 110 publications were initially identified, with 13 selected for detailed synthesis. The findings reveal that the research focus has shifted from traditional, static signage to adaptive, intelligent, and user-centered systems supported by IoT, AI, and real-time data algorithms. Bibliometric results highlight increasing interdisciplinary collaboration between engineering, psychology, and design fields. The review also underscores the significance of cognitive and behavioral factors, showing how stress, perception, and cognitive load influence evacuation efficiency. Meanwhile, semantic interpretation remains underexplored, suggesting the need for culturally universal sign systems. Future research should integrate smart technologies, cognitive adaptability, and cross-cultural semantics to create responsive, human-centered safety communication systems that can dynamically adapt to real-world emergencies.

Keywords: Exit Signs; Sign Systems; Cognitive Design; Semantics; Bibliometric Analysis; Systematic Literature Review; Emergency Evacuation

1. Introduction

Exit signs constitute one of the most essential components of safety and evacuation systems in modern infrastructure. They are designed to provide clear visual guidance that enables building occupants to identify and follow evacuation routes efficiently during emergencies such as fires, earthquakes, and other life-threatening events [1]. The primary function of exit signage is to assist individuals in safely navigating towards designated escape routes and assembly points, thereby reducing panic, confusion, and potential injury during crisis situations. In large and complex structures such as shopping malls, hospitals, transport hubs, and high-rise buildings, the importance of reliable exit signage becomes even more pronounced due to the intricate spatial layouts and the diversity of users who may not be familiar with the environment [2].

Over the years, the design and functionality of exit signs have evolved alongside technological and architectural advancements. Traditional static signs typically composed of fixed pictograms and text are increasingly being complemented or replaced by intelligent and adaptive systems capable of responding dynamically to environmental changes. For instance, the integration of digital technologies such as sensors, Internet of Things (IoT) devices, and Building Information Modelling (BIM) has enabled exit signs to deliver real-time guidance that can adapt to hazards like smoke propagation or blocked pathways [3][4]. These innovations mark a paradigm shift in safety communication, moving from passive indicators to context-sensitive evacuation tools that actively contribute to human decision-making during emergencies.

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However, despite technological progress, the effectiveness of exit signage remains influenced by multiple interrelated factors. Visual attributes such as luminance, colour contrast, symbol design, and placement significantly affect sign recognition and comprehension, especially under low-visibility or stressful conditions [5]. Additionally, human factors including cognitive load, cultural background, and psychological state play a critical role in determining how individuals interpret and respond to exit cues [6]. For instance, people under stress may exhibit tunnel vision, selective attention, or biased perception, all of which can diminish the intended clarity of safety signage. This highlights the necessity for an integrated design approach that considers ergonomic, psychological, and cultural dimensions in addition to technological functionality [7].

While previous studies have explored specific aspects of exit signage anging from readability and visibility to technological enhancement there remains a lack of comprehensive synthesis that bridges the technical, cognitive, and socio-cultural perspectives. Current research is often fragmented, focusing narrowly on single factors without examining how they collectively influence evacuation effectiveness and user behaviour. Consequently, there is a pressing need for a Systematic Literature Review (SLR) that not only consolidates existing findings but also maps research trends, collaborations, and emerging technologies shaping the domain of exit signage design. This study addresses that gap by conducting an extensive SLR on the design and effectiveness of exit signs, integrating insights from ergonomics, semiotics, cognitive psychology, and safety engineering.

To strengthen the conceptual grounding of this study, the theoretical foundation integrates perspectives from semiotics, cognitive psychology, and human factors engineering to explain how exit sign design influences perception, cognition, and behaviour during emergencies. According to Eco [8], signs act as carriers of meaning whose interpretation depends on the interaction between symbol, context, and user cognition. Within the context of safety design, exit signs function as *semiotic artefacts* that communicate critical evacuation information through visual and symbolic cues. Norman [9] further highlights that human cognition determines how individuals perceive and interpret design elements such as colour, contrast, and typography, while Sanders and McCormick [10] emphasise the need to account for perceptual limits and information load in high-stress conditions. When users interpret exit signage under duress, factors such as stress, familiarity, and cultural context can distort information processing [5][6].

From a behavioural perspective, evacuation decision-making is influenced not only by the visual clarity of signage but also by environmental feedback and contextual cues. Helbing et al. [11] demonstrated that collective crowd movement during emergencies follows cognitive heuristics shaped by factors such as signage, lighting, and spatial configuration. Consequently, the effectiveness of exit signs extends beyond visual design considerations to encompass behavioural outcomes, including evacuation speed, decision accuracy, and overall safety performance [2][7]. Building on these theoretical foundations, this study proposes a conceptual framework (Figure 1) that delineates the causal pathway from Exit Sign Design (visual, symbolic, and digital attributes) through Cognitive Interpretation (perception, comprehension, and cultural context), which subsequently influences Behavioural Response (decision-making, route selection, and evacuation time), ultimately determining Evacuation Effectiveness (speed, accuracy, and safety).

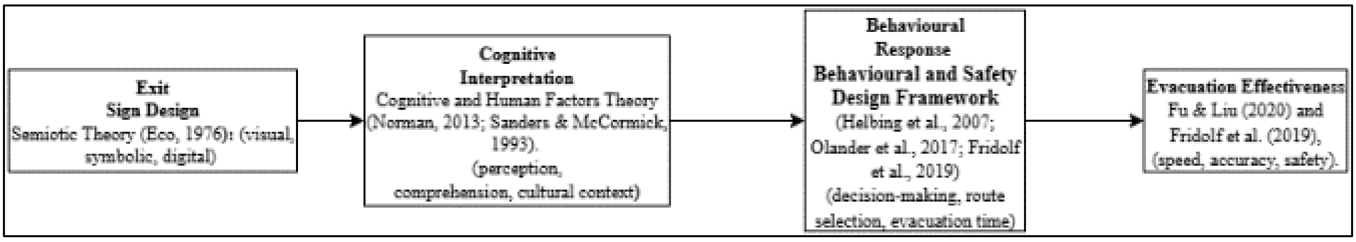

Figure 1 Conceptual Framework of Exit Sign Design, Cognition, and Evacuation Effectiveness (Author, 2024)

As illustrated in Figure 1, this conceptual framework integrates semiotic, cognitive, and behavioural perspectives to explain how exit sign design influences human interpretation and evacuation performance. It provides the theoretical foundation for this study and serves as the guiding structure for the bibliometric and systematic analyses presented in the subsequent section.

2. Research Methodology

A Systematic Literature Review (SLR) was employed to comprehensively identify, evaluate, and synthesize existing studies relevant to sign systems and cognitive interpretation. The SLR method provides a structured and transparent approach to exploring prior research, ensuring that the process is systematic, reproducible, and minimizes bias in article selection [12]. A literature review serves as a critical tool to understand what has already been established about a given topic or phenomenon, to summarize the evolution of theories and methodologies, and to identify knowledge gaps that remain unexplored. In this research, the SLR focuses on integrating insights from semiotics, cognitive psychology, and ergonomics, highlighting the interdisciplinary relationship between design, cognition, and human behavior [13]. The review process was structured following the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure methodological rigor and replicability [14][15]. The bibliographic data were obtained from the Scopus database, chosen for its comprehensive and multidisciplinary coverage of peer-reviewed research. The following search string was applied: "Sign System" AND "Cognitive" The initial search yielded 110 documents. Records were screened to ensure relevance and filtered based on several criteria, including language (English only), publication type (journal articles), and thematic alignment. Exclusion criteria included conference proceedings, review papers, and articles outside the topic area. After the screening and eligibility assessment, 39 full-text articles were reviewed, and 13 studies were included in the final synthesis. The stages of identification, screening, eligibility, and inclusion are summarized in the PRISMA flow diagram presented in Figure 11.

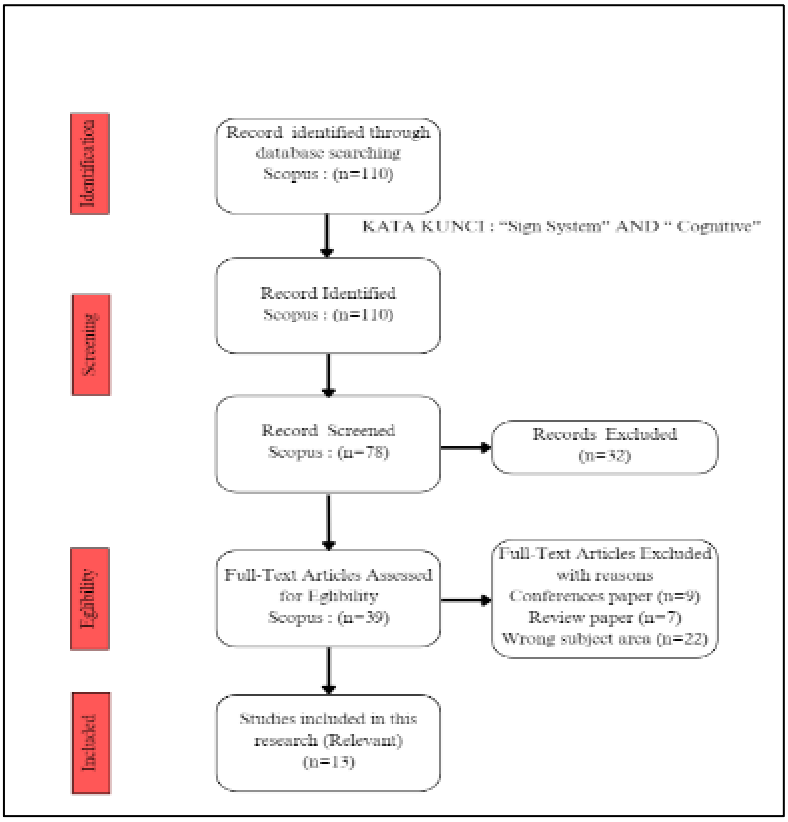

Figure 2 PRISMA Flow Diagram of the Systematic Literature Review Process (Author, 2024)

After completing the identification, screening, and eligibility stages illustrated in Figure 2, a total of 13 relevant articles were retained for in-depth bibliometric and thematic analysis. These studies represent diverse theoretical and empirical perspectives related to sign systems and cognitive research. The next stage of the review involved a comprehensive examination of the selected articles to evaluate their contributions, research contexts, and methodological orientations. This detailed literature synthesis aimed to identify key research trends and highlight existing knowledge gaps that inform the direction of the bibliometric and thematic discussions presented in the following sections. Such a systematic approach ensures that the subsequent analysis is grounded in verified, high-quality literature, reflecting the intellectual structure of semiotic–cognitive studies [16][17][18].

2.1. Data Source and Strategy

This study adopted a Systematic Literature Review (SLR) approach to collect and analyze relevant publications concerning sign systems, cognitive factors, and semantic interpretation in exit signage research. The bibliographic data were retrieved from the Scopus database, which provides extensive coverage of peer-reviewed literature across engineering, design, psychology, and safety science.

The search strategy followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines to ensure methodological rigor and transparency [14][15]. The search string applied was: “Sign System” AND “Cognitive” To refine the search toward semiotic and behavioral aspects, the additional keyword “Semantic” was incorporated. The search was limited to English-language journal articles to maintain consistency in interpretation. The initial query produced 110 publications, which included complete bibliographic information such as titles, authors, abstracts, keywords, and sources.

2.2. Inclusion and Exclusion Criteria

To ensure the relevance and quality of the reviewed studies, a set of inclusion and exclusion criteria was established based on thematic alignment, publication type, and methodological completeness.

Inclusion criteria:

- Peer-reviewed journal articles published in English.
- Studies addressing sign systems, cognitive or semantic factors, or exit signage design.
- Articles that include empirical, experimental, or simulation-based methods.
- Studies focusing on human perception, wayfinding, or technological innovation related to signage.

Exclusion criteria:

- Conference proceedings, review papers, or non-peer-reviewed sources.
- Publications unrelated to cognitive or semiotic perspectives of sign systems.
- Articles with insufficient methodological information or inaccessible full text.

After applying these criteria, 39 documents were retained for eligibility assessment and detailed review.

The selection process was conducted in four stages: identification, screening, eligibility, and inclusion, following PRISMA guidelines [14].

- Identification: The initial 110 articles were identified through database search.
- Screening: Duplicates and irrelevant titles/abstracts were removed.
- Eligibility: Full-text versions were assessed for relevance to cognitive, semantic, and exit signage themes.
- Inclusion: A final 13 studies were included for detailed synthesis.

2.3. Screening and PRISMA Flow

The SLR process followed the PRISMA four-stage approach identification, screening, eligibility, and inclusion [14]. From an initial 110 records identified, duplicates and irrelevant papers were removed, leaving 13 final articles that met inclusion standards. This process is illustrated in the PRISMA Flow Diagram (Figure 11).

2.4. Data Extraction and Analysis

The final dataset was analyzed through two complementary methods.

First, a bibliometric analysis was conducted using VOSviewer to visualize co-authorship networks, keyword co-occurrence, citation trends, and source distributions [16].

Second, a Systematic Literature Review (SLR) was carried out to qualitatively extract and synthesize key information from each article, including research focus, methodology, cognitive and semantic dimensions, and technological innovations.

A summary table (Table 1) presents detailed variables such as title, author, method, and findings. The integration of bibliometric mapping and systematic synthesis provides a comprehensive overview of the field, aligning with recommendations by Donthu et al [19] for hybrid bibliometric–SLR research.

This process is summarized in Figure 11 (PRISMA Flow Diagram), illustrating how records were filtered at each stage. The final dataset represents the most relevant and high-quality studies forming the analytical foundation of this review.

Table 1 Summary of Reviewed Literature on Sign Systems and Cognitive Research

No	Title	Author (Year)	Method / Techniques	Variables	Key Findings / Focus
1	*An Approach of Checking an Exit Sign System Based on Navigation Graph Networks*	Fu, M., & Liu, R. (2020)	Building Information Modelling (BIM) and navigation graph networks	Continuity, consistency, and directional accuracy	Proposed a graph-based model to verify exit sign logic and connectivity in BIM environments.
2	*On the Origin of Species on Road Warning Signs: A Global Perspective*	Tryjanowski, P., Beim, M., Kubicka, A. M., Morelli, F., Sparks, T. H., & Sklenicka, P. (2021)	Global literature review and data analysis from legal and web sources	Animal warning types, design evolution, psychological and conservation effects	Explored cultural and biological diversity in road signage evolution and its cognitive impact.
3	*An Automated Direction Setting Algorithm for a Smart Exit Sign*	Cho, J., Lee, G., & Lee, S. (2015)	Shortest-path algorithm	Exit node classification, hazard detection, evacuation route optimization	Developed an automated route-setting system capable of adapting to fire hazards.
4	*Prototype Development and Test of a Server-Independent Smart Exit Sign System*	Kim, H., Lee, G., & Cho, J. (2018)	Prototype development and communication testing	Network type, signal reliability, physical barriers	Evaluated communication reliability of decentralized exit sign systems.
5	*Application of Dijkstra's Algorithm in the Smart Exit Sign*	Cho, J., Lee, G., Won, J., & Ryu, E. (2014)	Automated Direction Setting Algorithm (ADSA) using Dijkstra's algorithm	Distance, safety route, recalibration	Implemented path recalibration based on hazard propagation in real time.
6	*Exploring Sign System Design for a Medical Facility: A Virtual Environment Study on Wayfinding Behaviors*	Wang, C. Y., Chen, C. I., & Zheng, M. C. (2023)	Experimental study in virtual environments	Wayfinding performance, anxiety, readability	Found that optimized color-coded signage reduced stress and improved wayfinding accuracy.
7	*IoT-Enabled Smart Emergency LED Exit Sign Controller Design Using Arduino*	Jung, J., Kwon, J., & Cha, J. (2017)	IoT-based Arduino system	Sensor types, response time, route accuracy	Developed a cost-effective IoT exit sign with multiple sensors for hazard detection.

No	Title	Author (Year)	Method / Techniques	Variables	Key Findings / Focus
8	*A Traffic Sign Recognition System Based on Lightweight Network Learning*	Zhang, G., Li, Z., Huang, D., Luo, W., & Lu, Z. (2024)	Convolutional Neural Network (CNN) using MobileNetV1	Model parameters, accuracy, FPS	Introduced lightweight AI architecture for real-time sign recognition.
9	*Traffic Sign Detection System for Locating Road Intersections and Roundabouts: The Chilean Case*	Villalón-Sepúlveda, G., Torres-Torriti, M., & Flores-Calero, M. (2017)	Template matching using Er and Eg color channels	Detection range, false alarm rate	Proposed a color-based algorithm to improve intersection sign detection.
10	*Applying an Interpretable Machine Learning Framework to Traffic Safety Order Analysis of Expressway Exits*	Qi, H., Yao, Y., Zhao, X., Guo, J., & Zhang, Y. (2022)	XGBoost with SHAP explanation	Traffic Order Index (TOI), road and weather conditions	Used interpretable ML models to analyze expressway safety at exit ramps.
11	*Optimal Design Alternatives of Advance Guide Signs on Urban Expressways*	Huang, L., Zhao, X., Li, Y., Ma, J., & Yang, L. (2020)	ANOVA and TOPSIS	Lane change, speed, driver success rate	Identified optimal guide sign configurations enhancing driver navigation.
12	*Fire Evacuation Supported by Centralized and Decentralized Visual Guidance Systems*	Zhao, H., Schwabe, A., Schläfli, F., & Helbing, D. (2022)	Virtual Reality and agent-based simulation	Guidance type, evacuation efficiency, stress	Showed that decentralized dynamic evacuation tools improves evacuation safety and reduces stress.
13	*Dissuasive Exit Signage for Building Fire Evacuation*	Olander, J., Ronchi, E., Lovreglio, R., & Nilsson, D. (2017)	Questionnaire with Affordance Theory framework	Sign color, flashing lights, symbol type	Found that flashing red lights and textual signs enhance warning salience.

3. Bibliometric

In this study, a bibliometric analysis was employed as a quantitative approach combining descriptive and evaluative techniques to identify publication characteristics and research trends [19][20]. This method is widely applied in systematic reviews to summarise the overall structure of a scientific domain, including authors, journals, institutions, keywords, and citation networks [16]. The bibliometric process began by utilising the Scopus database as the primary data source due to its comprehensive coverage of peer-reviewed literature across engineering, design, and behavioural sciences. The initial search query employed the keywords “sign system” AND “cognitive”, which yielded 110 publications. These records contained complete bibliographic metadata such as titles, authors, abstracts, keywords, sources, and references. To refine the dataset, the additional keyword “semiotic” was incorporated to focus on studies linking sign systems with cognitive and behavioural processes. The search was limited to English-language publications to maintain consistency in interpretation. Subsequently, an eligibility screening was conducted to remove irrelevant records, resulting in a final dataset of 39 documents selected for further analysis.

3.1. Based on Annual Publications

As illustrated in Figure 3, the annual publication trend concerning sign systems and semiotics in cognitive research can be categorised into three main phases. The first phase (2010–2017) shows limited and irregular publication activity, with only one to two documents per year. A minor inrease occurred in 2014, reaching three publications, which remained steady until 2016 before declining again in 2017. This early stage reflects the emergent nature of semiotic-based cognitive studies, which often develop slowly due to the need for interdisciplinary integration [21]. The second phase (2018–2021) represents a period of fluctuation. Although no documents were recorded for two consecutive years, a sharp rise appeared in 2020, reaching five publications, followed by a drop to two in 2021. Such volatility is typical in developing research areas where publication trends often respond to shifts in technological adoption and global academic priorities [22]. The third phase (2022–2024) indicates renewed scholarly attention, with four documents published in 2022, then slightly decreasing to three per year in both 2023 and 2024. This modest recovery suggests a gradual but unstable growth pattern, implying that research on semiotic and cognitive sign systems is gaining traction but has yet to achieve consistent expansion. Overall, these results reveal that interest in this topic is periodically renewed rather than continuously increasing. This phenomenon aligns with the behaviour of niche interdisciplinary domains, where publication output often depends on technological progress, conceptual maturity, and research funding cycles [23].

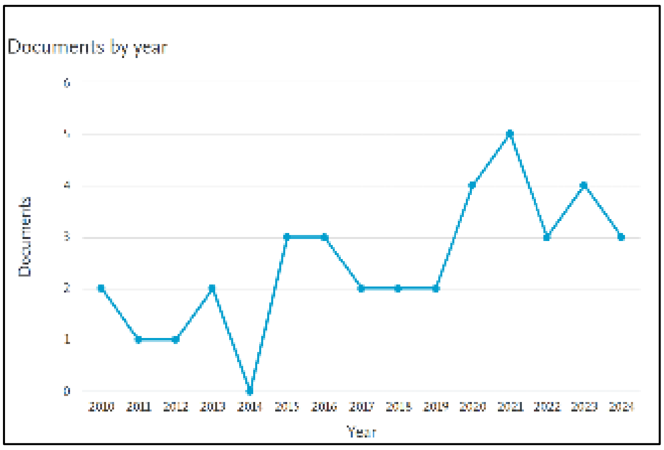

Figure 3 Annual Publication Trend on Sign Systems and Semiotics in Cognitive Research (2010–2024)

Figure 1 presents the annual distribution of publications related to sign systems and semiotics within the cognitive domain from 2010 to 2024. The trend shows fluctuating growth across the period, with three distinct phases. A low and irregular publication rate is observed between 2010 and 2017, followed by intermittent increases during 2018–2021 and a moderate recovery from 2022 onward. The sharp rise in 2020 indicates a temporary surge in research interest, likely driven by the growing relevance of cognitive and semiotic integration in humannsystem interaction studies. However, the overall pattern remains inconsistent, reflecting the developing and interdisciplinary nature of this research field.

3.2. Keyword C0-Occurance Analysis

In bibliometric studies, co-occurrence refers to how many times certain keywords appear together within the same document. A co-occurrence keyword network analysis offers researchers a window into the underlying structure of a domain, enabling the identification of how research topics cluster, evolve, and interconnect over [24]. By constructing keyword networks, one can trace emerging trends, thematic centrality, and conceptual linkages across distinct phases of a field [25]. Based on Figure 2, the co-occurrence map shows how the most frequently paired keywords in sign systems and semiotics–cognitive research coalesce into thematic clusters, revealing both dominant research domains and structural relationships among topics.

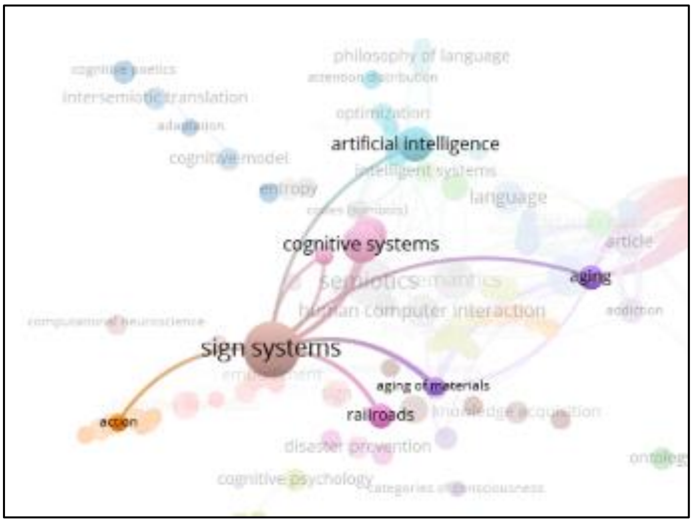

Figure 4 The keyword co-occurrence network generated from the bibliometric analysis of publications on sign systems and semiotic–cognitive research between 2010 and 2024

Each node represents a keyword, and the link strength between nodes indicates the frequency with which those terms appear together in the same document. Larger nodes signify higher keyword occurrence, while thicker connecting lines indicate stronger co-occurrence relationships. The visualization reveals that "sign systems" serves as the central theme, closely connected to terms such as "cognitive systems," "semiotics," "artificial intelligence," and "humanncomputer interaction." These associations suggest that recent research increasingly integrates semiotic principles with cognitive and computational frameworks, particularly in the context of intelligent systems and digital interaction. Peripheral clusters like "action," "aging," and "railroads" indicate niche or applied domains linked to specific case studies. Overall, this network reflects the evolving structure of the research field, demonstrating a shift from traditional semiotic theory toward data-driven cognitive modeling and AI-based semiotic applications, aligning with trends in emerging interdisciplinary science (Lim et al., 2024; Wu et al., 2024; van Eck & Waltman, 2010).

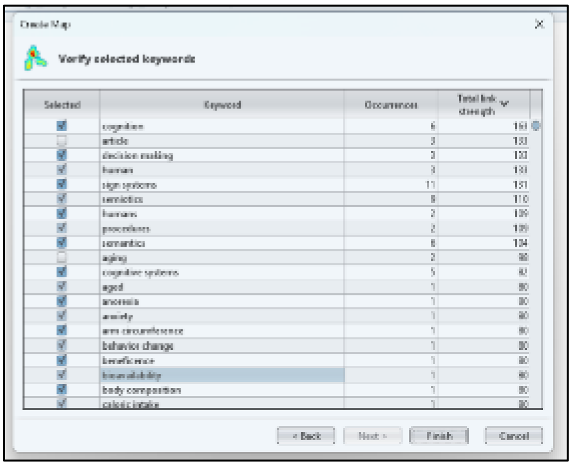

Figure 5 Frequency and Link Strength of Keyword Co-occurrence in Sign Systems and Cognitive Research (2010–2024)

Following the keyword co-occurrence network visualized in Figure 4, Figure 5 presents the statistical verification of the most frequent and interconnected keywords identified from the Scopus dataset using VOSviewer. The table lists the occurrence frequency and total link strength of each keyword, both of which serve as indicators of thematic centrality and research prominence within the analyzed domain. The results show that "cognition" ranks highest in occurrence (6) and total link strength (163), confirming its role as a pivotal concept linking various subdomains. Keywords such as "sign systems," "semiotics," "decision making," and "cognitive systems" also appear prominently, signifying a growing interdisciplinary integration between cognitive science, semiotic theory, and intelligent system design. Meanwhile, less frequent keywords such as "aging," "anxiety," "behavior change," and "bioavailability" indicate more specialized or emerging areas that, while peripheral, highlight the field's potential for thematic expansion. This quantitative verification supports the network findings, revealing how sign system studies increasingly intersect with human cognition, digital interaction, and adaptive decision-making frameworks. Such keyword-based analyses provide valuable insight into the conceptual evolution of research domains and help scholars identify central and peripheral themes that shape disciplinary growth [26][27].

3.3. Based on Authors

Citation analysis reflects the contribution and influence of authors within a specific research domain. In this study, co-authorship was used as the analytical basis, where authors served as the unit of analysis to evaluate collaborative relationships and academic performance. To assess research productivity, three main indicators were considered: the total number of publications, the total number of citations, and the average number of citations per publication. The minimum inclusion criterion was set at two documents per author, and those meeting this requirement were included in the analysis. The resulting table lists the authors with the highest number of publications and citations, while the corresponding figure illustrates the scientific collaboration network among researchers in this field. The average citation count for each author was calculated by dividing the total number of citations by the total number of publications. The co-authorship network revealed two primary clusters of collaboration, indicating regional or thematic research groupings within the sign system and semiotic–cognitive domains. Prominent contributors include Torres Martinez, S. and Zlaten, J., each with three publications, followed by Budaev, E. V., Chang, Y. J., Chen, C. N., and several others with two publications each. In terms of citation impact, these authors also demonstrate significant scholarly connections, as their works are frequently co-cited or referenced together across publications. The citation network further indicates that numerous researchers from different geographical regions are interconnected through shared themes in sign system and semiotic studies, reflecting a growing pattern of international collaboration. Such analyses help identify core authors and research clusters, providing insight into the intellectual structure and collaborative dynamics of the field [21][26][28].

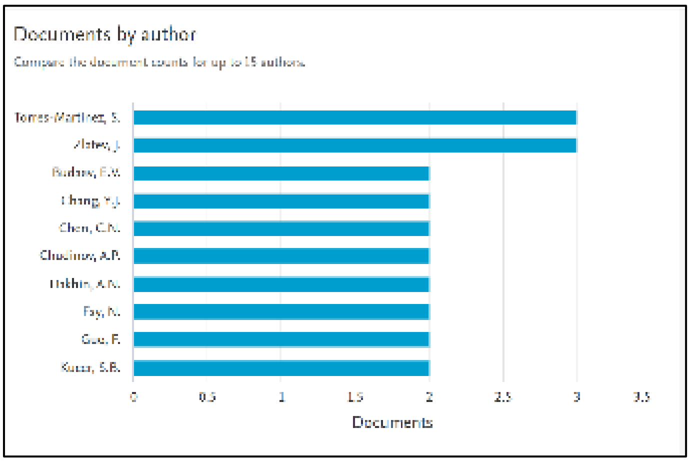

Figure 6 Total Publications and Citations by Author

To further explore the intellectual influence of authors, Figure 6 and Figure 7 summarize publication productivity and citation performance within the dataset.

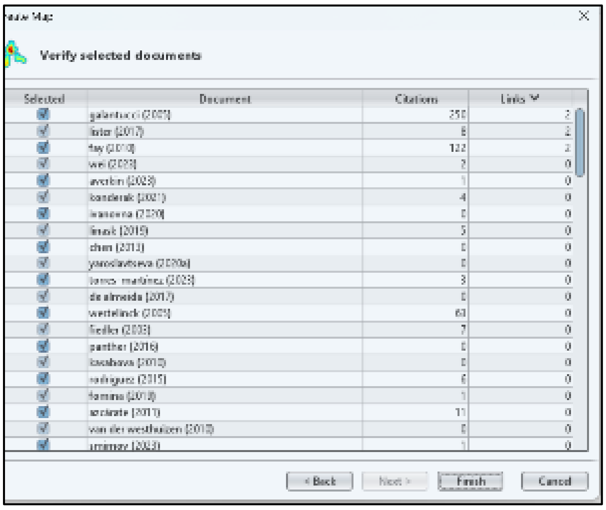

Figure 7 Distribution of Publications by Author in Sign Systems and Semiotic–Cognitive Research (2010–2024)

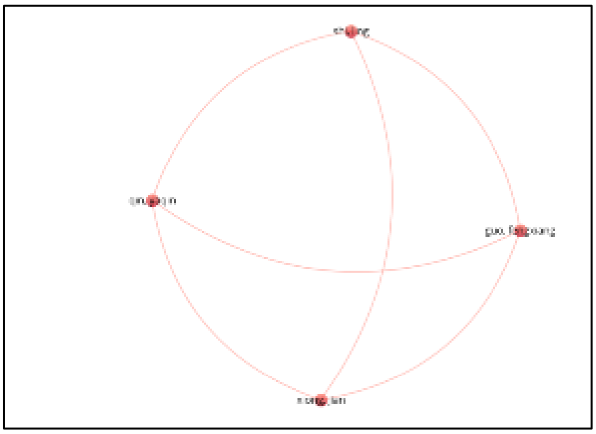

Figure 8 Verification of Highly Cited Documents in Sign Systems and Semiotic Cognitive Studies (2010–2024)

Figure 6 and Figure 8 present the distribution of publications among the most productive authors within the sign systems and semiotic–cognitive research domain. The visualization indicates that Torres-Martinez, S. and Zlatev, J. are the most prolific authors, each contributing three publications. They are followed by Budaev, E. V., Chang, Y. J., and Chen, C. N., each with two publications. Other contributors such as Chudinov, A. P., Dakhin, A. N., Fay, N., Guo, F., and Kucer, S. B. have also made consistent contributions, each with two or fewer documents. This distribution pattern demonstrates a moderate level of author concentration, where a small number of researchers account for a significant portion of the total output. Such a trend is typical in specialized interdisciplinary fields where collaborative efforts and theoretical diversity are still developing (Li et al., 2022; Koseoglu, 2016). Figure 6 displays the verification of highly cited documents identified through the bibliometric dataset. The most cited work is Galantrucci (2005) with 250 citations, followed by Fay (2010) with 122 citations, and Westelinck (2005) with 63 citations. These studies represent foundational contributions that established the theoretical and methodological underpinnings of semiotic and cognitive system research. Other recent works, including Torres-Martinez (2023), Wei (2023), and Averkin (2023), show lower citation counts but signal a growing research continuity and thematic renewal in the post-2020 period. The presence of recent publications with initial citations suggests that the field is experiencing active conceptual expansion and that new directions particularly those related to human computer interaction and applied semiotics—are gaining academic attention. Overall, these findings reveal that while the field remains relatively concentrated among a few core contributors, it is simultaneously broadening through new authors and interdisciplinary collaborations. The coexistence of established and emerging works underscores a dynamic, evolving intellectual landscape in semiotic–cognitive research.

3.4. Based on Source Journal

Scientific journals serve as central communication platforms that facilitate the dissemination of research findings and theoretical advancements across academic disciplines. In the field of ergonomics and semiotic studies, analyzing publication sources helps identify the most influential journals and academic spaces that contribute to the ongoing discourse on sign systems, cognition, and human behavior [29]. Figure 8 presents the distribution of publications by journal source, while Table 3 lists the most productive and influential journals in the dataset. The bibliometric mapping was conducted using VOSviewer, applying citations as the analysis type and source as the unit of analysis, with minimum thresholds for both publication count and citation number set to enhance the validity of results [27]. The analysis reveals that Semiotica (7 documents), Sign Systems Studies (4 documents), Chinese Semiotic Studies (3 documents), Praxema (3 documents), and Voprosy Filosofii (3 documents) are the most prolific journals in this research domain. Notably, Sign Systems Studies has demonstrated a consistent rise in publication activity over the last five years, indicating an expanding academic interest in the integration of semiotic perspectives within cognitive and ergonomic frameworks [22] [17]. As shown in Figure 4, larger nodes represent journals with higher publication volumes, whereas thicker links indicate stronger citation relationships between journals. The results demonstrate that Sign Systems Studies maintains strong bibliographic coupling with Semiotica, Chinese Semiotic Studies, and Voprosy Filosofii, forming a cohesive intellectual cluster within semiotic–cognitive research. Among these, Semiotica remains the most frequently cited journal, emphasizing its historical and theoretical importance in shaping foundational discussions on sign interpretation and meaning-making [30]. Overall, the concentration of publications within a few high-impact journals suggests that the semiotic–cognitive research field maintains both disciplinary depth and academic stability. Such journal dominance ensures continuity in theoretical evolution and provides a reliable platform for advancing empirical and conceptual work across related fields [18].

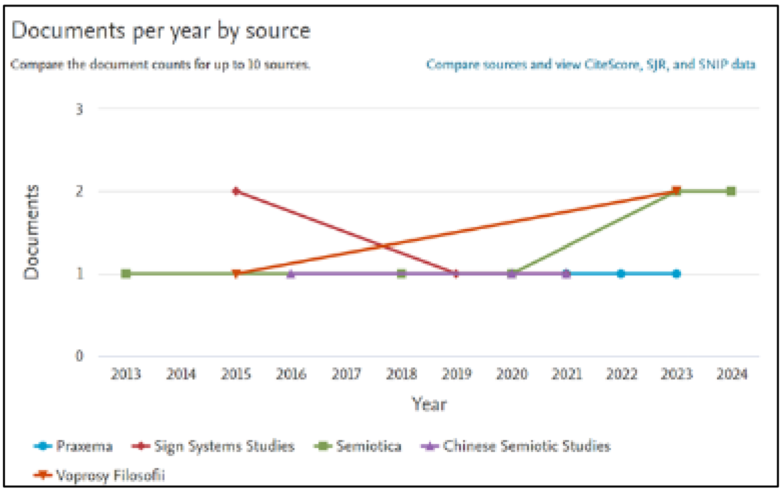

Figure 9 Annual Distribution of Publications by Source Journal (2013–2024)

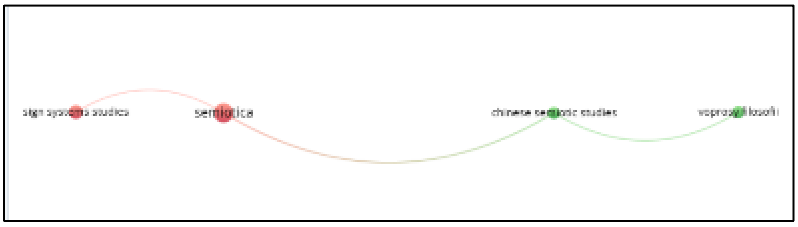

Figure 10 Network Visualization of Source Journals in Semiotic Cognitive Research

Figure 9 illustrates the yearly publication trends across the most productive source journals in the semiotic–cognitive research domain from 2013 to 2024. The results reveal that Semiotica, Sign Systems Studies, Chinese Semiotic Studies, Praxema, and Voprosy Filosofii are the primary journals contributing to this field. Among them, Sign Systems Studies and Voprosy Filosofii demonstrate a steady rise in publication numbers after 2020, reflecting a growing academic interest in semiotic approaches to cognition and language. Meanwhile, Semiotica maintains consistent output levels, highlighting its long-standing role as a cornerstone of semiotic theory [31][32]. The increasing presence of Sign Systems Studies suggests a diversification of research themes integrating cognitive science, philosophy of meaning, and communication studies. This indicates that the field is evolving toward a more interdisciplinary orientation, combining semiotics with cognitive ergonomics and human behavior research [33][34]. Figure 9 presents the network visualization of source journals, illustrating how frequently these journals are co-cited within the analyzed corpus. Larger nodes correspond to journals with a higher number of publications, while thicker lines represent stronger co-citation relationships. The network reveals that Sign Systems Studies maintains the strongest bibliographic coupling with Semiotica, followed by Chinese Semiotic Studies and Voprosy Filosofii. This close relationship emphasizes the shared theoretical foundation of semiotic cognitive studies and the mutual reinforcement among these leading journals [35][36]. Overall, the visual and statistical findings indicate that semiotic–cognitive research is supported by a small but cohesive cluster of high-impact journals. The strong interconnection between Semiotica and Sign Systems Studies reflects their central role in shaping conceptual developments and advancing discussions on human meaning-making processes across linguistic and ergonomic domains [37][38].

3.5. Based on Country Collaboration

Co-authorship analysis at the country level is an effective approach to visualizing patterns of international collaboration and the global distribution of research productivity. In this study, a country-level co-authorship network was constructed to explore the geographical landscape of semiotic–cognitive research. The minimum thresholds for both the number of documents and citations were set at five, and from a total of 26 countries, seven met these inclusion criteria. Figure 5 presents the visual network of country collaborations, while Table 4 summarizes publication counts, total citations, and total link strength per country. In the visualization, countries are grouped into clusters with distinct colors to indicate collaboration networks. The node size represents the number of publications, and the link thickness shows the intensity of co-authorship ties between nations. The results highlight that Russia (28 documents), the United States (14), China (12), Germany (7), and Sweden (6) are the most active and collaborative countries in this research domain. The strong linkage between Russia and other European countries indicates a long-standing intellectual influence in semiotic and cognitive studies, rooted in traditions such as the Tartu–Moscow Semiotic School. Similarly, the United States and China have recently increased their scientific output, reflecting their growing participation in cross-disciplinary research integrating semiotics, cognition, and ergonomic design [6][17]. The geographical distribution of co-authorship suggests a shift toward international research integration, where scholars across Europe, North America, and Asia are building interconnected networks that promote the global exchange of ideas. This trend supports the growing recognition of semiotics and cognitive ergonomics as multidisciplinary fields that bridge theoretical philosophy with applied human factors [18]. Moreover, the visible collaborations between Western and Eastern countries particularly among Russia, China, and the USA illustrate how cultural and linguistic perspectives are increasingly incorporated into contemporary semiotic–cognitive frameworks [39][40]. Overall, these findings indicate that while Europe remains the historical foundation of semiotic research, Asia and North America are now emerging as major contributors, driving the globalization and diversification of semiotic and cognitive ergonomics research [41].

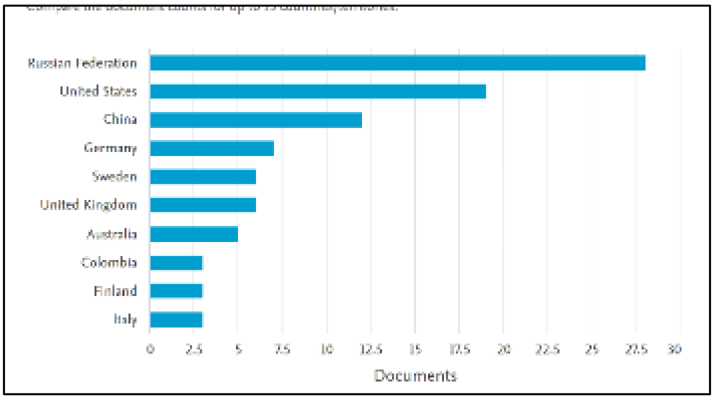

Figure 11 Country Collaboration Network in Semiotic–Cognitive Research (2010–2024)

3.6. Overview of Reviewed Studies

The systematic review identified a total of 13 core studies that met the inclusion criteria, as summarized in Table 1. These publications collectively represent the interdisciplinary nature of sign system research, integrating perspectives from engineering, cognitive psychology, design, and safety science. Across the reviewed literature, three dominant thematic clusters were identified: technological innovation, cognitive and behavioral factors, and semantic interpretation. From a technological standpoint, many studies explored the integration of Internet of Things (IoT), Artificial Intelligence (AI), and algorithm-based evacuation systems [3][4][42]. These works aimed to enhance the adaptability and real-time responsiveness of exit signage systems during emergency situations. Simulation-based methodologies were the most frequently employed, including agent-based modeling, virtual environment experiments, and shortest-path algorithm simulations, which allowed researchers to assess user movement and system performance under dynamic hazard conditions. In parallel, several studies focused on human cognitive and emotional responses during wayfinding and evacuation tasks [6][42]. These investigations revealed that factors such as stress, anxiety, and cognitive load significantly influence a person's ability to interpret and respond to exit signage effectively. Meanwhile, a smaller but significant subset of research examined semantic and cultural dimensions, emphasizing the need for universally interpretable symbols and color codes that transcend linguistic and cultural boundaries [5][43]. Overall, the reviewed studies highlight a clear evolution in signage research from static, visually oriented designs toward adaptive, intelligent, and user-centered systems. This progression reflects a broader shift toward integrating technology, cognition, and semantics as core foundations for developing the next generation of emergency communication systems.

3.7. Technological Innovations in Exit Sign Systems

Technological innovation has become one of the most significant driving forces in the evolution of exit sign systems. A growing body of research demonstrates how the integration of Internet of Things (IoT), Artificial Intelligence (AI), Convolutional Neural Networks (CNN), and pathfinding algorithms can transform traditional signage into adaptive and intelligent guidance systems. Several studies, including those by Cho et al. [3] and Kim et al. [4] introduced smart exit signage that automatically adjusts evacuation routes in real time based on hazard detection and environmental changes. These systems employ algorithms such as Dijkstra's shortest-path to continuously compute and update the safest evacuation paths, thereby improving both evacuation efficiency and route optimization during emergencies. Building upon these algorithmic foundations, researchers have also incorporated IoT-based sensor networks to enhance environmental awareness. For instance, Jung et al. [44] developed an IoT-enabled LED exit sign controller using multiple sensors to detect smoke, heat, and occupancy. This approach allows the signage system to communicate with other sensors and update its directional cues instantly without relying on a centralized server. Similarly, Zhang et al. [42] applied CNN-based vision recognition to improve the accuracy of real-time sign detection and interpretation, ensuring that automated systems can recognize and adapt to environmental obstacles or visual disruptions such as smoke or low visibility. These technological advancements signify a shift toward context-aware and responsive evacuation systems, capable of autonomously analyzing situational data and guiding occupants dynamically. By integrating smart algorithms, AI perception models, and sensor communication, exit signage can transcend its traditional role as a static indicator and evolve into an intelligent safety interface. Collectively, these studies underscore the transformative potential of technology in enhancing situational awareness, route reliability, and overall evacuation safety, ultimately contributing to the development of resilient and human-centered built environmentssystems.

3.8. Cognitive and Behavioral Factors

The cognitive and behavioral dimensions of exit sign systems play a crucial role in determining the effectiveness of emergency evacuation. Human response to visual signage is not purely perceptual it is strongly influenced by cognitive load, emotional state, and situational stress. Under emergency conditions such as fire or smoke, individuals often experience anxiety, reduced attention span, and slower decision-making, which can significantly impair their ability to interpret and follow exit directions accurately. Wang et al. [6] demonstrated through a virtual environment study that participants exposed to optimized color-coded signage exhibited lower stress levels and improved wayfinding accuracy compared to those navigating with standard signage. This finding highlights how visual clarity and intuitive design can help reduce cognitive burden and support faster orientation during crises. Similarly, Zhao et al. [45] employed a combination of virtual reality and agent-based simulations to investigate behavioral responses under varying guidance conditions. Their study found that decentralized dynamic evacuation tools which updates directional cues in real time according to crowd movement and environmental hazards leads to more efficient evacuations and lower perceived stress among occupants. This suggests that static signs may no longer be sufficient in complex built environments where conditions change rapidly. Collectively, these studies underscore the necessity of adopting a user-centered design (UCD) approach in developing modern exit signage systems. By understanding how cognitive limitations, perceptual cues, and emotional factors interact during emergencies, designers can create behaviorally adaptive systems that not only direct movement but also support human psychological stability under pressure. Integrating insights from cognitive psychology and human–computer interaction can therefore enhance the intuitiveness, accessibility, and reliability of emergency wayfinding systems, ultimately improving life safety outcomes in built environments.

3.9. Semantic and Cross-Cultural Dimensions

The semantic and cultural interpretation of signs represents one of the most complex yet underexplored areas in sign system research. While technology and cognitive understanding have advanced significantly, the way people from different cultural and linguistic backgrounds interpret visual symbols remains inconsistent. Semantic clarity—the degree to which a sign's meaning is understood as intended is essential to ensure that users can make fast and accurate decisions during emergencies, regardless of cultural context. However, studies indicate that visual cues such as color, shape, and symbols are often interpreted differently across societies due to variations in semiotic conventions and cultural symbolism [5][43]. For instance, Tryjanowski et al. [43] conducted a global review of road and warning signage, revealing that even standardized symbols may evoke distinct meanings depending on local cultural references and design traditions. Similarly, Olander et al. [5] explored dissuasive signage and demonstrated that subtle design modifications such as the use of red flashing lights or textual warnings can significantly influence user perception and behavioral responses. These findings underscore the importance of understanding cross-cultural semiotics in creating universally interpretable signs that minimize misinterpretation and hesitation in high-risk situations. To address these challenges, future signage design must incorporate semantic universality as a guiding principle. This involves developing visual vocabularies grounded in cross-cultural research and semiotic analysis, ensuring that critical messages such as exit directions or hazard warnings are understood regardless of language or cultural background. Collaboration between designers, cognitive psychologists, and cultural communication experts is crucial for achieving a globally coherent design language. In this way, semantic research can complement technological and cognitive approaches, leading to more inclusive, comprehensible, and effective exit signage systems in diverse built environments.

3.10. Integration of Bibliometric and SLR Insights

The integration of bibliometric mapping and systematic literature review (SLR) provides a comprehensive understanding of how research on sign systems, cognitive factors, and semantic design has evolved over time [19][22]. The bibliometric analysis revealed the quantitative landscape of this domain identifying key authors, journals, and countries contributing to the advancement of intelligent and dynamic evacuation tools systems [16]. It highlighted growing collaboration between engineering, psychology, and design disciplines, indicating that the study of sign systems has become increasingly interdisciplinary [46]. Meanwhile, the SLR results complemented these findings by offering a qualitative synthesis of theoretical and practical advancements [14][15]. The reviewed studies showed a steady transition from static, rule-based signage toward dynamic, sensor-integrated systems supported by AI, IoT, and data-driven algorithms. This shift aligns with the bibliometric trend of rising keyword frequency related to intelligent guidance, IoT systems, and cognitive wayfinding, confirming a shared research trajectory across different methodological approaches [19][20]. Integrating both perspectives underscores a crucial insight: the future of exit sign system research depends on the synergy between technology, cognition, and semantics. Bibliometric trends reveal where research energy is concentrated, while SLR findings explain why certain topics gain prominence often due to practical demands for human-centered, adaptive safety systems. Together, these analyses emphasize that effective signage design requires not only technological intelligence but also a deep understanding of human perception, cognitive processes, and cultural interpretation. Therefore, the hybrid approach employed in this study combining bibliometric visualization and systematic synthesis demonstrates the value of cross-method integration in uncovering both structural patterns and conceptual depth. Such integration enables researchers to identify gaps, emerging themes, and potential interdisciplinary collaborations that can guide the development of more responsive, inclusive, and intelligent sign systemfuture.

3.11. Future Research Directions

Building upon the integrated insights from the bibliometric mapping and systematic literature review, future research on sign systems, cognitive factors, semantics, and exit signage continues to present a broad and evolving field for exploration. As modern environments grow increasingly complex, signage no longer functions merely as a static visual cue but as an adaptive communication interface that dynamically interacts with human cognition and smart technology [47][48]. One of the most promising directions for future research lies in evaluating the effectiveness of adaptive exit sign systems in real emergency scenarios. Previous studies have proposed the use of IoT-based systems and shortest-path algorithms for evacuation guidance [3][4]. However, these studies often relied on controlled simulations and lacked behavioral realism. Recent works have suggested that agent-based modeling and Virtual Reality (VR) simulations can bridge this gap by incorporating human behavioral variability into evacuation models [45][47]. Such approaches enable researchers to analyze how dynamic signage adaptation influences route selection, evacuation efficiency, and crowd flow under stress. Beyond technological systems, cognitive and behavioral factors remain underexplored dimensions. Studies have shown that stress, anxiety, and cognitive load significantly affect an individual's ability to interpret visual information during emergencies [6]. Future research should adopt user-centered design (UCD) methodologies to tailor signage toward different cognitive profiles and stress responses [44][47]. This focus on cognitive adaptability would enhance situational comprehension and improve human decision-making under pressure, promoting inclusivity and accessibility in emergency communication. The semantic and cross-cultural dimensions of signage design also deserve greater attention. As demonstrated by previous cross-national studies, symbolic meaning and color interpretation can vary widely across cultural contexts [5][43]. Future research could work toward developing a universal semantic framework for exit signage by integrating semiotics, cognitive psychology, and cross-cultural communication studies. Such an effort would help create globally interpretable symbols that maintain their clarity and meaning in diverse environments.

In addition, the emergence of Artificial Intelligence (AI) and machine learning offers exciting opportunities for real-time hazard detection and adaptive decision-making. Leveraging Convolutional Neural Networks (CNNs) and data-driven models, AI-powered signage can autonomously detect hazards, predict evacuation bottlenecks, and dynamically guide users to safer routes [45][48]. These innovations demonstrate how intelligent guidance can evolve into context-aware and self-optimizing systems capable of learning from environmental feedback and human movement patterns. Furthermore, the concept of dissuasive or behavior-guiding signage presents a novel approach to managing panic and promoting orderly evacuation. Studies based on affordance theory have shown that visual stimuli such as flashing red lights, motion cues, or contextual textual messagescan subconsciously influence crowd behavior and reduce chaos during emergencies [5]. Interdisciplinary collaboration between behavioral scientists, ergonomists, and human–computer interaction researchers could further refine this approach to optimize signage for emotional regulation and behavioral guidance.

Finally, combining bibliometric–SLR hybrid methods with emerging behavioral modeling techniques 48] can help researchers map future directions more systematically. Such integration not only reveals research hotspots and collaboration networks but also identifies conceptual and methodological gaps that can guide the development of responsive, intelligent, and human-centered sign systems. In conclusion, future research should focus on integrating technological intelligence, cognitive adaptability, and semantic universality to build signage that not only communicates direction but also responds empathetically to human needs and environmental dynamics. The convergence of IoT, AI, and VR technologies, supported by cross-disciplinary collaboration, will pave the way for next-generation adaptive exit sign systemstransforming traditional signage into life-saving communication infrastructures for the built environment [6][32][49].

This study contributes by mapping the intersection of technology, cognition, and semantics, revealing the need for empirically validated, behaviorally adaptive, and culturally inclusive intelligent sign systems.

4. Conclusion

This study emphasises that research on sign systems, particularly those concerning cognitive, semantic, and exit signage, remains an evolving and interdisciplinary domain with considerable potential for future development. As technology and human behaviour become increasingly intertwined, the role of signage has shifted from a static visual indicator to an adaptive, intelligent, and interactive communication medium capable of responding dynamically to environmental and behavioural changes in real time. Future research in this field should focus on three critical directions. First, the integration of advanced technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), and Virtual Reality (VR) offers significant potential to create smart and context-aware exit sign systems. These systems can autonomously adapt to emergency scenarios by recalculating evacuation routes and providing real-time guidance, thereby enhancing overall safety performance. Second, greater attention should be given to cognitive and behavioural dimensions. Understanding how individuals perceive, interpret, and respond to signage under stress or limited cognitive capacity is vital to improving sign effectiveness. Signage designed in alignment with human perception, cognitive load, and decision-making processes can enhance inclusivity and efficiency within evacuation systems, ensuring accessibility for all user groups. Third, achieving semantic clarity and cross-cultural universality remains a continuing challenge. Cultural differences significantly influence the way individuals interpret visual symbols and warnings, reinforcing the need to establish universal visual semantics. This goal necessitates multidisciplinary collaboration among designers, semioticians, cognitive psychologists, and communication experts to develop a shared visual language that transcends linguistic and cultural barriers. In summary, the future of sign system research lies in harmonising technological intelligence, cognitive understanding, and semantic universality. Integrating these three dimensions will enable signage to evolve into a responsive safety communication system that not only guides but also protects individuals during emergencies. Such innovations are expected to contribute to safer, smarter, and more human-centred built environments while enriching our understanding of human interaction with visual information in critical situations.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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