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Review Article

Unraveling the Potential of Immersive Virtual Environments for Behavior Mapping in the Built Environment: A Mapping Review

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Introduction/Purpose. Behavior mapping is a crucial practice to capture precise data on human activities. Over the years, technological advancements have improved reliable data collection over the conventional "paper and pen"-based methods. Likewise, researchers increasingly utilize IVE (immersive virtual environment) technology in the built environment for its experiential capabilities. The aim of this research is to comprehensively investigate the most recent research and technological trends, data collection methods, and challenges and opportunities associated with IVE adoption for behavior mapping. *Design/Methodology/Approach*. This study investigates the current status of behavior mapping in the built environment through a mixed qualitative–quantitative study. A systematic background review was conducted on 353 articles, and a bibliometric analysis was performed on 123 journal articles retrieved from Scopus. The analysis generated science maps, unveiling technological advancements, data types, collection methods, research trends, and potential directions to address the research questions at hand. *Findings*. A thorough qualitative review presented deeper insight into major transitions and technological contributions, whereas the quantitative study revealed current research trends and future directions. Furthermore, it discussed the contribution, opportunities, and challenges of IVE technology for data collection. *Research Limitations*. The review and bibliometric study findings are circumscribed by literature data retrieved from Scopus data only, and potential research directions, opportunities, and obstacles are proposed based on analysis of review results, which might cause an incomprehensive nature. *Practical Implications*. This study highlights the importance of behavioral mapping research and the potential for technology to assist it. The paper also identifies current shortcomings and constraints in the literature, emphasizing the need for interventions in IVE technology.

1. Introduction

The immersive virtual environment (IVE) has been investigated extensively in human psychology as a methodological tool to research human behavior [1, 2]. The proliferation of technology has expanded research in this area, leading to an enhanced comprehension of human behavior patterns within built environments. Current research on behavior mapping relies on diverse technologies such as video cameras, GPS tracking, RFID (radio-frequency identification) tagging, and mobile applications to collect and analyze human behavior patterns [3, 4]. This provides an opportunity to understand how people interact with their environment and offers insights to inform the design and planning of future built environments. Among all available technological tools, the investigation into the use of immersive technologies is progressing at its full potential and opening up new research possibilities. Specifically, in the context of the built environment, behavior mapping of humans is a prominent area of research to make well-informed and optimized decisions [5]. Immersive technologies are being investigated as promising tools for researching behavior mapping in the built environment. It is a critical research domain that enables designers, architects, and planners to understand how people use space, improving its usability, safety, and overall user experience. Using such technologies also opens up new research possibilities, enabling more extensive and sophisticated investigations into the complex relationship between people and their environments [6].

IVE technologies extend beyond achieving total immersion and exert a notable influence on research across diverse domains, encompassing the built environment. This influence is evident in multiple studies conducted to investigate human behavior utilizing IVE. For instance, in a study published in the "Human Factors The Journal of the Human Factors and Ergonomics Society," immersive virtual environments are particularly beneficial for studying the user experience and behavioral responses [7]. Another study published in "Engineering, Construction, and Architectural Management" highlights the benefits of using virtual reality to make quick design decisions and early design stage support for optimized design [8]. Moreover, Table 1 highlights key research demonstrating the usefulness of IVE in the built environment.

Behavior mapping and immersive virtual environments (IVEs) have been extensively studied as independent research areas. This research is aimed at integrating both areas and conducting a systematic review of the qualitative and quantitative data available in scientific databases to identify current research trends and potential unexplored research paradigms. By taking a comprehensive approach to these two related research areas, this study seeks to identify new insights and opportunities for future research in behavior mapping and IVEs. Overall, these studies demonstrate the potential of immersive virtual environments as a valuable tool for behavior mapping research in the built environment. The study is aimed at answering the following research questions:

(1) How has the evolution and advancement of various technologies influenced behavior mapping research in the built environment?

(2) In what ways have different technologies been used for collecting behavior data in the built environment?

(3) What are the current trends and hotspots in behavior mapping research in the context of IVEs?

(4) What are the potential unexplored research paradigms and future directions for behavior mapping and immersive virtual environments (IVEs) in the setting of the built environment?

2. Research Methodology

This study is aimed at achieving a comprehensive and in-depth understanding of the evolutionary trajectory of technological evolution and its support in behavior mapping research while also exploring the potential applications of virtual reality (VR) technologies within the built environment. A mixed method approach has been adopted to reach this goal; it includes literature mapping analysis and bibliometric study. This "mapping review" methodology helped to dive deep into the subject area's qualitative aspect, including identifying and summarizing the key concepts, theories, methodologies, and findings from existing studies. Additionally, it supported screening trends and research patterns, identifying hotspots and emerging fields. This type of mapping review involves a systematic search for published articles to collect qualitative information [13]. Further steps include synthesizing the qualitative findings from these articles and categorizing them into an inductively outlined set to answer predefined research questions.

Table 1: Possible applicability of IVEs in built environments.

Author	Pervasive usefulness of IVE in built environment
[8, 9]	Effective tool for conceptual design to study user preferences
[10]	Virtual reality as tool to understand future working environment
[11]	Virtual reality to collect and analyze user behavior data for building energy performance
[12]	Tool to study human behavior with respect to environmental psychology

The research methodology can be split into two stages: the initial phase entails conducting a comprehensive background study or literature review, while the subsequent phase involves bibliometric analysis (see Figure 1). The background study can be further divided into two subparts based on the research objectives: technological interventions and behavior mapping as a data collection tool. This background study is conducted using a mapping analysis approach. Figure 2 illustrates the sequential steps undertaken within this approach.

Furthermore, Figure 3 presents an overview of bibliometric analysis. It is a type of quantitative method to examine patterns and metrics derived from large-scale bibliographic data, providing insights into the productivity, impact, and interconnections within the scholarly landscape [14]. The mixed review method enables the integration and cooperation of conflicting perspectives in both types of analyses [15, 16]. Additionally, the findings derived from these distinct methods can reinforce one another and remove subjective interpretations of research trends and opportunities (Y. [17]). In this study, the qualitative review and quantitative bibliometric analysis are carried out in sequence, so the results from the quantitative analysis can be used to develop the subsequent qualitative assessment. This approach strengthens the validation of reported outcomes in the discussion section of this study.

3. Mapping Review of Background Research

A systematic review of previous research has been undertaken to identify the links between behavior mapping and other fields of study, as well as the development of technological interventions over time. The titles and abstracts of the research have been chronologically reviewed by year. Shortlisted articles undergo further intense review, focusing solely on two areas: technological evolution and support and BM adoption as a data collection tool.

	Step 1: Background study	Step 2: Bibliometric study
Identification	Keyword search: “behaviour mapping” OR “behavior mapping”) Database: Scopus Items received: 353	Keyword search: “behaviour mapping” OR “behavioural analysis” OR “behaviour study” OR “behavior mapping”AND TITLE-ABS-KEY (“immersive virtual environment” OR “IVE” OR “IVR” OR “virtual reality” OR “immersive virtual reality” OR “VR”) Database: Scopus Items received: 123
Screening	Inclusion criteria (IC): language - english only Exclusion criteria (EC): non-english articles Items received after screening through IC & EC: 345	Inclusion criteria (IC): language - english only Exclusion criteria (EC): non-english articles Items received after screening through IC & EC: 120
Included	Study summarization Reporting the key findings – discussion on RQ1 and RQ2	Bibliometric analysis using VOSviewer (bibliometric data visualization tool and ‘analysis search results’ section of Scopus database) Reporting the key findings – discussion on RQ3

Figure 1: Data retrieval procedure.

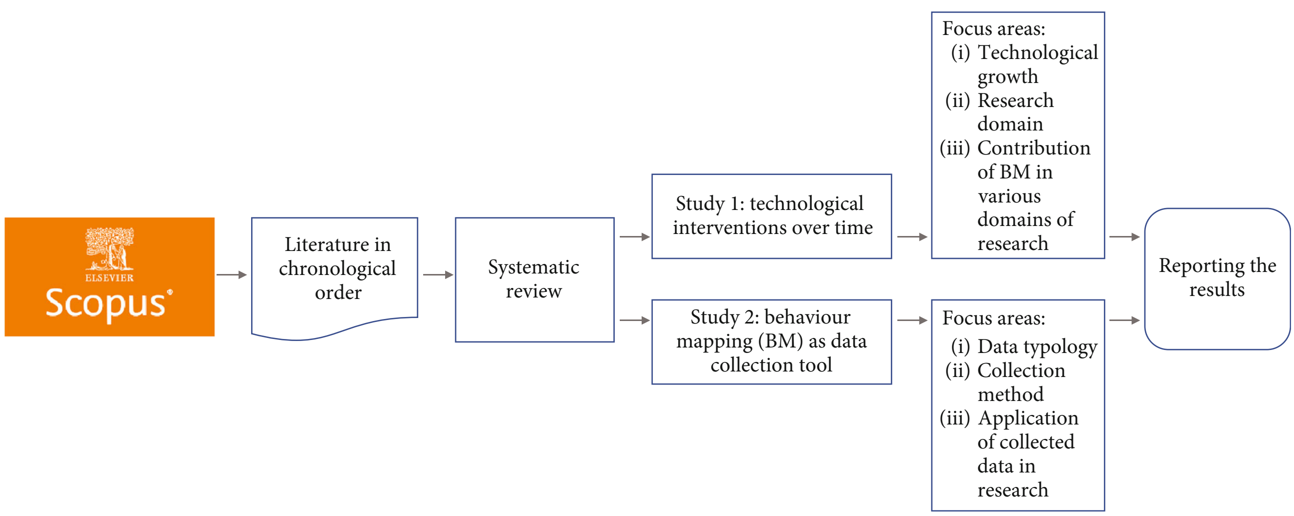

Figure 2: Outline of background study.

3.1. Technological Interventions. Initial research on human behavior mapping had not exclusively been focused on human behavior in built space. However, these studies concentrated on environmental adaptation based on age, sex difference, physical location, and social space. The first study in this direction was published in 1976 with a sample size of 48 elderly residents [18, 19]. A study on the behavior of repeated hospitalization of chronic psychiatry came in 1979 [20]. Similarly, studies on animal behavior are now being investigated concurrently [21, 22]. From 1989 to 1994, research focused on nonverbal and agitated behavior. The very first behavioral study in indoor environment was performed by Shepley et al. in 1995 on design guidelines for women’s medical centers [23]. Greuel et al., therefore, undertook the first research with IVR. This article explores using music to control object behaviors and create visually active immersive virtual environments [24]. The article by Bell and Smith, [25] presented a behavior mapping strategy to measure the impact of spatial changes in special care units, using an Alzheimer unit as an example, to improve quality of care, and Shepley and Wilson [26] used behavior mapping to gather information about the design of a new HIV/AIDS skilled nursing facility. This study’s results have come in the form of guidelines for designing facilities for people with AIDS. It can be seen that in both studies, behavior mapping has been used as a tool for gathering data. The researchers continued the studies on agitation in dementia patients until 2004. At the same time, a study by Zacharias et al. [27] examined user behavior in San Francisco plazas and the effects of microclimate and environmental design on behavior. The majority of studies conducted were related to medical research and concentrated on brain-behavior mapping and agitation in dementia patients.

However, in 2007, a study was conducted that focused on user behavior mapping as a means of investigating the effect of daylighting on the comfort of occupants in an actual

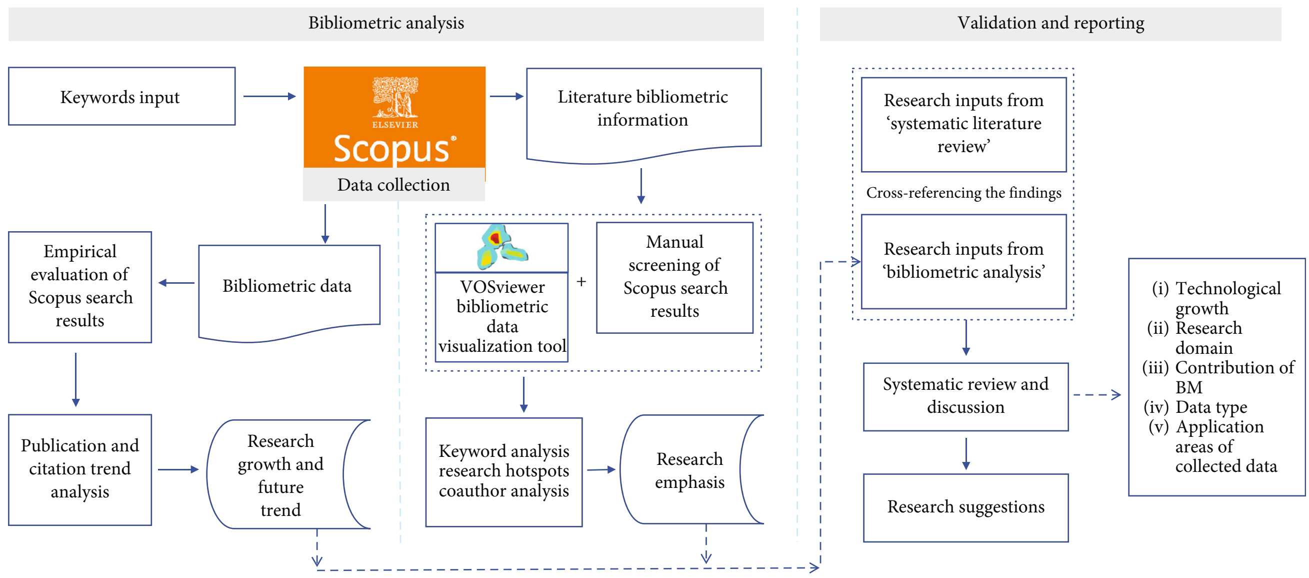

Figure 3: Overview of bibliometric analysis.

space. This study showed that diverse daylighting in buildings creates visually comfortable spaces. Different evaluations of comfort were observed among occupants, highlighting the importance of diverse luminous conditions [28]. Ozdemir and Yilmaz [29] used behavior mapping as a tool to assess the outdoor school environments and physical activities of students. Dubois et al. [30] used various methods, including behavior mapping, to study how daylighting affects occupant comfort and found that it creates diverse luminous ambiances, promotes comfort, and increases activity in real spaces. The use of behavior mapping as a tool to research the use of space and well-being was explored in 5 studies published in 2010 and 2011 on outdoor environments [31–33]. Moreover, Thuesen et al. [34] published an article that proposed a user-oriented approach to lighting design in hospital wards, dividing them into zones based on user needs and activities. The research publications on behavior mapping from 2012 to 2015 demonstrate a consistent rise in studies in the field of medicine, particularly in the areas of neurology, dementia, and agitated behavior. The use of behavior mapping as a method for studying social behavior in urban and outdoor settings has also gradually grown [35–37]. Figure 4 shows the emergence of behavior mapping research in medicine (medical, neuroscience, and psychology), engineering (computer science, basic sciences, electronics, and electrical engineering), urban and open space design, architecture and indoor environment, and other (visitors studies, mathematics, interdisciplinary, geography, and social science) domains.

Moreover, Figure 5 illustrates the trajectory of diverse technological evolution and their integration with behavior mapping research. It elucidates the initial adoption of sensors while highlighting the ongoing prevalence of IVE, software utilization, UAVs, and filming. It also shows a steady growth trend for the adoption of IVE technology.

Currently, immersive virtual environments (IVEs) have emerged as a useful tool in various research fields, including emergency evacuation [38, 39], building design [40, 41], and occupant behavior prediction [42]. A growing body of research has highlighted the potential of IVEs in studying human-building interactions. For instance, [43] used IVE to study occupant lighting preferences in a single office and concluded that it facilitated the understanding of human-building interactions and satisfaction with different design options. Saeidi [44] validated human-building interaction in light switching using IVEs and demonstrated that they were capable of replicating experiences in a real environment. Niu et al. [11] developed a framework that integrated building designs with IVEs to help designers capture human-building interactions and identify contextual patterns. Bozkurt [45] developed behavior mapping using GIS technology. The Journal of Interior Design published two studies in 2017 that employed behavior mapping in indoor spaces. Thus far, the majority of studies have solely looked at floor spatial planning [46–48].

Chokwitthaya et al. [49] proposed a method called spatial-temporal event-driven (STED) modeling to design experiments and collect human-building interaction data in IVEs. They validated the method by comparing human-building interaction data obtained from an IVE experiment with that obtained from a physical environment and found no significant difference, confirming the capability of IVEs to capture human-building interactions. As is customary, neurological research and urban and outdoor space have dominated the studies on behavior mapping in 2019 and 2022. Therefore, Park et al. [50] developed a technological intervention with unmanned aerial vehicles (UAVs) for behavior mapping at the urban scale. The number of studies on behavior mapping in urban and outdoor areas that have been published in 2022 has significantly increased, and it now dominates the field almost as much as neurological research. Technological interventions in behavioral research have been consolidated and presented in Table 2, accounting for their initial adoption instances.

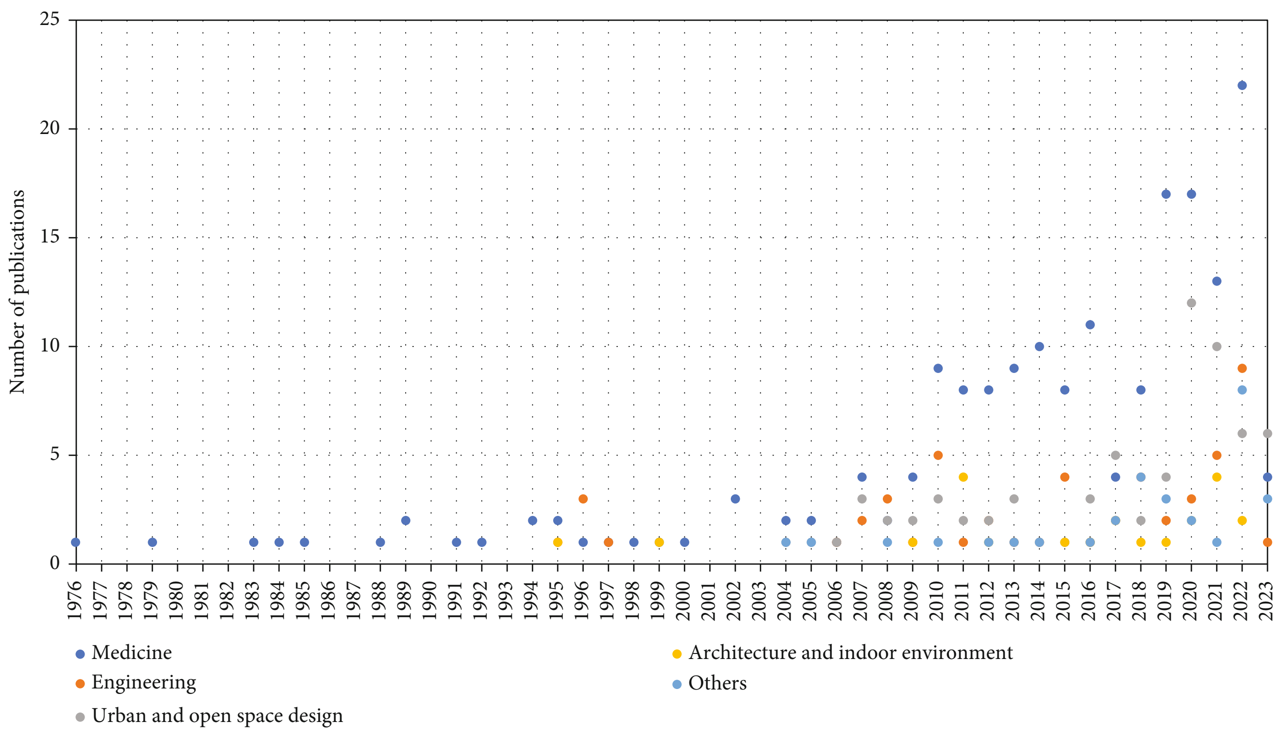

Figure 4: Domain-specific publications on behavior mapping.

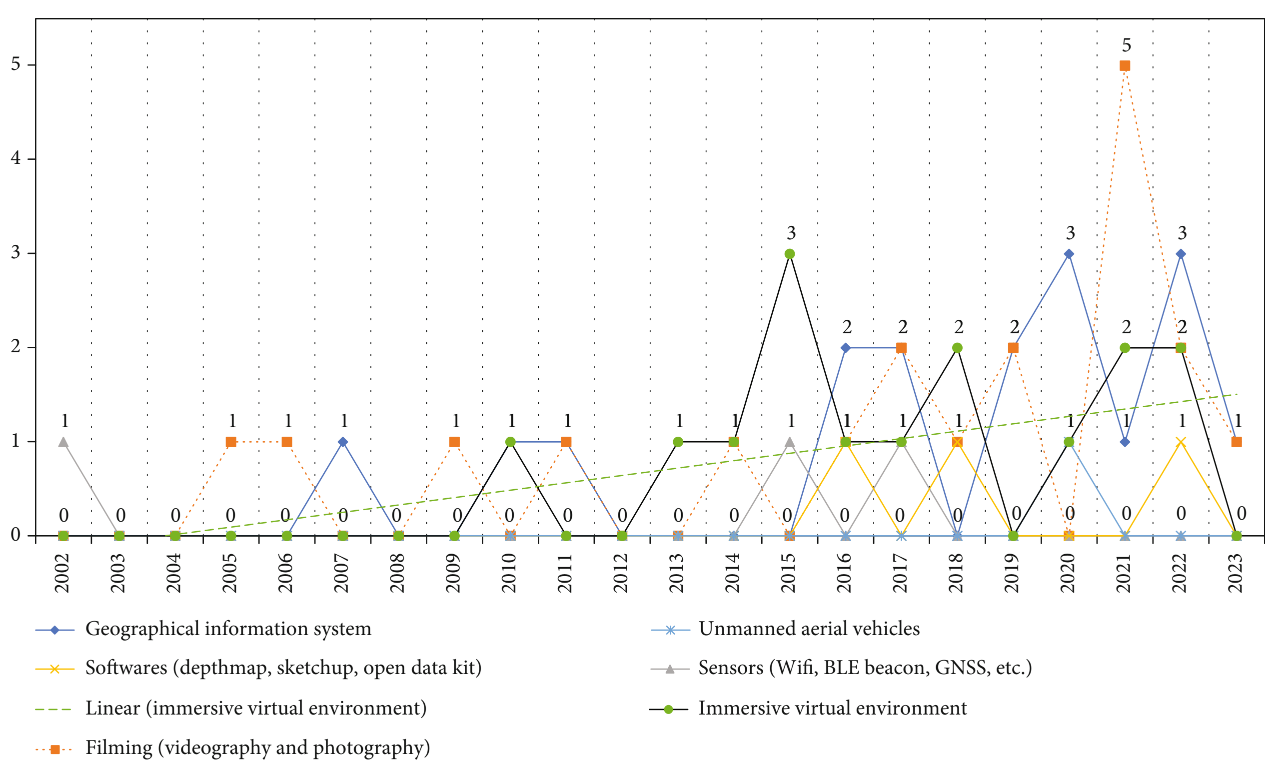

Figure 5: Trend of technological integration for behavioral research.

3.2. Behavior Mapping as a Data Collection Tool. The concept of a "behavioral map" originated from using architectural floor plans as prototypes [62]. It is a nonintrusive, direct observational technique used to record the spatial positions of individuals and simultaneously measure their levels of activity. The outcomes derived from this method aid researchers in comprehending the intricate behavioral patterns within the built environment [31]. In behavioral

Table 2: Chronological use of technology in behavior mapping data collection in built environment.

Sr. no.	Year (first introduced)	Research study	Technology	Data type collection/ technological support	Research domains
1	2002	Architecture for Wellness: A Post-Occupancy Evaluation of a University Student Recreation Center [51]	Pedometers	Step count	Indoor environment
2	2007	GIS behaviour mapping for provision of interactive empirical knowledge, vital monitoring and better place design [52]	Geographical information system	Activities outdoors: (1) Social activities (2) Recreational activities (3) Physical activities Comparative data of pre and post intervention	Urban design Landscape architecture Environmental psychology Geography
3	2010	Exit choice, (pre-)movement time and (pre-)evacuation behaviour in hotel fire evacuation — Behavioural analysis and validation of the use of serious gaming in experimental research [53]	VR (virtual reality)	Emergency evacuation	Indoor environment
4	2011	Optimizing lighting design for hospital wards by defining user zones [34]	RFID	Activities: (1) Flow of occupants (2) Time taken	Indoor environment
5	2015	Towards understanding end-user lighting preferences in office spaces by using immersive virtual environments [54]	IVE (immersive virtual environment)	Actions taken for visual comfort	Indoor environment
6	2015	A mobile application as an unobtrusive tool for behavioural mapping in public spaces [55]	Smartphone application	Usage pattern of indoor space	Indoor environment
7	2017	Resilience in Latin American Cities: Behaviour vs. Space quality in the Riverbanks of the Tomebamba River [56]	Smartphone application: Open Data Kit (ODK)	Usage pattern of indoor space	Urban design
8	2017	Early steps in automated behavior mapping via indoor sensors [57]	Wi-Fi, BLE beacon, and UWB sensor technology	Position of occupants	Indoor environment
9	2019	Impact of the physical environment on user behavioral psychology in urban district park [58]	Satellite maps	Tech. support: referencing and representation of data	Urban design
10	2019	Urban plaza design process using space syntax analysis: El-Houria plaza, Biskra, Algeria [59]	Depthmap software (VGA tool)	Tech. support: representation and analysis of data	Urban design
11	2020	Unmanned aerial vehicles (UAVs) in behavior mapping: A case study of neighborhood parks [50]	Unmanned aerial vehicles (UAVs)	(1) People density (2) Outdoor activity level	Urban design
12	2021	Spatiotemporal fluctuations in urban park spatial vitality determined by on-site observation and behavior mapping: A case study of three parks in Zhengzhou City, China [60]	Google maps	Tech. support: spatial and temporal distribution	Urban design
13	2022	Local Elements Defining Transitional Spaces as a Territorial Strategy at an Urban Village in the City of Yogyakarta, Indonesia [61]	SketchUp	Tech. support: understand space visually and spatially	Urban design

mapping research, two primary approaches are employed: place-centered mapping and individual-centered mapping [55]. However, both approaches rely on direct observation as a basic conduct for data collection. Research databases demonstrate that observational data are commonly gathered alongside other data collection methods, such as interviews, questionnaires, site surveys, photographs, video recordings, and the utilization of sensors.

The background shows that behavior mapping between 1976 and 1994 was primarily used in the fields of psychology and psychiatry. The data collection methods involved direct observation, interviews, and video recordings, focusing on psychiatric patients, dementia patients, and the elderly [18, 63, 64]. However, Shepley et al. [23] came first with research on the indoor environment and collected data on activities inside hospital buildings through interviews, questionnaires, and direct observations. Similarly, they conducted another study in 1999 focusing on the utilization of courtyard spaces, employing interviews, questionnaires, and direct observations to collect activity-related data [26]. From that time until 2007, data collection in behavioral mapping research has predominantly followed a consistent approach. Since then, researchers have collaborated with various methods and technologies for data collection.

3.2.1. Geographical Information System (GIS). Since its emergence in 2007, GIS technology has gained significant prominence in research focused on urban design and open public spaces. It has become an indispensable tool for collecting, organizing, analyzing, and visualizing spatial data [32]. Notably, over 30% of research conducted in the field of urban and open public space design extensively relies on GIS technology for various purposes. According to the Scopus database, researchers have extensively collected a diverse range of data utilizing GIS for various outdoor activities, such as social, recreational, commercial, health, and physical activities, from 2007 to 2022 [65–67].

Specifically, the integration of GPS (global positioning system) technology with GIS allowed the collection of direct information about people's movement in/through places. The studies have taken advantage of this approach in collecting reliable movement data [68]. This integration of GIS with GPS enables the study of behavior–environment interactions and relationships for a selected sample of individuals [69]. In contrast, it is evident that the development of GIS applications for indoor positioning has been limited and necessitates extensive research [70]. Additionally, the development of technologies was in its initial stage for application in the real world [71].

3.2.2. Filming. Photography and videotaping have been utilized for capturing activities since the inception of behavioral research. The detailed filming of various activities was started by Rosaneli [72]. Filming urban landscapes poses significant challenges due to the coverage of large segments; however, it can serve as a valuable tool for capturing behaviors in indoor environments. Onojeghuo et al. [73] conducted a notable indoor behavior mapping study using video recording in conjunction with the Observational System for Recording Physical Activity in Children-Preschool (OSRAC-P) version.

Video recording also comes with some limitations, as it relies on interpreting the recorded behaviors by the researchers or observers. Similarly, different observers may perceive and interpret behaviors differently, leading to potential subjectivity and inter-rater variability. Moreover, video recordings may lack detailed contextual information about the environment, social interactions, or individual characteristics, which could provide deeper insights into behavior.

3.2.3. Sensors. The research database exhibits the deliberate utilization of sensors for the acquisition of indoor movement statistics. Initially, a pedometer was used to gather step count data to study students' behavior for recreational activities by Davis and Shepley [51], followed by the research conducted by Bahillo et al. [55], who collected data using mobile phone applications that use inbuilt sensors, i.e., GNSS receivers, Wi-Fi, and Bluetooth adopters, while Arsan and Kepez [57] gathered data by placing Wi-Fi, BLE beacons, and ultrawideband (UWB) sensors in indoor spaces. Furthermore, these studies demonstrate that Wi-Fi is a low-cost, easy-to-use technology that does not need calibration but provides low accuracy. However, BLE beacon needs extra hardware and dedicated infrastructure to provide data with medium accuracy. However, UWB is an expensive technology but provides high accuracy among all. When direct observational data collection, database setup, data analysis, and assessments are taken into consideration, manual mapping is labor-intensive, time-consuming, and tiring [57]. Instead, using sensor-based devices with high precision can support indoor built environments significantly.

3.2.4. Records of Visitors. The records of individuals' ingress and egress from premises have served as a valuable database for behavioral research, whereas keeping records does not come under the study of technological support. Furthermore, its applicability remains contextual, yet it can function as a pertinent instrument for data collection in indoor settings. A study conducted by Harris [47] provided significant information about the amount of time visitors and staff spent with patients. This further helps in the investigation of interior material applications and their impact.

3.2.5. Depthmap Software (VGA—Visibility Graph Analysis Tool). It can assist in spatial analysis along with behavior data. Generating depthmaps provides valuable information about the spatial layout and positioning of objects within a scene. In the study, a correlation was established between occupancy of space and visual integration value [59]. However, it can be explicitly used to study through visual cues to estimate depth, whereas it is difficult to collect data for rapidly changing environments.

3.2.6. Focus Group. Utilizing focus groups provides a chance to observe how individuals interact within a social setting. Focus groups are especially suitable for gathering insights and experiences and exploring various perspectives related to a specific social context [74]. The studies conducted till now primarily concentrated on opting for the focus group study approach to gather data from the children's perspective. Student groups were recruited in these studies, and a designated time interval was allocated for the discussion, which was concurrently recorded for subsequent analysis. Additionally, physical maps were provided to the participants to support effective communication in two studies [75, 76], whereas in another study, they were supported by mental mapping [77].

Generally, focus group studies have consisted of participants from similar ethnic backgrounds. This limits the generalizability of the findings to a more diverse population. Furthermore, the public nature of the focus group discussions may influence participants to express socially acceptable views rather than challenging or unconventional perspectives. This may result in the underrepresentation of dissenting or nonconforming viewpoints [78].

3.2.7. Unmanned Aerial Vehicles (UAVs). UAV technology is remarkable due to its cost-effectiveness, high movement, convenience provided by aerial perspectives, and capability to survey larger surface areas in a shorter time [79]. It is a highly recent approach in urban and built environment research and is excellent in obtaining data collection for user density and level of sedentary and vigorous activities [50].

3.2.8. System for Observing Play and Leisure Activity in Youth (SOPLAY). This system has been used as an observational data collection instrument. SOPLAY was developed to gather observational data regarding the number of participants and their physical activity levels during play and leisure. The system uses PLACHECK (Planned Activity Check) recording, which employs group time sampling techniques and is based on momentary time sampling [80]. Gu further used this approach in his postoccupancy playground study research [81].

3.2.9. Spatiotemporal Behavior Mapping (STBM). The STBM is a method used to study behavior by considering both time and space aspects at a specific location. It involves observing and mapping behavior to understand how the characteristics of that particular space affect user behavior. The four-step process for behavior mapping includes the following:

(1) Creating an accurate scale map of the observation area

(2) Defining different types of activities

(3) Establishing coding rules for behavior classification

(4) Implementing a repeated observation schedule at specific times

This approach focuses on the specific setting rather than the entire site. STBM provides visual and statistical representations of behavioral patterns. However, few studies have been performed in this direction [82].

3.2.10. Immersive Virtual Environment (IVE). There is a substantial research gap in the field, characterized by a scarcity of studies focusing on behavior mapping utilizing IVE technology. A thorough search of the Scopus database yielded nearly no results when using the keyword "behavior mapping" in conjunction with IVE technology within the built environment. Nevertheless, a very limited number of researchers have explored IVE technology in the realm of building performance analysis (BPA) to investigate human actions within built spaces [83, 84]. However, researchers have not placed as much emphasis on precise research using the "behavior mapping" keyword as compared to other research domains, such as urban design and psychiatry. These studies are aimed at providing valuable insights to building designers, enabling them to make informed decisions that optimize building performance and foster a more human-centered approach to design.

Table 3 presents a chronological overview of the adoption of IVE in behavioral studies. Notably, its initial application involved the investigation of emergency evacuation scenarios [53]. Niu et al. [85] initially proposed the integration of immersive virtual environment (IVE) technology in the indoor environment. Their study focused on utilizing virtual reality (VR) technology to develop an innovative analytical approach for building designers, facilitating the identification of energy-efficient design patterns and addressing the energy performance gap caused by occupant behavior. Building upon this work, Niu et al. [11] validated their study and proposed a framework that combines the Design with intent (DwI) design method and VR technology that is devised to gather occupancy information for building energy design purposes. In this study, they categorized different occupants' behavior such as normal task-oriented and energy-oriented behaviors. Following that, Chokwitthaya et al. [42] studied the lighting discrepancy aspect between IVE and in situ using a software program UE4 (Unreal Engine 4), RADIANCE, and computer language (C++). In 2018, researchers were looking to identify obstacles and remedies for better use of IVE for occupant behavioral studies. Saeidi et al. [86] have worked in this direction and developed a spatial-temporal event-driven (STED) modeling method to enable IVEs for longitudinal studies.

Similarly, Chokwitthaya et al. [49] tried to resolve the small sample size issue using the hidden Markov model (HMM) Baum–Welch algorithm. At this stage, researchers were clearly using occupant behavior as a focus of their studies of IVE. Hegazy et al. [91] conducted an experiment and validated the hypothesis of using IVE for daylight subjective evaluations. In another study, Hegazy et al. [88] validated a game engine as a daylight simulation tool. This study is among the initial endeavours to investigate the effectiveness of game engine (IVE)-based renderings in daylighting research, particularly in relation to real-time ray tracing techniques. However, the findings of this study are not definitive. Mahmoudzadeh et al. [83] explored lighting choices between artificial and natural lighting using IVE. In another study, the researcher opted for IVE to identify the thermal perception of people in the proposed space [84].

However, IVE technology has two major limitations for direct applications in built environment studies: (1) real-world calibration of a computational environment for visual, thermal, and acoustic scenarios and its validation [17, 38, 88, 89] and (2) complex frameworks for adaptation in building performance evaluation [85, 86, 92].

The primary findings of the literature review are as follows:

(1) Behavior mapping has been widely utilized as a data collection tool to study behavior in various subject areas, such as agitated behavior, neurological studies, urban and public spaces, dementia patients (primarily elderly individuals), and animal behavior

(2) Studies on behavior mapping in indoor settings have primarily focused on medical facilities and schools prior to 2006. However, the origins of indoor environment behavior mapping can be traced back to 1995, whereas the emergence of IVE technology began in 2015

Table 3: Chronological use of IVE technology in the built environment.

Sr. no.	Year	Research study	Type of data collected	Potential challenges and limitations
1	2010	Exit choice, (pre-)movement time and (pre-)evacuation behaviour in hotel fire evacuation — Behavioural analysis and validation of the use of serious gaming in experimental research [53].	(1) Pre-evacuation behavior	Data collection through questionnaire. Such studies encounter technological limitations in gathering physiological data for evacuation behavior
2	2013	Journeys through the CAVE: The use of 3D immersive environments for client engagement practices in hospital design [41].	(1) Engagement of people with the built space	Video data collection lacks immersion, limiting the capture of minor sensory responses
3	2014	Social influence in a virtual tunnel fire - Influence of conflicting information on evacuation behaviour [38].	(1) Evacuation behavior	Author has stated the limitation of realism of simulation, although the rendering of smoke is created over the screen. Therefore, It is lacking physiological responses
4	2015	Towards understanding end-user lighting preferences in office spaces by using immersive virtual environments [54].	(1) Lighting intensity with respect to the reading task (2) Opening/closing blinds (3) Turning on/off light bulb	People's preferences may differ on the basis of individual differences (e.g., mood, gender, and personality)
5	2015	Immersive virtual environments, understanding the impact of design features and occupant choice upon lighting for building performance [43].	(1) Lighting intensity (2) Occupant lighting use behavior with respect to natural and artificial lighting operation	Design features influence the participants' behavior specifically in case of lighting source
6	2015	A virtual reality integrated design approach to improving occupancy information integrity for closing the building energy performance gap [11].	(1) Lighting switch control	Advanced VR devices and human–machine interaction technologies need to be worked on
7	2016	LumiSpace: a VR architectural daylighting design system [40].	(1) Scale (2) Distance	
8	2017	The impact of lighting simulation discrepancies on human visual perception and energy behaviour simulations in immersive virtual environment [42].	(1) Lighting intensity	Discrepancy in in situ and IVR lighting environments in terms of illuminance level
9	2018	Spatial-temporal event-driven modeling for occupant behavior studies using immersive virtual environments [86].	Using sensors: (1) Occupancy pattern (2) Lighting status (3) Lighting intensity (4) Air temperature (5) Relative humidity Using IVEs: (1) Interaction with lighting fixtures (2) Window blinds (3) Lighting choice (4) Intensity of light	Consideration of participants' physiological and psychological conditions during experiments
10	2018	Enhancing the prediction of artificial lighting control behavior using virtual reality (VR): A pilot study [49].	(1) Blind (up/down/open/close) (2) Occupancy (yes/no) (3) Break time (none/short/long) (4) Outdoor light level (dark/normal/bright)	VR data using the Baum–Welch algorithm could introduce bias
11	2020	Applying the Gaussian Mixture Model to generate large synthetic data from a small data set [87].	(1) Illuminance level	Small sample size due to limitations of technology

Table 3: Continued.

Sr. no.	Year	Research study	Type of data collected	Potential challenges and limitations
12	2021	Analyzing occupants' control over lighting systems in office settings using immersive virtual environments [83].	(1) Illuminance level	Limited control options during experiment
13	2021	Validating game engines as a quantitative daylighting simulation tool [88].	(1) Luminous level data	Advancement of hardware, real-time ray tracing
14	2022	A calibration methodology for light sources aimed at using immersive virtual reality game engine as a tool for lighting design in buildings [89].	(1) Luminance distribution in Unreal Engine 4 (UE4) and DIAlux	Complexity in calibration of UE4
15	2022	A novel approach for occupants' horizontal and vertical movement modeling in non-residential buildings using Immersive Virtual Environment (IVE) [90].	(1) Occupants' movement pattern (horizontal and vertical)	Validity of IVE-based experiments and modeling

(3) Researchers have used various emerging technologies to map behavior, depending on the data type, context, and collection method. However, until 2002, there was minimal support from technologies for conducting behavior mapping in indoor environments, and direct observation was the only approach available. Research in this direction is still lacking and seeks technological empowerment; therefore, IVE has been taken by researchers hand by hand

(4) The current research trend of behavior mapping using IVE is focused on lighting design for improved building energy performance. Researchers examine lighting intensity, control, and movement patterns, but validation is hindered by various limitations of IVE

4. Bibliometric and Mapping Analysis

A bibliometric study is performed to investigate dissemination and research findings of behavior mapping in IVE. Additionally, mapping analysis has been used to visualize the structure and relationships within a field of study. It consists of five steps, including publication and citation-related analysis, keyword co-occurrence and coauthorship analysis, and prolific author and their work.

4.1. Publication-Related Analysis. In Figure 6, the annual publication trend of behavioral research using virtual reality shows that the publication trend fluctuates highly on yearly bases, whereas it shows a growth in the publication and author count. The first attempt was made in 1996 by publishing the article titled "Sculpting 3D worlds with music: advanced texturing techniques." It discusses a different approach to using sound in virtual environments, including controlling object behaviors in a computer-generated virtual environment [24]. In contrast, a notable publication in this field emerged in 2006 with the article "Integrating video tracking and virtual reality in environmental behavior study," which demonstrated a clear and effective approach to incorporating video tracking and virtual reality in environmental behavior [93]. Howbeit, the number of publications specifically focusing on behavior study in virtual reality is still unsatisfactory and out of the context of the built environment. Nonetheless, the growing publication is promising, suggesting that an increase in research will continue in the near future. To support this claim, a simple linear regression model was built. The results reflect an adjusted R-square of 0.63 with a standard error of 2.39.

4.2. Citation-Related Analysis (Total Citations and Average Citations). In this analysis, the impact of a publication is evaluated by examining the number of citations it receives, providing valuable insights into influential publications within a specific research field [94]. Figure 7 highlights the highest total citation count in 2018 (273 citations) and the average highest citation count in 2002 (61 citations). Notably, the year 2010 also stands out for its citation count per publication, with the article titled "Differentiating malware from cleanware using behavioral analysis" receiving the highest citation count (144 citations) [95]. Additionally, the paper "Data collection methods for studying pedestrian behavior: A systematic review" published in 2021 has received the highest number of citations (33 citations) for behavior studies in virtual reality [96].

Furthermore, it is to note that citation-related analysis has few limitations, such as potential biases, variations in citation practices across disciplines, and the dynamic nature of citation counts over time.

4.3. Keyword Co-occurrence Analysis. The software name VOSviewer has been used to generate a keyword co-occurrence network by using author keywords. Author keywords are extensively used by researchers for identifying

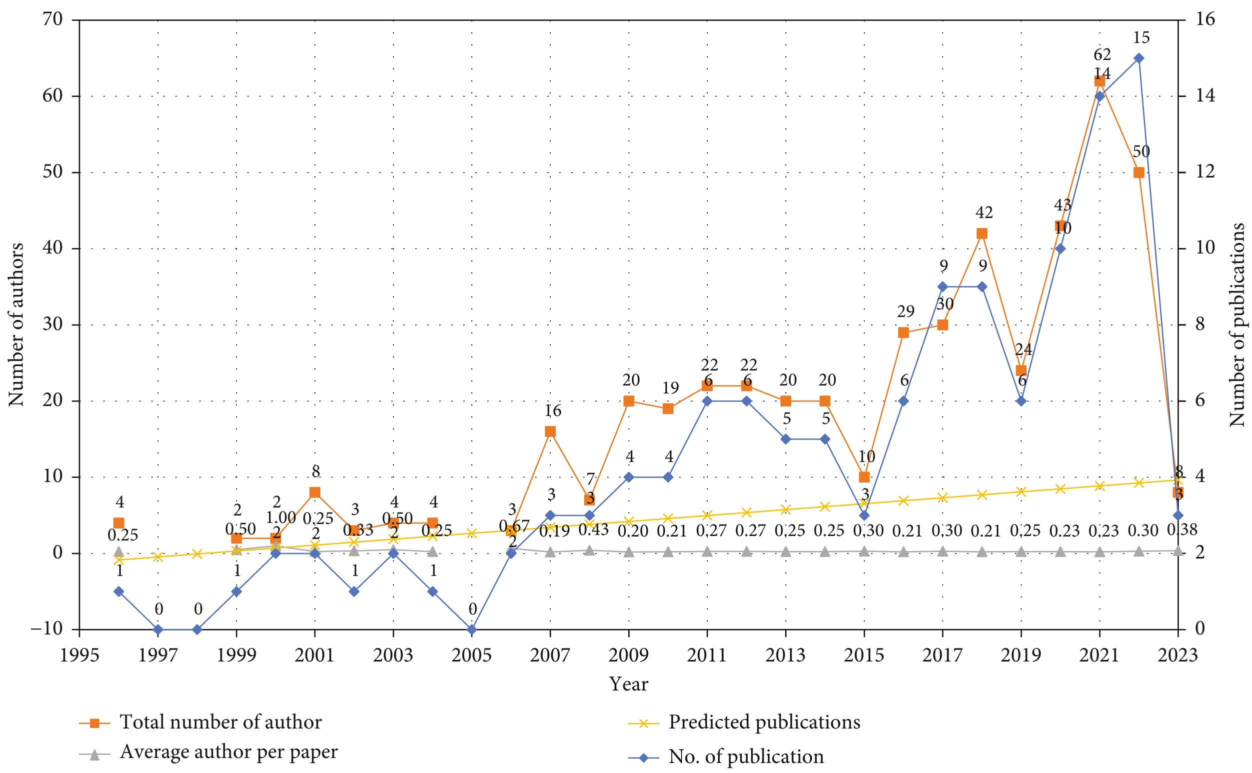

Figure 6: Publication count, author participation (total authors and average authors per paper) from 1995 to 2023, and future publication trends.

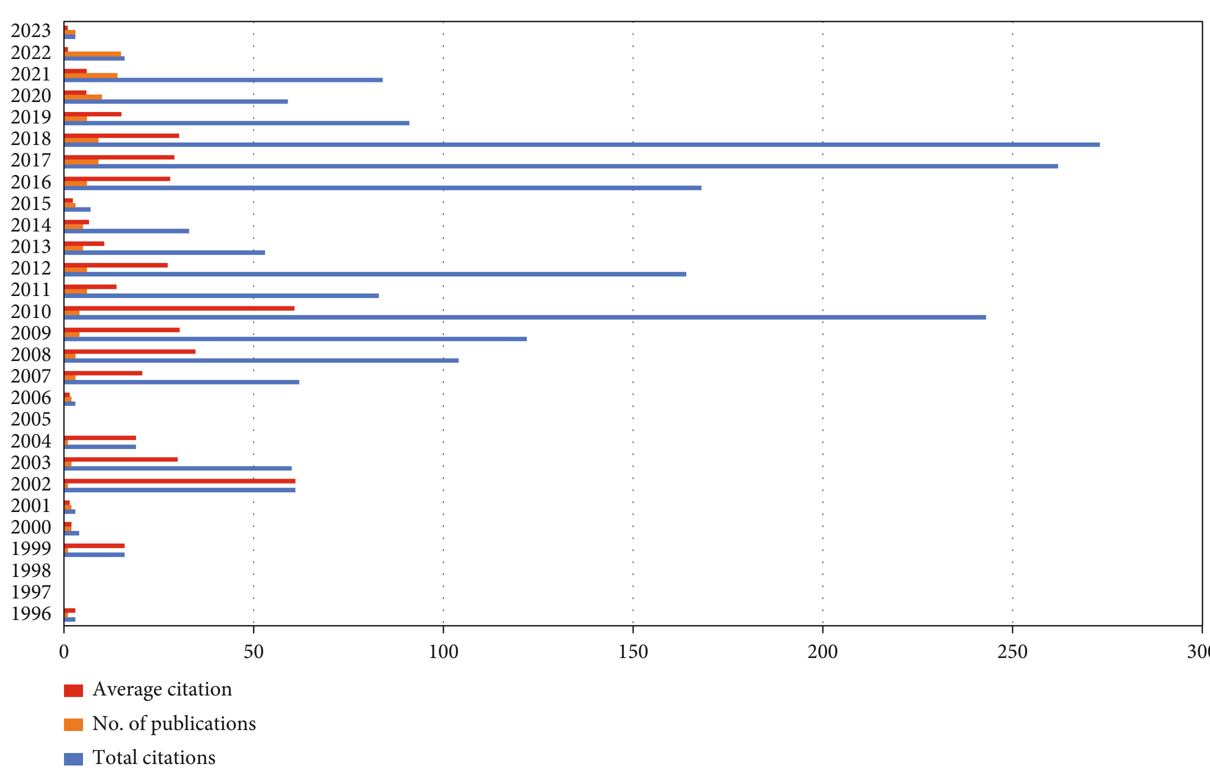

Figure 7: Citation trend of behavior study in virtual reality.

connecting research domains [14]. In the VOSviewer network, the map distance between two items indicates relational strength, with a smaller distance depicting a stronger relationship. The bubble size of the indicated keyword indicates the frequency of the terms in relevant publications [97].

The keyword co-occurrence network map consists of different clusters, which indicate the relationships or associations between keywords based on their co-occurrence patterns. It helps in identifying the pattern of collaboration between different research domains. Degree centrality is a network metric that quantifies the number of direct connections (edges) a node has with other nodes in the network. Nodes with higher degree centrality possess a greater number of connections, indicating their centrality in terms of the volume of direct linkages with other nodes. Degree centrality is a straightforward and commonly utilized measure that provides insights into a node's popularity or significance within the network [14]. The average year of publication indicates that the research related to the keywords is more recent, while a lower average year of publication may suggest that the research is older or has been conducted over a longer period of time. It can provide insights into the level of impact or influence of the research related to the keywords being studied. A higher average citation count may indicate that the research related to the keywords has been highly influential and well cited by other researchers, while a lower average citation count may suggest that the research has received less attention or recognition [97].

As noted earlier, behavior mapping in IVE received limited attention, as the Scopus search yielded only 123 relevant articles. From the 123 articles, a total of 423 keywords were found using fractional counting. The "minimum number of occurrences" was set to 2, a threshold met by 44 keywords. The resultant network 13 comprised 13 numbers of clusters and the top 35 keywords in Figure 8 based on degree centrality.

Key findings are discussed based on the visual representation in the network map, degree centrality, average publication year, and average citations (Table 4).

(i) First, "Virtual reality" is the top keyword in terms of the highest network connections and has three cluster connections, including "behavioral analysis," that show the strongest link strength among all the clusters. Degree centrality is also the highest among all the connecting research areas

(ii) Second, the average year publication shows that the literature review in this area of research is the most recent. However, the "virtual reality" and "behavioral analysis" research domains are also the latest in research trends

(iii) Third, "Functional magnetic resonance imaging' is a keyword that received the highest average citations, followed by "HCI" and "exterior interaction." This shows that the studies in these domains are highly influential

4.4. Prolific Authors and Their Work. The researchers Saeidi, Sanaz, Zhu, and Yimin were found to be the most prolific authors in the field of IVE and behavior mapping, with each receiving a total of 27 citations individually. Additionally, Saeidi and Sanaz coauthored four articles with Zhu and Yimin. Figure 9 shows the top 10 authors ranked by total citation counts. Other prolific authors in the figure are distinct from the research domain of this study.

4.5. Coauthorship Analysis. In generating a network map, fractional counting has been used for 123 articles retrieved from the Scopus database. A minimum number of authors have been set to 2. Through the process, VOSviewer shortlisted 31 authors and generated 11 scattered clusters due to limited research and weak collaboration. Within the identified clusters, a sole cluster is dedicated to research on the built environment. Notably, Zhu emerges as a prominent contributor with a total of 5 documents, while Saeidi closely follows with four documents. Interestingly, these two researchers have collaborated and jointly published four articles together. Furthermore, Chokwitthaya has collaborated with Zhu and Saeidi as coauthors in two published articles (refer to the highlighted cluster in Figure 10).

The primary findings of the bibliometric study are as follows:

(1) Until 1994, behavior mapping research was predominantly confined to the medical domain, as evident in Figure 4. However, bibliometric analysis with respect to indoor environments shows that relevant keyword searches do not yield equitable contributions in citations and coauthorship. Notably, behavior mapping using immersive virtual environments (IVE) lacks top-cited articles and exhibits weak coauthorship clusters (Figure 10), highlighting the need for increased research attention. Moreover, the publication trend line, characterized by a shallow slope, further emphasizes the necessity for research attention in this area (Figure 6)

(2) IVE technology is recent in behavior mapping research, wherein researchers have encountered various obstacles (Table 3) However, the degree centrality of virtual reality and behavioral analysis shows strong popularity within the network (Table 4)

(3) Research on behavior mapping with IVE is limited and primarily focused on lighting design for building performance analysis. However, these studies are aimed at overcoming the challenges of using IVE, including calibrating the system in real-world scenarios and establishing a universal framework for adaptation

5. Discussion and Future Directions

This study comprehensively reviews the progression of "behavior mapping" and its utilization in data acquisition within the built environment. Additionally, it tracks the trajectory of scholarly endeavors that have embraced cutting-

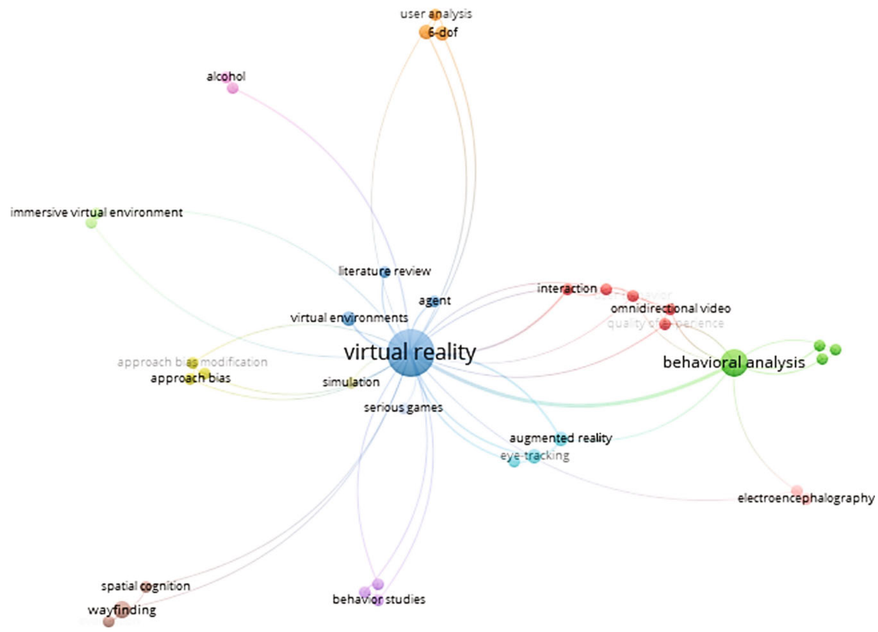

Figure 8: Main research areas of behavior mapping in IVE (co-occurrence network of keywords).

edge technologies. As a result, the investigation concentrates on the identification of publication patterns and forthcoming prospects in the field of immersive virtual environments (IVE) technology, which has garnered increasing attention relative to alternative technologies. This section furnishes an exhaustive summary of insights gleaned from the literature review and bibliometric analysis, concurrently discerning the voids within the existing literature, thereby guiding future research endeavors.

Question 1: How has the evolution and advancement of various technologies influenced behavior mapping research in the built environment?

Before the evolution of technological support, researchers exclusively relied on manual direct observational methods, employing pen and paper, to specifically acquire nonverbal and agitated behavior data from elderly individuals. This trend is evident in research conducted between 1976 and 2002, with a predominant focus within the medical domain for behavioral studies. Notably, the inception of behavior mapping in the built environment can be traced to Shepley's 1995 study within medical indoor environments, which employed questionnaires, interviews, and direct observations for data collection. After 2002, the evolution of technology significantly reshaped behavior mapping research. Initially, researchers utilized direct observations, interviews, and video recordings (as technological support) for data gathering indoors until 2011. However, the introduction of advanced technologies such as geographical information systems (GIS), global positioning systems (GPS), sensors, and unmanned aerial vehicles (UAVs) enabled more precise and comprehensive data collection. The first GIS-based research was performed in 2007, albeit limited to outdoor applications. Beyond 2015, a multitude of technological interventions emerged, encompassing immersive virtual environments (IVEs), extensive utilization of videography and photography, sensors, and software. These technologies enable the collection of movement data, spatial analysis, and study of behavior–environment interactions. Furthermore, integrating technologies with behavior mapping research has expanded the scope of investigations to urban and outdoor spaces and indoor settings.

Question 2: In what ways have different technologies been used for collecting behavior data in the built environment?

Behavior mapping, traditionally relying on direct observation, interviews, and questionnaires, is being complemented by technological advancements, enabling more reliable data collection in the built environment. The pedometer was the first instrument used in 2002 as technological support to gather step count data. After that, in 2007, the geographical information system (GIS) facilitated the collection, organization, analysis, and visualization of spatial data in urban and public spaces. GPS integration with GIS allowed the capture of movement data in outdoor environments. However, RFID was also employed for research in 2011 to gather data on occupant flow and time taken. Furthermore, sensors, such as Wi-Fi, Bluetooth, and ultrawideband, have been utilized later to collect movement data in indoor settings. Filming as technological support paced up in 2021, although photography has used extensively with other methods in the data collection approach. However, unmanned aerial vehicles (UAVs), focus groups, and specialized software tools such as Depthmap and SOPLAY have also been employed for physical activity data collection and analysis in urban contexts. Nonetheless, immersive virtual environments (IVEs) are emerging as a sophisticated approach to capture human behavior within prospective built spaces, enabling the detailed examination of microlevel actions. Existing research shows that IVEs capture data related to emergency evacuation, wayfinding, actions taken

Table 4: Top 37 behavior mapping/study areas in IVR.

Research areas	Cluster	Degree centrality	Average year publication	Average citations
Virtual reality	3	29	2018	16.0
Behavioral analysis	2	9	2019	12.0
User behavior	1	5	2015	22.0
Omnidirectional video	1	4	2018	46.0
Quality of experience	1	4	2018	46.0
6-dof	7	3	2021	1.3
Approach bias	4	3	2021	5.0
Approach bias modification	4	3	2021	5.0
Augmented reality	6	3	2018	12.3
Behavior operation management	2	3	2017	3.0
Behavior studies	5	3	2017	50.0
Cigarette smoking	4	3	2021	5.0
Evolutionary game	2	3	2013	0.5
Exterior interaction	5	3	2017	50.0
Eye tracking	6	3	2019	13.7
Grouped bid evaluation	2	3	2017	3.0
HCI	5	3	2017	50.0
Point cloud	7	3	2021	1.3
User analysis	7	3	2021	2.0
User study	1	3	2011	6.5
Virtual environment	10	3	2017	4.0
Wayfinding	8	3	2018	33.3
Emotion	6	2	2018	1.5
Functional magnetic resonance imaging	9	2	2014	67.0
Immersive virtual environment	11	2	2020	14.0
Interaction	1	2	2015	19.0
Occupant behavior	11	2	2020	14.0
Spatial cognition	8	2	2013	12.0
Agent	3	1	2009	15.5
Alcohol	9	1	2013	38.5
Electroencephalography	10	1	2017	1.0
Evacuation	8	1	2016	47.5
Literature review	3	1	2022	17.0
Serious games	12	1	2021	8.5
Simulation	13	1	2014	15.5
Virtual environments	3	1	2018	0.7

for visual comfort, physiological and physiological responses, and movement in designated spaces only.

Question 3: What are the current trends and hotspots in behavior mapping research in the context of IVEs?

The bibliometric study demonstrated the research on behavior mapping, and IVE has grown irregularly, but publication prediction suggests that growth will be slow and steady in the near future. Citation analysis has revealed cross-citations among a few researchers working on IVE in indoor built environments, with a maximum citation count of only 28. It also discloses "virtual reality" and "behavioral analysis" as research hotspots. It is worth noting that the average year of publication indicates that the research area is relatively recent. Similar findings can be observed when tracing the literature, which shows that the first publication on behavior mapping in indoor spaces using IVE as a data collection tool was in 2015.

Question 4: What are the potential unexplored research paradigms and future directions for behavior mapping and immersive virtual environments (IVEs) in the setting of the built environment?

The literature reveals several future directions and potential research areas in behavior mapping utilizing IVE technology within the built environment. These include addressing the research gap in this field, focusing on building performance analysis, investigating occupant behavior

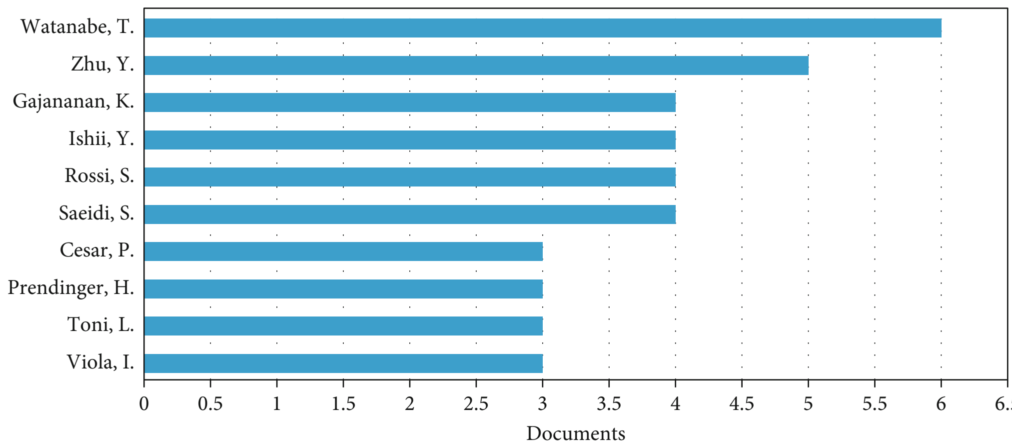

Figure 9: Prolific authors (source: Scopus database analysis).

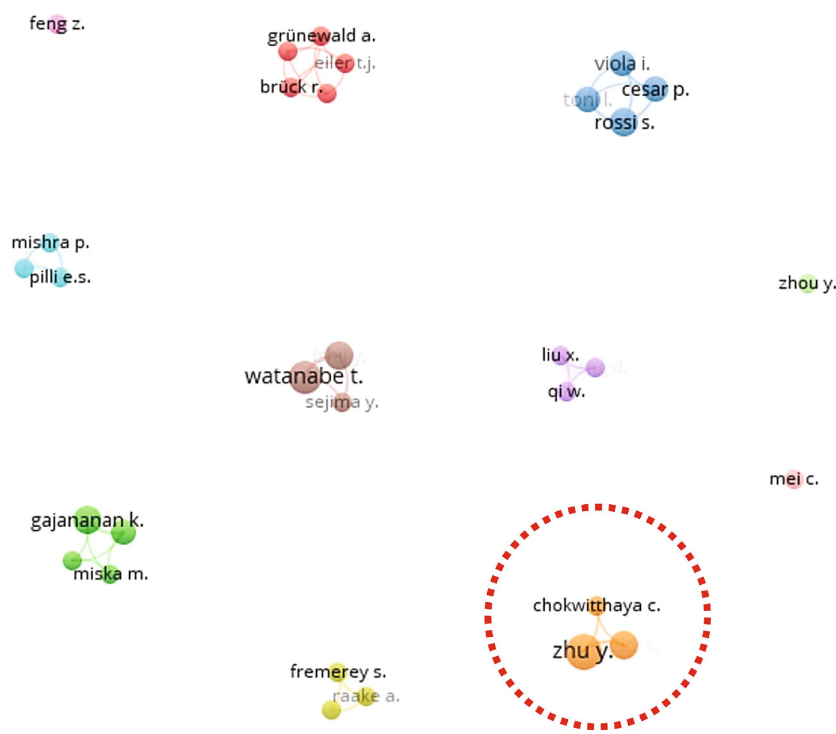

Figure 10: Coauthorship network map.

patterns, exploring lighting and thermal aspects, validating the effectiveness of game engine-based renderings, and studying the integration of IVE technology for energy-efficient design and occupant comfort. A thorough review of extant research further reveals significant challenges and limitations intrinsic to IVE implementation in behavior mapping studies. Notable issues include the precise calibration of IVE systems for assessing lighting, acoustical, and thermal perceptions within the virtual realm. Existing studies, for instance, reference the "pixel inspector" method for lighting calibration, which may inadequately represent illuminance levels on the working plane [89]. In thermal studies, respondents' reactions are gathered by exposing them to various color temperature scenarios, which may not accurately capture the nuanced psychological facets of human thermal behavior [84]. There are other limitations, including technological capabilities with respect to the type of behavioral data collection. Therefore, the researchers must assess the technological capabilities of opted data collection methods. However, it is important to note that IVE has certain limitations in its process of data collection itself, including small sample size [49] and its development as a simulation engine for "building performance analysis" [88]. These limitations pose significant obstacles and require careful attention from researchers.

Furthermore, virtual reality (VR) research provides a secure and economical approach, enabling the replication of studies while offering extensive control over the presented scenarios. VR technology facilitates the creation of intricate built environment scenarios within the confines of a controlled laboratory, guaranteeing a safe experimental environment and granting researchers full control over the variables involved [90]. This research contributes in terms of integrating behavior mapping and IVEs to explore new ways of studying human behavior in the indoor built environment. This study outlined the research performed over time and torch light on partially hidden obstacles in using IVE for research on behavior mapping.

6. Conclusion

Research demonstrates a shift in technological adaptation and methods for behavioral mapping from neurological research to urban and outdoor environments to indoor built spaces. Similarly, the use of different technologies for behavioral data collection in diverse contexts and the emergence of IVE technology can be marked. The research findings indicate a notable absence of established linkages between IVE technology and behavior mapping within the built environment, whereas IVE studies offer cost-effectiveness, replicability, safety, and maximum control over scenarios, enabling the creation of complex built environments in controlled laboratory settings. Consequently, researchers have initiated investigations in this direction in recent years, yet the correlation remains significantly tenuous. Hence, this research strongly advocates researchers' attention to IVE use and development for behavioral studies.

Overall, this study is aimed at drawing the attention of researchers toward future endeavors that focus on identifying solutions to mitigate obstacles, specifically real-world calibration of computational environments and development or simplification of existing frameworks to adopt IVE for behavioral data collection.

Data Availability

Data will be made available on request.

Conflicts of Interest

The author declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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