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The Cognition of Smart City Design and its Own Research Direction

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ABSTRACT

Rapid Urbanization has intensified challenges related to efficiency sustainability, and quality of life, exposing limitations in technology-centric smart city models that insufficiently address human cognitive needs. This study aims to examine how integrating cognitive, human-centric design principles with advanced technologies- specifically the Internet of Things (IoT), Artificial Intelligence (AI), and Big Data Analytics-can enhance smart city performance and livability. Using a systematic review of interdisciplinary literature combined with comparative case analysis, the study evaluates smart city applications across core domains including smart infrastructure, mobility, energy, health, and governance. Methodologically, the research contributes urban design frameworks with AI-driven urban systems, offering a structured analytical lens that links human behavioral patterns with data-intensive technologies. Findings significantly improve real-time urban decision-making through applications such as traffic forecasting, predictive maintenance, waste management, and predictive policing. Empirical evidence from global case studies shows measurable impacts, including an 18% improvement in travel efficiency in Shanghai, a 22% reduction in waste management costs in Copenhagen, a 15% decrease in crime rates in Singapore and a 30% reduction in energy distribution losses through AI-enabled smart grids. The study concludes that cognitively informed that cognitively informed, AI integrated smart city designs not only optimize urban efficiency but also sustainability. These insights provide practical implications for policymakers and urban planners seeking scalable, human-centric smart city solution.

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1. Introduction

Smart cities are a giant leap into the future of urban development replete with technology integrated with what we know as traditional urban design to become adaptive and sustainable. The Internet of Things (IoT), big data analytics, and Artificial Intelligence (AI) are essential for creating urban services and quality of life for citizens (Kirimtat et al., 2020) in these cities. There are, however, still technologies that can feed into the development of smart city projects, but it should not be done in the absence of understanding how interactions of individuals and systems within these complex urban environments occur (Stübinger & Schneider, 2020). The designs of urban design that promote the human-centered approach, imply interaction between the smart system and human behavior and the societal needs. Finally, we provide some cognitive aspects related to smart city design and provide research directions about future urban development.

Figure 1: Designing Smart Cities: A Human-Centered Approach of Masdar City


Source: (Andreani et al., 2019)

1.1. Smart Cities and Cognitive Cities

The Differentiation While the terms smart cities and cognitive cities are commonly used interchangeably by the broader urban community in recent times, they are different, yet complementary, paradigms. Smart cities mainly focus on the technological optimization of the urban systems with the use of digital infrastructure, Internet of Things (IoT), big data analytics, and artificial intelligence (AI). Their fundamental goal is to enhance efficiency, sustainability, and service delivery using real-time data and automated decision-making systems (Appio, Lima, & Paroutis, 2019); (Kirimtat et al., 2020). In contrast, cognitive cities go beyond the intelligence of technology and take into consideration human cognition, perception, and behavior as key motives for design. Cognitive cities are not only data-driven environments but sense-making environments, in which urban systems learn, adapt and react to human cognitive patterns such as wayfinding, risk perception, decision-making and social interaction (Kashef, Visvizi, & Troisi, 2021). Whereas smart cities pose the question "How can technology optimize urban systems?" cognitive cities pose the question "How do humans perceive, interpret and interact with these systems?" This distinction is of crucial importance in the present study.

Rather than only dealing with technological smartness, this paper is an attempt to make cognitive city design a human-centered evolution of smart cities, which emphasizes more on urban legibility, behavioral adaptation and intuitive interaction between people and intelligent systems. Smart Cities as a Technological Paradigm Smart cities have become a dominant response to urbanization at a very fast pace, environmental stress, and infrastructural inefficiencies. Through the combination of IoT, artificial intelligence, and big data analytics, smart cities can expect to improve their mobility, energy efficiency, governance transparency and service delivery (Khan et al., 2020); (Silva et al., 2018). Empirical studies show that the use of data-driven traffic management, smart grids, and digital governance platforms can go a long way in decreasing congestion and energy loss, as well as administrative inefficiencies (Nikitas et al., 2020);(Farmanbar et al., 2019). However, despite these advancements in technology, many smart city initiatives are still technocentric in their nature and fail to consider the way citizens cognitively experience and adapt to these systems.

1.2. Cognition and Human Centered Urban Design

Cognition in urban design is the way that individuals perceive, navigate, interpret and emotionally respond to the built environment. Inspired by cognitive psychology, environmental behavior studies and the field of human-computer interaction (HCI), cognitive urbanism pays attention to legibility, intuitive navigation, perceived safety or behavioral feedback loops (Dasgupta et al., 2019); (Barr et al., 2021). When applied to smart cities, cognition allows design of environments that will be not only efficient, but also understandable, inclusive, and psychologically responsive. AI-driven traffic systems, participatory digital platforms and adaptive public spaces are the ways in which the precepts of cognition make the intelligence of technology became lived in the city (Kashef, Visvizi, & Troisi, 2021).

1.3. Research Gap and Objectives

Although there are several researches that talked a lot about smart technologies, fewer studies investigate the systematic combination of cognitive theory into smart city design frameworks. The lack of conceptual clarity between smart and cognitive cities also adds to the scholarly obfuscation. This study fills this gap by: Conceptually differentiating smart cities and cognitive cities; Looking at the role human cognition plays in intelligent urban design decisions; Studying real world cases that illustrate principles of cognitive design; and Proposing a research framework for future cognitive smart city research.

1.4. Background and Importance of Smart Cities

Figure 2: Cognitive Cities: Advancing Smart Cities-X Infrastructures

Source: (Al Nuaimi et al., 2015)

1.5. Cognition in Urban Design

It examines how people sense, understand, and make urban environments. In the context of a smart city, cognitive urban design attempts to generate an intuitive interface and environment, that lives and nurtures user demands (Kashef, Visvizi, & Troisi, 2021). Examples of this are the AI traffic systems that predict and regulate traffic jams based on driver patterns (Ullah et al., 2020). It also makes it possible to design safer and more inclusive urban spaces (Barr et al., 2021). Cognitive approaches bring in the participatory design, where citizens supply insights into the urban planning process to create communities that experience a piece of them, they belong in (Falanga, 2020).

1.6. Objectives and Structure of the Report

This Report is written to explore the cognitive aspects involved in smart city design and outline further research opportunities for smart city development. The specific objectives are stated as: (1) To explore the foundational principles and evolution of smart cities. (2) To examine the role of cognition in smart city design and systems (3) To identify challenges and propose solutions for cognitive urban design. (4) To present actionable recommendations for future research.

2. Smart City Design: Key Concepts and Cognitive Aspects

2.1. Core Components of Smart Cities

These are smart cities that want to enhance the life of an urban region by using various new technologies to improve the way of administering the required resources and services, urbanization, etc. In other words, smart infrastructure, smart mobility, smart energy, smart healthcare, and smart governance are the core components that are complemented (Appio, Lima, & Paroutis, 2019). For instance, smart infrastructure consists of sensors and intelligent systems in the management of public amenities such as water, and electricity as well as waste management that enhances efficiency and sustainability. Transportation networks use live information to facilitate smart mobility systems to reduce traffic congestion, improve road safety, and encourage courtesy options in transport (Nikitas et al., 2020). Smart grids and renewable energy sources are implemented for energy supply having high energy efficiency and the highest level of reliability and sustainability (Farmanbar et al., 2019). The quality and access to healthcare have been improved by telemedicine and digital health solutions for healthcare services. Finally, smart governance is performed through digital platforms to improve transparency, elevating citizen participation levels and other aspects of public service delivery (Pramanik et al., 2017).

Figure 3: Smart Governance for Smart Cities

Figure 4: Smart Cities Components

Source: (Sanad et al., 2024)

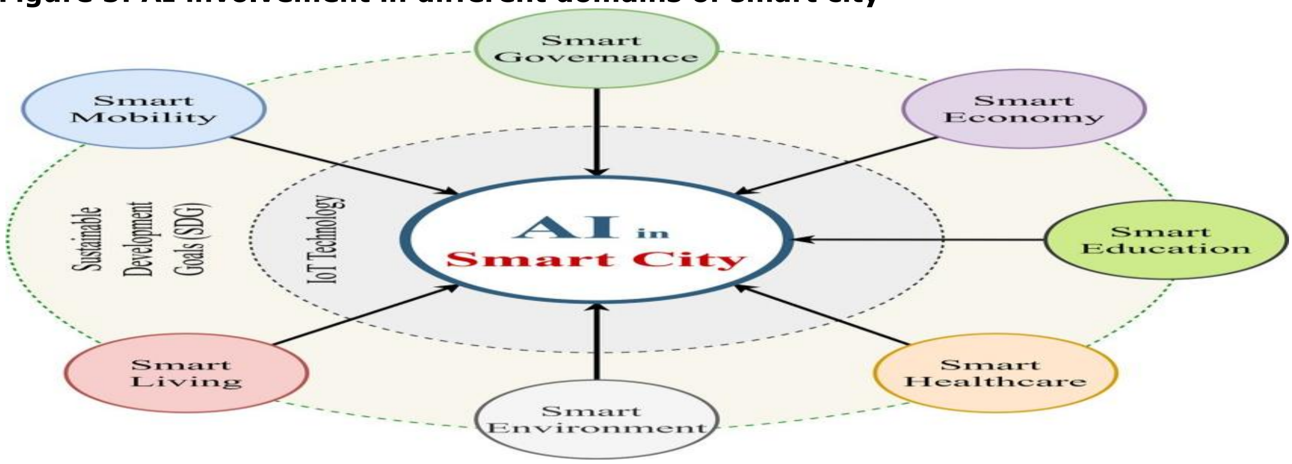
2.2. Human-Centric and Cognitive Design Principles

Human-centric design principles in smart cities aim to create lives and living spaces that are one for the citizens of the smart cities. Human behavior is included as a part of the cognitive principles of design when planning to make the city's systems simple and understandable to the user through the discipline of urban planning (Andreani et al., 2019). In this context, an approach is encouraged that allows the environments in which people may easily interact with technologies and cities to evolve. Therefore, it is essential to understand how people perceive and respond through the urban environment, in which the aim is to enhance accessibility and security; and user experience (UX), an urban design strategy. For instance, smart city' cognitive urban systems adapt to individual's ways/preferences and serve as an interface through interactions between the users and the sources to provide individualized services such as transportation scheduling or environmental control (Elahi et al., 2021). Human-centric designs are achievable design when there is an understanding of the psychology of human cognition and urban sociology to suitably and properly design a technology that is context-sensitive and human-centric.

2.3. Role of Technology and AI in Urban Environments

Artificial Intelligence makes technology an important factor in making conventional urban environments smart. The capability of AI systems to assist cities to function in real-time such as traffic management, energy distribution, public safety, and more on their autonomous systems (Katal, 2024). Urban transportation employs AI-powered systems for traffic forecasting used in traffic signal algorithms of machine learning to predict traffic patterns thus reducing carbon emissions (Ponnusamy et al., 2024). It is also used for predictive maintenance; predictive maintenance aims to predict the failure of infrastructure, such as roads, bridges, and power lines before failure, hence minimizing downtime and extending the asset life (Van Hoang, 2024). Furthermore, it is also capable of maximizing public safety by analyzing immense volumes of data gathered by surveillance cameras and sensors (Srivastava, Bisht, & Narayan, 2017), making discoveries in terms of crime patterns and accident prediction. The smart cities made by using AI have created smart cities that adapt to changes in the challenges and are extremely near to the real scenarios.

Figure 5: AI involvement in different domains of smart city



Source: (Herath & Mittal, 2022)

2.4. Data Analytics and Decision-Making Frameworks

Data analytics are used for decision-making in smart cities. By collecting large amounts of data through sensors, devices, and other connected technologies, smart cities can make data-driven decisions to enhance urban living (Karimi et al., 2021). The data-driven approach provides the ability to observe the traffic flow, the energy consummated, and air quality among other data in real-time, which can be useful in decision-making Predictive analytics in the cities can be used to predict the events that are likely to happen in the future by studying their trends and patterns and then planning rather than tackling the event (Silva et al., 2018). Moreover, various machine learning algorithms are employed to handle the historical data and operate the systems, such as street lighting, water distribution, and waste collection, among others, as efficiently as possible (Hui et al., 2023). Despite this, such decision–making frameworks considerably rely on big data and AI fusion to enhance both the predictive accuracy and efficiency in allocating available resources to required places. In this way, the data analytics influence the strategic planning and process efficiency in the smart cities (Shahat Osman & Elragal, 2021).

3. Research Methodology

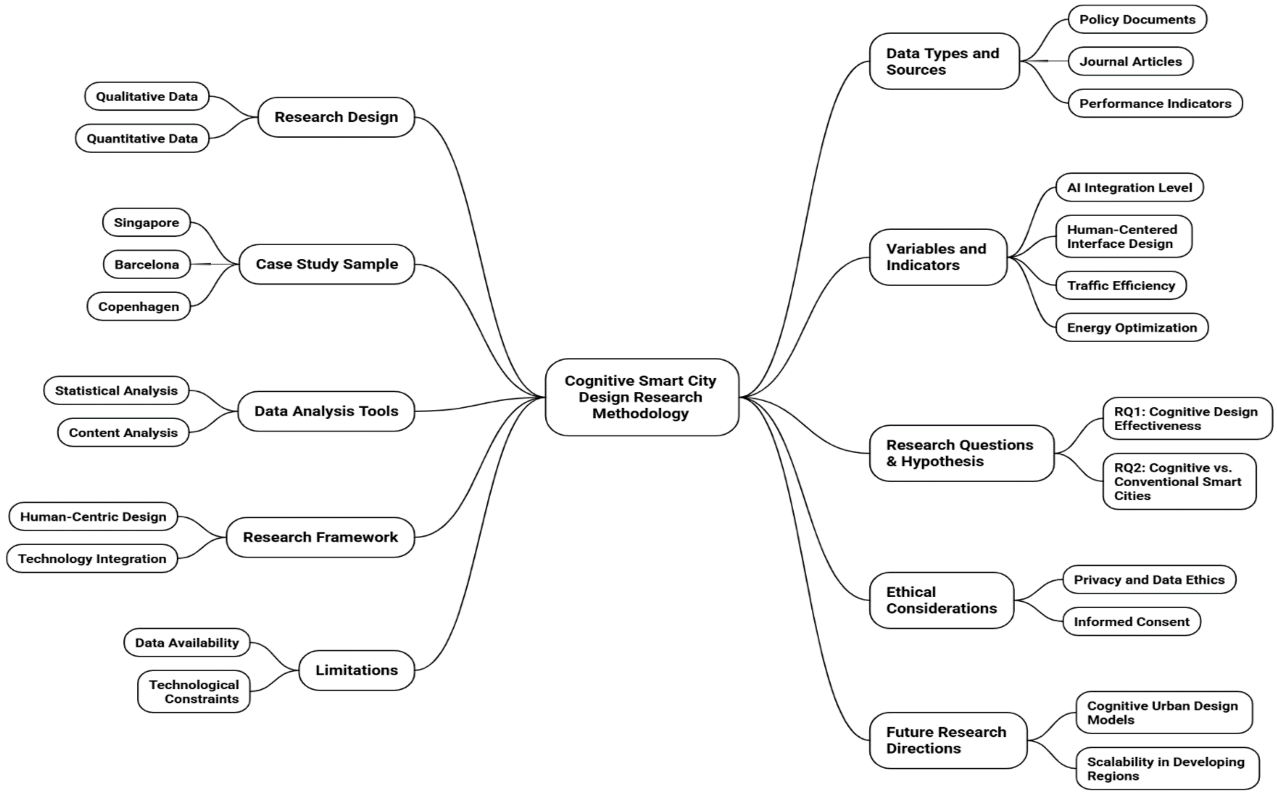
3.1. Research Design

This study takes a mixed method exploratory research design, which is appropriate for exploring new issues like that of cognitive smart city design. The method combines qualitative and quantitative data to investigate performance of the technology and cognitive interaction among humans. Data Types and Sources Qualitative data: Policy document and planning reports Peer reviewed journal articles Semi-structured interviews (secondary sources) of urban planners and smart city expert's Quantitative data: Secondary performance indicators (traffic reduction %, energy efficiency gains, rate of crime reduction) Data sets related to benchmarking Smart cities from academic and governmental publications. Case Study Sample Three cities (Singapore, Barcelona and Copenhagen) have been selected based on: Advanced smart city maturity Explicit integration of human centered or adaptive systems Accessibility of peer reviewed empirical data These cities are examples of best practice cognitive design environments and not generalized smart city examples. Variables and Indicators Independent variables: AI integration level Human centered interface design System cognitive flexibility Dependent variables: Traffic efficiency Energy optimization Public safety outcomes User experience indicators. Data Analysis Tools Statistical analysis with the help of the statistical software (SPSS) for the quantitative indicators Thematic content analysis on qualitative sources Cross-case comparative analysis to find cognitive design patterns Research Questions & Hypothesis. The cognitive smart city design research methodology is shown in Figure 6.

3.2. Case Studies

A comprehensive analysis of global smart cities (e.g., Singapore, Barcelona, Copenhagen) where cognitive elements in design (like AI-powered traffic systems, smart grids, etc.) have been implemented. Data from city reports, academic papers, and interviews with urban planners will be used**.** The chosen cities provide a good example of cognitive design through the measurable city's assize human system interaction outcomes. Singapore's predictive policing combines behavioral analytics, Barcelona's water management system adjusts to consumption patterns while Copenhagen's waste management optimizes routes based on human activity cycles. Collectively these cases show the presence of cognition-driven adaptability and not simply technological deployment.

Figure 6: Cognitive smart city design research methodology



3.3. Research Framework

3.3.1. Human-Centric Design

The research will explore human-centric design principles and cognitive theories to understand how these can be applied to smart cities. This framework will assess how urban spaces can be designed to align with human cognitive abilities, enhancing usability, accessibility, and safety.

3.3.2. Technology Integration

The integration of AI, IoT, and data analytics into urban infrastructure will be a focal point of the research framework. The study will examine how cognitive technology is used to optimize urban operations and improve user experience (McDaniel & Pease, 2021)**.**

3.4. Data Analysis Methods

3.4.1. Statistical Analysis

To assess the impact of cognitive design on smart city performance, statistical analysis tools like SPSS will be used to analyze collected data, such as traffic flow data, energy usage statistics, and safety improvement metrics

3.4.2. Content Analysis

This method will be used to analyze qualitative data from interviews, surveys, and case studies. Content analysis will help identify patterns, themes, and insights related to cognitive design and urban user behavior (Ghasemi, 2015).

3.5. Ethical Considerations

3.5.1. Privacy and Data Ethics

Given the role of data in smart cities, the research will include a review of ethical considerations such as user privacy, data security, and the potential for algorithmic bias in decision-making systems. (Penmetsa et al., 2019).

3.5.2. Informed Consent

Ensuring informed consent for participants in surveys and interviews will be a critical ethical aspect, particularly when dealing with sensitive information about urban residents and their interactions with smart city technologies

3.6. Limitations

3.6.1. Data Availability

Limited access to proprietary data from smart cities might be a challenge, especially about user behavior data or real-time system metrics (Li, Saidi, & Chen, 2020).

3.6.2. Technological Constraints

Variability in the level of technology adoption across cities may impact the generalizability of findings. Some cities may not have fully implemented cognitive technologies, limiting comparative analysis.

3.6.3. Geographic Limitations

The research will primarily focus on cities that have advanced smart city projects, which may not represent the broader scope of urban environments globally (Kamrowska-Załuska, 2021).

3.7. Future Research Directions

3.7.1. Cognitive Urban Design Models

The study will suggest future research into the development of comprehensive cognitive urban design models that incorporate the latest advancements in AI, IoT, and big data analytics. Investigating the scalability of cognitive urban design in developing regions with limited technological infrastructure could be an essential area of future research (Brey, 2004).

3.8. Research Questions and Hypothesis

RQ1 How does cognitive design help to improve the effectiveness of smart city systems?
RQ2: How do cognitive cities differ, or not, compared to conventional smart cities in real life?
Hypotheses H1: Smart cities with the cognitive concept of design show greater user adaptability and system efficiency.
Hypotheses H2: Human-centered AI systems are much better than purely automated systems, in optimizing life perception in cities.

4. Research Directions and Emerging Trends

4.1. AI, Machine Learning, and Urban Innovation

AI and ML could change urban innovation through better, adaptive, and efficient monitoring of infrastructure and services. In the transportation sector, AI is playing a leading part in congestion management. To this end investigated the impact of how an AI traffic system on the roads of Shanghai cuts down travel time by up to 18% with the use of an online learning method to forecast traffic patterns and optimize traffic light cycle (Zhang et al., 2020). The use of ML algorithms in the waste collection by Copenhagen City for instance has reported a 22%

reduction in the cost of waste management through demand predictability and networked collection routes (Ghasemi, 2015). On a second front, they are used in public safety and emergency service, for instance, in Singapore, predictive policing algorithms (that utilize historical crime data) have resulted in a decrease in crime of up to 15% in the two years after she launched them (McDaniel & Pease, 2021). Further, in the domain of energy management, AI-based smart grids can reduce energy distribution losses by 30% effectively by optimizing the electricity demand based on the prediction of weather, historical consumption data, and in real-time (Salvati, Roura, & Cecere, 2017). These advancements help to make a case for the use of AI and ML to help in the creation of a smarter and more resilient urban ecosystem.

Table 1: Impact of AI and Machine Learning in Urban Innovation

S. No	Area	AI/ML Application	Impact
1	Transportation	AI-powered traffic systems	18% reduction in travel time
2	Waste Management	ML algorithms for waste collection	22% cost reduction
3	Public Safety	Predictive policing algorithms	15% reduction in crime rates
4	Energy Management	AI-based smart grids	30% increase in energy efficiency

4.2. Comparative Case Studies of Smart Cities

The smart cities comparative case studies provide an insight into how urban innovation is put in place with different strategies out of those cities. For example, the introduction of IoT devices for this purpose in the case of Barcelona has led to a 17% decrease in water consumption by monitoring real-time consumption patterns (Ocampo-Martínez et al., 2009). However, in London, the city is considering using an app to measure air quality and pollution levels in the new digital platform for citizen engagement. This initiative has empowered citizens to report pollution hotspots; which caused the air quality to improve by 9% in high pollution zones (Hswen et al., 2019). Secondly, in artificial transportation solutions, New York City is also using AI since it is one of the cities that had worsened traffic congestion in the recent past, however, this problem has been reduced to 20% of travel delays in the central areas using real-time predictive algorithms (Van Cuong & Aziz, 2023). Additionally, the city of Dubai also experiments with blockchain technologies for services to the government since it could save 12% of the administrative costs and improve transparency of the public transactions (Khan et al., 2017), The first set of examples demonstrates how smart technologies are being used by cities across the globe in different ways toward differing priorities, to solve city-specific problems.

Table 2: Comparative Case Studies of Smart Cities and Their Impact

S. No	City	Smart Technology Application	Impact
1	Barcelona	IoT devices for water conservation	17% reduction in water usage through real-time monitoring
2	London	Digital platforms for citizen engagement	9% improvement in air quality in high-pollution zones
3	New York City	AI-driven transportation solutions	20% reduction in travel delays in central areas
4	Dubai	Blockchain for government services	12% reduction in administrative costs and increased transparency

Table 2 shows the case studies along with the key applications, impacts, and the source of each of the smart technology cases studied.

4.3. Ethical and Privacy Considerations

Since smart cities have an abundance of data that they need to use to optimize their services, ethical and privacy problems in such cases of data approach are more significant. The collection of personal data, such as location tracking and biometric data, raises significant privacy issues. From the study of (Chang et al., 2022), 38 out of 100 people living in Sejong are uncomfortable as they worry about the privacy that facial recognition systems would be used in the public. In addition to that, there is another ethical problem of data bias as (Kamrowska-Załuska, 2021). Following this Studies also emphasize that 58% of urban smart cities in Europe use fully integrated systems that are in line with GDPR, something peculiar to cases in which citizen's personal information is deemed not safe. In addition, smart cities must consider how surveillance technologies impact the public trust in the administration as smart cities use network technologies. In cities such as San Francisco, the use of AI in public places has become a center of feasible mass law surveillance (Brey, 2004).

Table 3: Ethical and Privacy Considerations in Smart Cities

S. No	Issue	Details	Impact/Concern
1	Privacy Concerns	Collection of personal data (location tracking, biometric data)	38% of residents in Sejong uncomfortable with facial recognition
2	Data Bias	AI-based decision-making systems in public housing	Racial bias leading to unfair targeting of minority populations
3	GDPR Compliance	European Union's General Data Protection Regulation (GDPR) implementation	Only 58% of European smart cities fully comply

The ethical and privacy concern of smart cities is outlined in Table 3 which has the issue (the same case), the impact, and the concern which includes the issue.

4.4. Cross-Disciplinary Research Opportunities

Imbuing a smart city is contingent upon integrating technological advances with societal needs through collaboration among many disciplines. If urban planners, data scientists, environmentalists, and sociologists come together, then only it is possible to make our cities efficient and inclusive. (Kaluarachchi, 2019). This is also true from postulation, which asserts that green infrastructure in smart cities is a case in point and that it is an avenue to which urban planners may evaluate but are not limited to, ecological considerations in the design of smart cities to achieve sustainability. It then helps in the development of more effective climate-resilient solutions such as by using the sensor data, Amsterdam maintains the water level and avoids flood, and decreases damage by 30% from flooding (Peters et al., 2021).

5. Challenges and Future Prospects in Smart City Development

5.1. Technological and Governance Barriers

Some technological and governance barriers are preventing the deployment of smart cities. Many cities in the technical sense do not have the robust and scalable infrastructure to integrate systems such as but not limited to ITS, AI, and Big Data (Anand & Navío-Marco, 2018). Present an argument that the expense of hiring cutting-edge technology for smart city solutions such as smart grids or sensor networks is rather very high for cities in countries generally, and developing economies in particular. Moreover, the incompatibility arises because the earlier urban infrastructure is incompatible with the newer and more advanced ones because of the faster rate of technology evolution. Common governance challenges in the deployment of smart city projects are caused by the multiple players involved like local government, private companies, and citizens (Peters et al., 2021). According to fragmentation of policy frameworks along with inconsistencies of regulations further complicates the smart city initiative implementation, as a city cannot fully leverage smart technology (Kunzmann, 2020).

5.2. Enhancing Cognitive Systems in Urban Design

Urban design is getting increasingly molded by cognitive systems, such as new ways of optimizing city living as our cities become more populated, and with the use of AI/machine learning technologies. According to urban planning, at best, can be improved using these cognitive systems to better allocate resources that is, personalized energy management, public safety, and crowd flow give an AI-enabled instance of using predictive analytics to anticipate and manage environmental issues such as waste management or climate change (Ullah et al., 2020). Another way in which cognitive systems would assist in the decision-making process is by detecting patterns beneath all kinds of the huge information that can assist policy and planning. Furthermore, cognitive systems can be used to increase citizen engagement in design that allows public input to the process to ensure that urban spaces are responsive to the needs of multiple population segments. With the increasing use of data to help run cities, the integration of cognitive systems is believed to greatly impact the generation of more livable and sustainable urban environments (Bibri, 2020).

5.3. Sustainable and Adaptive Smart City Solutions

As a sustainability issue, it must rank high in the priorities of smart cities employing adaptive solutions to ensure long-term viability. The study states that the smart grid system should necessarily involve the utilization of renewable energy sources like solar and wind to improve urban sustainability (Bergsrud & Vaseeharanathan, 2024). Moreover, optimal green infrastructure like urban farming and green roofs are also actively involved in smart city design to counter urban heat island problems and to improve air quality Smart city solutions are an additional need of the city to be resilient against climate change since the smart technologies in use gather real-time information regarding the environmental conditions that will allow the cities to respond to natural disasters and extreme weather events. Similarly, as smart technologies developed, flood prediction and early warning systems are now obligatory for cities that are in flood-prone areas (Popescu, 2022).

5.4. Recommendations for Future Research

Further research on smart city development should focus on overcoming technological and governance incumbents' barriers and further research on how cognition systems should be further integrated into sustainable solutions. There is now also an area of interest in developing countries, where technological infrastructure is limited, for smart city frameworks in investigation, which now also poses challenges in terms of scalability (Hattum et al., 2016). In another area of research, an attempt is made to develop governance models that encourage public and private stakeholders to collaborate on smart city projects that would be inclusive and equitable. It is further necessary to conduct further research regarding the ethical aspects of data collection and surveillance in smart cities from a viewpoint of privacy. According to this aspect, ethical guidelines and regulatory frameworks will be very important in smart city technologies development centered on the public good and preventing citizens' rights infringements. Lastly, concerning AI and sustainability for smart cities, this research can contribute to the development of solutions that would enable smart cities to adaptively adjust through time in response to varying conditions of climate change and other challenges that cities' populations face (Sharifi & Yamagata, 2022).

6. Conclusion

This study contributes to smart city scholarship by conceptually and empirically locating cognitive cities as a human-centered evolution of smart urbanism. Unlike previous stories of technology, the paper shows that cognition - how people perceive, navigate and interact with intelligent systems - is fundamental to sustainable urban performance. The important contributions are: A better distinction made between smart and cognitive cities; a theory-based framework of interplay between human cognition and AI-based urban systems; Empirical justification for cognitive design via worldwide case study; and Hypothesis-driven structure for increased academic rigor. By combining cognitive science and urban technology, this research opens a new interdisciplinary way of designing cities that are not only intelligent but also intuitive, inclusive and resilient - hence, it justifies its relevance for smart city research and practice in the future. A smart city is a very promising vision for urban development in general, though the actual realization of this vision still falls onto the continued technological, governmental, and moral challenges yet to be as researched and collaborated. In the development of scalable, inclusive, and sustainable frameworks wherein innovation prevails, and on which future advancement depends, neither should the public's well-being be neglected.

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