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Integrating Human, Space, and Kinematics in Interactive Architecture for Experimental Framework

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Abstract (250 words

In contemporary architectural environments, accommodating diverse functions and heterogeneous user groups within a single physical setting has become increasingly essential. Against this backdrop, interactive architecture, which actively interprets and anticipates user intentions and reactions to provide tailored spatial experiences, has emerged as a central direction for future spatial design. To make spatial movements acceptable to users, it is essential to establish kinematic and cognitive foundations that clarify how spaces adapt to user intentions and reactions. This requires an integrated understanding of the interplay between human responses, spatial contexts, and the parameters governing movement. However, most prior studies have addressed these aspects in isolation, without offering a systematic framework for their integration. Therefore, this study proposes the Human–Space–Kinematics framework as a theoretical foundation for analyzing interactions in moving spaces. Based on an analytical literature review, we categorize key interaction components into three domains: Human, capturing user attributes and multi-layered responses; Space, encompassing actuated elements and contextual conditions; and Kinematics, defining movement parameters of spatial components. These three domains are structured into a closed-loop interaction model with five stages: scene recognition, contextual interpretation, user response, translation into spatial requests, and kinematic execution. Through this cyclical process, the framework explains how spatial movements are perceived and interpreted, how they trigger measurable human responses, and how these responses recursively influence subsequent spatial adaptation. Beyond integrating fragmented findings in interactive architecture, the framework provides a foundation for advancing user-centered design and a systematic lens for developing experimental and simulation approaches adaptable across diverse spatial contexts and user groups.

Keywords: Interactive Architecture; Human–Space Interaction; Kinematics; Experimental Framework; User-Centered Space Design

Highlights

- Introduces a Human–Space–Kinematics framework to explain moving architectural interactions.
- Identifies fragmented research focus and integrates variables into a unified model.
- Provides guidance for experiments and simulations in user-centered interactive space design.

1 Introduction

Contemporary architectural environments are increasingly confronted with the demand to accommodate multiple users and heterogeneous activity contexts within a single physical setting (Boychenko, 2017). In activity-based offices, multipurpose public facilities, and post-pandemic dwellings, for instance, the same location is often required to transform into a meeting room, learning space, resting place, or online work environment depending on user groups and purposes (Alonso et al., 2022; Chen et al., 2024; Lee & Kim, 2023; Shrestha & Li, 2022; Nguyen & Vande Moere, 2024). Consequently, architecture is no longer confined to fixed functional roles but is expected to be reconfigurable in response to temporal patterns, privacy requirements, and activity-specific demands (Alavi et al., 2016; Boychenko, 2017).

Against this backdrop, *interactive architecture* has emerged as a critical direction in future-oriented spatial design. By integrating embedded computation with physical actuation, interactive architecture enables real-time spatial transformation through reciprocal interactions between people and the built environment (Haque, 2006; Achten, 2019). Such an approach extends beyond reactive systems that merely respond to environmental conditions, aspiring instead to interpret and anticipate user intentions and behaviors to deliver personalized spatial configurations.

The implementation of dynamic spaces in a manner acceptable to users requires careful consideration of how movement is perceived and enacted. This entails a kinematic and cognitive foundation for determining how spatial elements should respond to users' intentions and reactions. A holistic understanding of the interplay among psychological responses, spatial contexts, and kinematic variables is therefore indispensable. However, existing studies have largely remained limited to partial explorations. Prior efforts, ranging from robotic furniture and gestural wall systems to autonomous partitions, have predominantly emphasized displacement or isolated gestures, without sufficiently extending the spectrum of kinematic parameters (Sirkin et al., 2015; Wang et al., 2020). Similarly, research on spatial arrangements has often neglected contextual conditions such as density or visibility (Onishi et al., 2022).

Such partial approaches reduce space–user interaction to short-term responses under specific conditions, thereby limiting generalizability across diverse user groups and situations. For example, the extent to which kinematic factors, such as velocity and acceleration, amplify user discomfort in social settings, or how contextual elements, such as spatial density and visual obstruction, modulate behavioral responses, remains insufficiently understood. Establishing a foundation for dynamic spatial design thus requires a systematic framework that integrates user traits and reactions with both kinematic and spatial variables.

To address this gap, this study proposes the Human–Space–Kinematic (H–S–K) Integrated Framework. Through an analytical literature review, core variables are distilled and organized along the three axes of H, S, and K. These variables are further structured into descriptive hierarchies and relational interactions, enabling the quantification and integration of kinematic parameters, spatial contexts, and user psychology·behavior within a unified analytical schema. This framework offers a design instrument for synthesizing fragmented prior findings and for facilitating experimental and simulation-based studies that reflect dynamic effects across varied contexts. Ultimately, it provides theoretical and methodological foundations to support user-centered interactive architectural design.

2 Foundations of Interactive Architecture

2.1 The Evolution of Interactive Architecture

Interactive architecture refers to a mode of building design that combines embedded computation with physical actuation, enabling spaces to transform and reconfigure in real time through reciprocal interactions between people and their environment (Haque, 2006; Achten, 2019). Fox and Kemp (2009) defined this as an intelligent environment that alters its form in response to users and external stimuli. Earlier, within the concept of kinetic architecture, William Zuk and Roger Clark (1970) argued that architecture should be capable of transforming in response to social change and environmental pressures.

Building upon these conceptual foundations, early explorations in kinetic architecture and media façades largely focused on structural and formal transformation. *Villa Girasole*, for example, rotated its entire building volume to follow the sun, offering a precedent for "moving architecture" (Domus, 2025), while the *Institut du Monde Arabe* introduced a responsive façade system in which sensor-driven lattice windows controlled the penetration of sunlight (ArchDaily, 2011; Jean Nouvel, n.d.). However, research from this period was primarily concerned with formal variability and visual effects, with limited attention to the systematic relationship between user psychology·behavior, and spatial responses. In other words, while these works demonstrated the potential of "moving architecture," they often lacked a user-centered perspective necessary to secure genuinely interactive significance.

Subsequent advancements in robotics, sensing, and HCI technologies accelerated the expansion of interactive architecture, extending responsiveness to interior elements such as walls, partitions, and furniture. For instance, Hong et al. (2023) examined how wall movements influence work scenarios and user preferences, while Suzuki et al. (2020) proposed a modular interface capable of altering floor and wall heights to demonstrate how spaces may be actively reconfigured.

More recently, there has been a growing emphasis on linking spatial transformations with users' cognitive and emotional responses. Schnädelbach et al. (2012) explored the synchronization between space and physiological state by embedding real-time respiratory and cardiac data into architectural structures. Wang et al. (2020) revealed that people can perceive robotic surfaces as social actors, suggesting that the motion of spatial elements can transcend physical transformation and acquire meanings as social interactions. Such studies illustrate that the kinematic properties of space can exert a direct influence on psychological and cognitive responses.

In sum, research on interactive architecture has shifted from an early focus on formal variability toward a more recent orientation that emphasizes user experience and analyses grounded in cognition and behavior. Furthermore, contemporary research in Human–Building Interaction (HBI) seeks to extend interactive architecture beyond technological experimentation, adopting multidisciplinary approaches that integrate space, humans, and technology to advance a user-centered paradigm of spatial design (Alavi et al., 2016).

2.2 Empirical Approaches and Current Challenges in Interactive Architecture

Based on these developments, this study investigates how recent research has designed and conducted user studies with respect to three dimensions: users' psychology and responses, spatial context, and the kinematic variables governing movement. To this end, relevant literature was systematically collected from ACM Digital Library, IEEE Xplore, Scopus, Web of Science, and Google

Scholar. The search query was formulated as *(interactive OR adaptive OR reconfigurable OR kinetic OR robotic) NEAR/3 (space OR architecture OR wall OR partition OR furniture OR façade)*, supplemented with terms relating to human behavior and kinematics.

Inclusion criteria required peer-reviewed publications between 2020 and 2025 that: **(i)** implemented dynamic elements within an architectural or interior context; **(ii)** addressed user–space interaction through experiment, observation, or design; and **(iii)** explicitly defined variables and evaluation measures. Excluded were purely structural or mechanical studies without human interaction, as well as mobile robotics research unrelated to spatial reconfiguration. After removing duplicates, screening titles and abstracts, full-text analysis, and backward/forward reference tracing, a total of 12 studies were selected for review.

Through analytical reviewing, this study classified prior works according to user response measures, spatial contextual variables, and manipulated kinematic parameters, organizing them along the three axes of Human, Space, and Kinematic (Table 1). While recent research has made attempts to encompass all three dimensions, tendencies toward imbalance remain evident. For example, several studies emphasized kinematic variables such as velocity, displacement, and shape transformation to explore the potential of spatial movement but treated user responses and contextual conditions only as secondary considerations (Suzuki et al., 2020a; Suzuki et al., 2020b; Gonzalez et al., 2023). Others concentrated on spatial factors such as façade coloration, lighting environments, or simulation scenarios, while paying limited attention to kinematic dynamics (Hosseini et al., 2020; Schaumann, 2024). Conversely, studies focusing on user experience and cognitive responses provided detailed analyses of perception, immersion, and social appraisal, but did not systematically integrate these measures with spatial contexts or kinematic control (Balcı et al., 2025; Onishi et al., 2022; Wang et al., 2020).

Table I. Mapping of Kinematic, Human, and Spatial Variables in Interactive Architecture Studies (2020–2025)

Authors (Year)	Kinematics: Manipulated Variables	Human: User Responses/Measures	Space: Contextual Variables	Primary Focus Axis
Hosseini et al. (2020)	Façade panel opening/closing	Visual comfort (indirect)	Colored glass, lighting environment	Space (primary), Kinematics (secondary)
Suzuki et al. (2020)	Chair movement speed and noise	Immersion, perception of realism	Spatial size, layout	Kinematics (primary), Space (secondary)
Suzuki et al. (2020)	Tile height and shape variation	Usability, naturalness	Layout reconfiguration	Kinematics (primary), Space (secondary)
Wang et al. (2020)	Wall speed (0.3–3 cm/s), trajectory	Spatial experience, sense of safety, appropriateness	Activity zones, privacy	Kinematics (primary), Human (secondary)
Nguyen et al. (2022)	Wall speed and response mode	Interaction perception, spatial experience	Office zone differentiation	Kinematics (primary), Space (secondary)
Onishi et al. (2022)	Partition movement and height	NASA-TLX, SUS, preference ratings	Layout conditions	Kinematics (primary), Human (secondary)
Gonzalez et al. (2023)	Surface waves and vibrations	Haptic experience, perception evaluation	Partition arrangement, positioning	Kinematics-only
Hong et al. (2023)	Wall deformation (formation/removal), cube size	Strategies, preferences, interaction types	Distance between user and wall	Kinematics (primary), Space (secondary)
Nguyen et al. (2024)	Partition speed, collision avoidance	UEQ survey, satisfaction, interviews	Spatial density, privacy	Space (primary), Kinematics (secondary)
Schaumann, D. (2024)	None (simulation-based)	Behavioral strategies, adaptability, well-being	Various spatial contexts (library, hospital, office)	Space (primary), Human (secondary)
Balcı et al. (2025)	Partition speed (0.2–5 cm/s), gestures	Immersion, privacy, social perception	Office layout, visibility, lighting	Human (primary), Space (secondary)
Nguyen et al. (2025)	Gesture attributes (size, intensity, direction)	Gesture recognition and evaluation	Office layout	Kinetics (primary), Human (secondary)

Only a small number of studies attempted a balanced approach across all three axes (Hong et al., 2023; Nguyen et al., 2022, 2024, 2025). However, even these studies remained limited in experimental conditions and scope of variables, making it difficult to comprehensively capture the interactions among Human, Space, and Kinematic dimensions. As a result, research in interactive spaces has accumulated in parallel across separate emphases on movement, user response, or spatial context, but lacks an overarching theoretical framework.

To fill this gap, the present study proposes an integrated framework that simultaneously considers the three axes of Human, Space, and Kinetic. This framework aims to enable a holistic understanding of interaction within moving architectural environments and to provide an analytical basis for designing experiments and simulations that support the implementation of such interactive spaces.

3 Designing Human–Space–Kinematics Framework

3.1 Three Key Components of the Framework

This study derived the components of the proposed framework based on the review of prior research presented in Section 2.2. Recurrent concepts across the selected studies were collected through open coding, and overlapping meanings were consolidated through axial coding to construct a variable codebook (ontology). The codebook included the definition and scope of each variable (with units when applicable), along with synonyms, abbreviations, and multilingual equivalents.

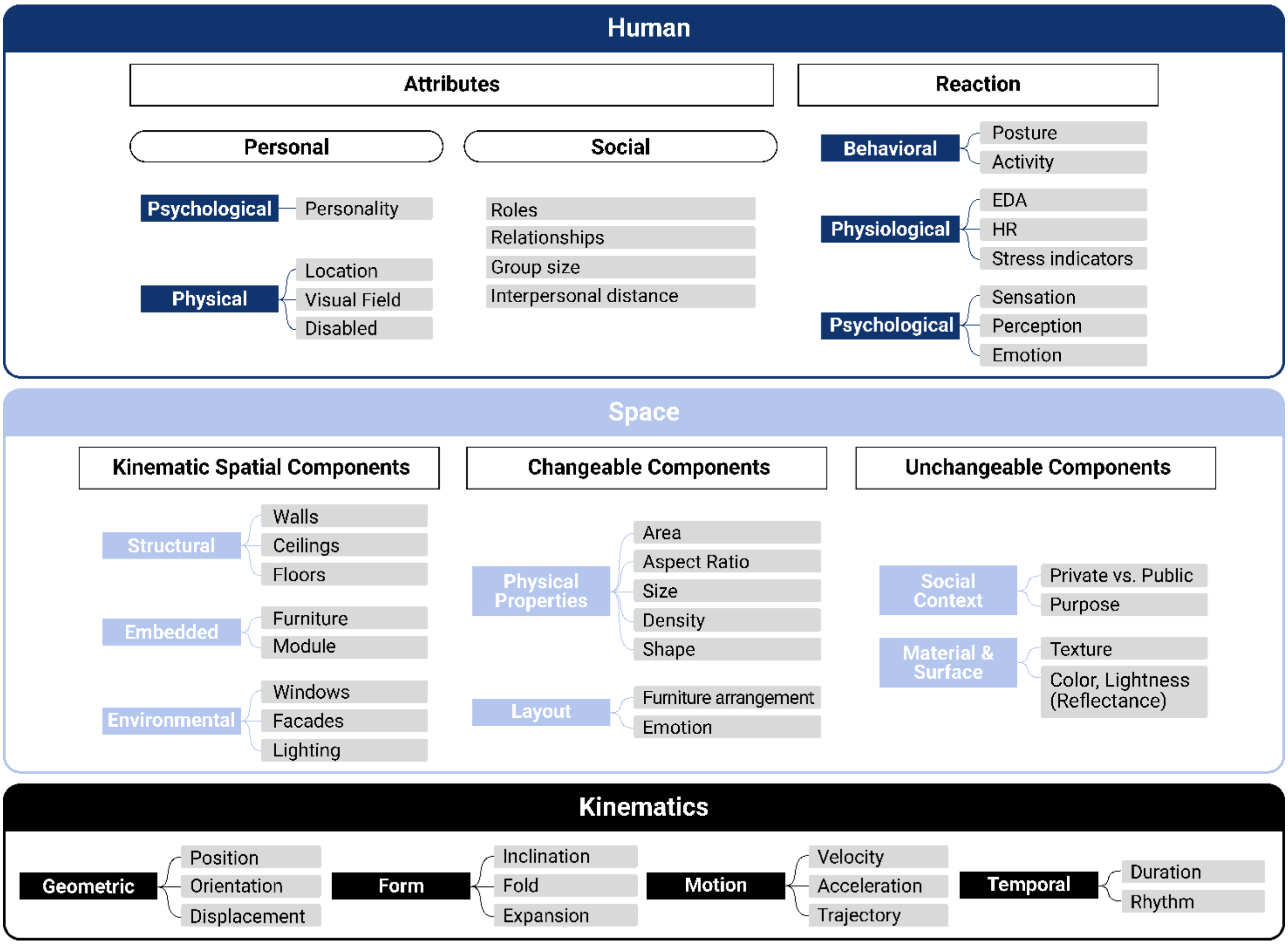

Figure 1. Three key components of the framework

For interpretive clarity, each variable was categorized under one of the three upper domains, Human, Kinematic, or Space, while the actual analysis was conducted at the individual variable level. Text extraction was performed using multiple parsing tools and, when necessary, OCR processing. Candidate sentences were identified through a lexicon derived from the codebook, and the inclusion of each variable was finalized through contextual review by experts in architecture, design, and HCI. The selected variables were then structured descriptively to represent their hierarchical relationships and interactional dynamics across the three components of Human–Space–Kinematics (Figure 1).

Human: The *Human* component encompasses user attributes and responses. *Attributes* include personal factors (psychological traits and physical conditions) and social factors (roles, relationships, group size, interpersonal distance), which form the basis for interpreting spatial experiences. *Reaction* refers to human behaviors (posture and activity), physiological responses (EDA, HR, and stress indicators), and psychological responses (sensation, perception, and emotion). These function as evaluative measures of spatial movement.

Space: The *Space* component defines the physical environment and contextual conditions surrounding the human. Spatial elements are categorized as *Kinematic Spatial Components* (structural, embedded, and environmental elements) that serve as the direct agents of motion; *Changeable Spatial Components* (physical properties and layout) that are indirectly altered through such motion; and *Unchangeable Spatial Components* (social context, material, and surface) that remain relatively fixed. Space receives *spatial requests* from human, estimating which components can be moved and to what extent. At the same time, spatial context moderates the effects of Kinematics, amplifying or attenuating their impact. For example, the same movement velocity may cause greater discomfort in dense or visually obstructed environments.

Kinematics: The *Kinematics* component quantifies the movement properties of *Kinematic Spatial Components*. These kinematic variables are organized into *Geometric parameters* (position, orientation, and displacement), *Motion parameters* (velocity, acceleration, and trajectory), *Form parameters* (inclination, folding, and expansion), and *Temporal parameters* (duration and rhythm). These variables specify the movement of spatial components selected by space and generate actual motion, thereby eliciting human reactions.

3.2 Closed-Loop Model of Human–Space–Kinematics Interaction

Within the proposed framework, the three axes, Human, Space, and Kinematics, do not operate independently but are tightly interrelated through mutual constraints and moderating effects. Numerous studies have quantitatively examined kinematic features, such as velocity, displacement, and trajectory, and systematically linked them to user evaluation metrics, including safety and acceptability (Wang et al., 2024; Neggers et al., 2022).

The interconnections among these variables can also be explained from a cognitive perspective. Research in HCI and HBI has shown that users first recognize the spatial environment as a scene (Gibson, 1979), then interpret it within personal and social contexts (Norman, 2013), and finally translate it into behavioral, physiological, or affective responses (Schnädelbach et al., 2012). Empirical studies further support this three-stage flow. Özçelik et al. (2019) analyzed how architectural stimuli shape cognitive judgments and behavioral reactions, while Payedar-Ardakani et al. (2024) demonstrated through VR–EEG experiments that lighting variations evoke corresponding neural and subjective responses.

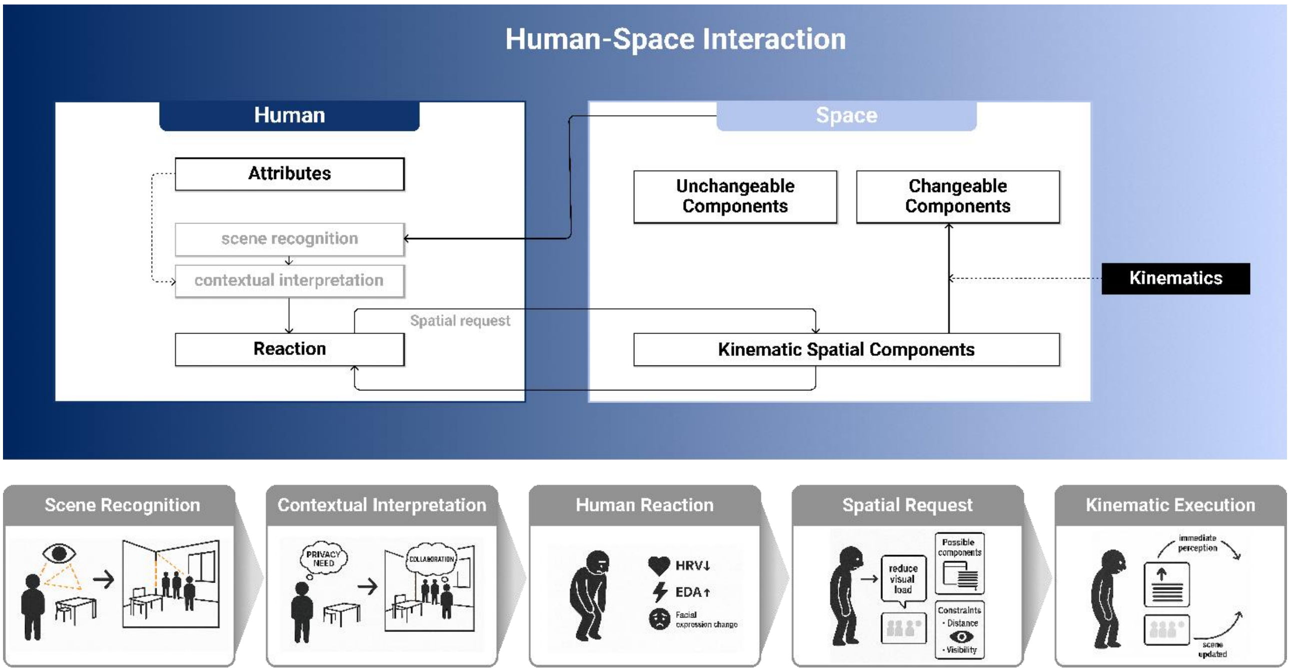

Figure 2. Closed-Loop Model of Human-Space-Kinematics Interaction

Thus, spatial movement and user experience should be understood not as a simple stimulus–response mechanism but as a sequential process mediated by cognitive interpretation. Based on these interdependencies, the proposed framework assumes as its core principle that changes in the dynamic states of kinetic spatial components influence humans, thereby connecting the three axes into a closed loop cycle (Figure 2). This process is structured into five stages:

Scene Recognition: Users perceive physical and visual cues provided by the environment and recognize them as a coherent scene. This stage can be understood through Gibson's (1979) affordance theory as the detection of possibilities and constraints in the environment. In this sense, space emits physical and social signals, and users interpret them as situational contexts.

Contextual Interpretation: The recognized scene is interpreted considering users' personal characteristics. As described in Norman's (2013) action model, raw sensory inputs do not directly lead to actions but undergo a meaning-making process shaped by goals and background knowledge. For instance, the same wall movement may be interpreted by one user as an "invasion of privacy," while another may perceive it as a "signal of collaboration."

Human Reaction: The interpreted information manifests as concrete responses. These may include behavioral, physiological, and psychological responses. Schnädelbach et al.'s (2012) ExoBuilding project also confirmed that spatial transformations can synchronize with users' physiological and affective states.

Spatial Request: User responses are translated into signals that space can interpret. For example, a perceived need to reduce visual load may map onto shielding/opening gestures; a need for collaborative engagement may correspond to orientation adjustments; and a need for facilitation of access may translate into opening expansions. Such requests are evaluated against the movable components available, as well as constraints such as safety distances, collision avoidance, and changes in visibility or illumination.

Kinematics Execution: The selected spatial components are specified through kinematic parameters and executed as actual movements. This execution closes the loop in two ways: (1) users directly perceive the movement of kinematic spatial components, eliciting new reactions; or (2) they indirectly alter changeable components, which are reintegrated into the spatial scene and subsequently recognized by users.

Through this process, components and cyclical operating structure of the Human–Space–Kinematics framework have been presented, establishing a theoretical foundation for comprehensively explaining interactions between moving spaces and users. This framework integrates user responses, kinematic variables, and spatial contexts, which had previously been presented only in fragmented ways across individual studies.

4 Conclusions

This study establishes a theoretical foundation to ensure that interactive spaces function in ways acceptable to users. Although previous studies have demonstrated the potential of interactive spaces through approaches such as robotic furniture (Sirkin et al., 2015), gestural walls (Onishi et al., 2022), and autonomous partitions (Hong et al., 2023), these efforts have often focused only partially on kinematic variables or spatial contexts. As a result, interactions were frequently reduced to short-term responses under specific conditions (Wang et al., 2020; Onishi et al., 2022). Such partial perspectives have limited the ability to account for contextual moderators or individual differences in user responses, thereby constraining the generalizability and practical applicability of the findings (Balcı et al., 2025; Hosseini et al., 2020).

To address this, this study proposes an integrated framework that structures variables, derived from literature analysis and expert consultation, along the three axes of Human, Space, and Kinematics. The framework describes the transformation of spatial movement into user experience through a cyclical structure consisting of *Scene Recognition*, *Contextual Interpretation*, *Reaction*, *Spatial Request*, and *Kinematics Execution*. In doing so, it connects research that has previously been discussed in fragmented terms and provides an analytical basis for systematizing experimental and simulation design across diverse contexts.

Despite its potential, the framework of this study remains at the conceptual level. It does not yet include empirical validation through prototype implementation or user experiments. Future research is therefore required to examine how the proposed interconnections operate in real-world contexts. Furthermore, the relationships and variables presented here should be understood not as a fixed structure but as an open analytical scheme. As subsequent studies uncover new interactions among variables or refine elements such as autonomy and control distribution (Onishi et al., 2022; Balcı et al., 2025), the framework may be further revised and extended.

In summary, the primary contribution of this study lies in moving beyond experiments partially focused on individual variables and in providing a theoretical and methodological foundation that organically integrates the three elements of human, space, and kinematics. This framework not only offers a starting point for supporting user-centered interactive architectural design but also contributes to the systematic development of experimental and simulation approaches applicable to varied contexts and user groups.

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Conflicts of Interest

The authors declare no conflict of interest.

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