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Perceptual Intelligence and Passive Energy-Saving Strategies in Building Systems: Adaptive Frameworks for Sustainable Performance in Hot Climates

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ABSTRACT

This paper investigates how perceptual awareness of daylight contributes to passive energy-saving strategies and the overall performance of building systems in hot climates. The study aims to identify how human cognition and environmental perception—often neglected in technologically oriented sustainability approaches—affect the energy efficiency of built environments.

Methodologically, the research applies a comparative qualitative framework, combining theoretical analysis of environmental perception models with case studies of vernacular architecture in arid regions. Architectural examples from Qajar-era buildings in Kashan, Iran, were analyzed to examine how spatial configuration, material selection, and daylight modulation enabled adaptive thermal comfort and visual quality without mechanical intervention. Results indicate that vernacular passive systems effectively integrated perceptual feedback and user participation, allowing occupants to regulate comfort through intuitive spatial behaviors. In contrast, contemporary mechanically controlled buildings often disrupt this cognitive-environmental connection, leading to increased energy use and reduced user engagement. The findings highlight the need to reintegrate perceptual feedback mechanisms into modern green-building technologies—including smart façades, daylight-responsive dashboards, and adaptive lighting systems. Embedding behavioral and perceptual intelligence into building-management frameworks enhances both energy efficiency and occupant satisfaction. The study concludes that future sustainability depends on systemic cooperation between human perception and adaptive control systems. Integrating passive design principles with perceptually informed technologies provides a pragmatic pathway toward low-carbon, high-performance building systems that cultivate user awareness alongside technological precision.

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1. Introduction

Passive energy-saving strategies are central to sustainable building design, particularly in hot climates where solar exposure and high ambient temperatures strongly affect performance. Although modern green technologies—from high-efficiency HVAC systems to automated shading—have improved environmental control, they often neglect cognitive and perceptual aspects of energy behavior (Hegger et al., 2012; Abdallah & Rashid, 2022).

Daylight, as a renewable resource, governs thermal comfort, lighting demand, and visual well-being (Tregenza & Wilson, 2011). Yet, increasing reliance on artificial lighting and mechanical cooling has diminished users' awareness of natural light and microclimatic variation. In many urban contexts, occupants rarely adapt their routines to solar rhythms, relying instead on technology for constant comfort. This detachment not only raises energy consumption but also weakens the feedback loop between architectural space and environmental awareness (Frontczak & Wargocki, 2011).

Vernacular architecture in hot and arid regions illustrates how environmental comfort and energy efficiency can be achieved through perceptual participation and spatial intelligence rather than mechanical control. Understanding this relationship between perception and performance provides valuable insight for improving green-building system efficiency today.

2. Technological Mediation and the Limits of Control

Modern sustainable buildings employ daylight-responsive systems—roof monitors, diffusing panels, photo-sensors, dimming controls, and adaptive façade blinds—to optimize lighting and reduce loads (Li & Lam, 2013; Yoon & Kim, 2020). These advanced tools combine active and passive subsystems to balance visual comfort with thermal efficiency.

However, their success depends on user engagement. Automated controls underperform when occupants are unaware of their purpose or override settings for convenience (O'Brien & Gunay, 2020). True energy efficiency therefore requires perceptual literacy—an informed relationship between users and environmental systems. Sustainable architecture must be understood as a communicative process that aligns technological mediation with human cognition.

3. Architecture as a Communicative Energy System

Böhme (2017) defines atmosphere as the shared spatial reality between the perceiver and the perceived. Lasswell's (1948) communication model—source, message, channel, receiver, and effect—helps explain how architecture transmits environmental information.

In energy-efficient design, environmental data or regulations form the source; architectural space is the channel; the message is the perceptual experience of light, temperature, and airflow; and occupants are the receivers. The resulting effect is behavioral adaptation, which determines real performance.

Viewing architecture as an energy-communication system underscores that spatial and material cues must clearly convey environmental change. When users perceive and respond to daylight variation, they co-operate with building systems, achieving higher passive efficiency (Nicol & Humphreys, 2002).

4. Vernacular Passive Systems in Hot-Climate Architecture

Traditional architecture in arid regions of the Middle East, North Africa, and South Asia offers exemplary models of passive environmental control. Courtyard houses and compact urban fabrics used orientation, massing, and transitional spaces to mediate light and heat (Fathy, 1986; Edwards et al., 2006).

Shaded courtyards, deep-set windows, and semi-open verandas acted as thermal buffers and daylight moderators. During summer, occupants moved to shaded, ventilated areas; in winter, they occupied sun-lit zones. Wind catchers, high openings, and reflective plaster improved airflow and diffused light, achieving comfort without mechanical input.

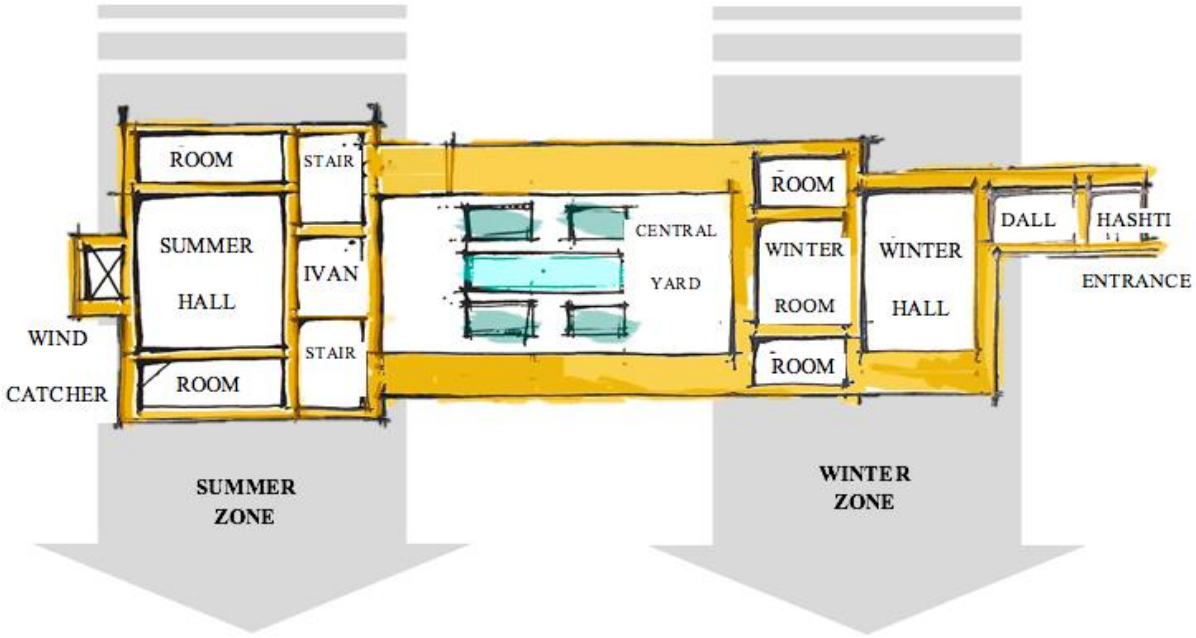


Fig.1. Typical space arrangements of earthen architecture during the Qajar dynastyFig.1. Typical space arrangements of earthen architecture during the Qajar dynasty

Figure 1. illustrates a typical Qajar building in Kashan. Separated parts of the house surrounding a central garden were used for family members' privacy as the merchants used to have business meetings at home. Meanwhile, different positions of rooms towards the sun provided various microclimates according to changing climatic conditions during days and seasons in the desert.



Fig. 2. An overview of Borujerdi House, Kashan, Iran.

Top: Winter ivan. Botom: Summer ivan.

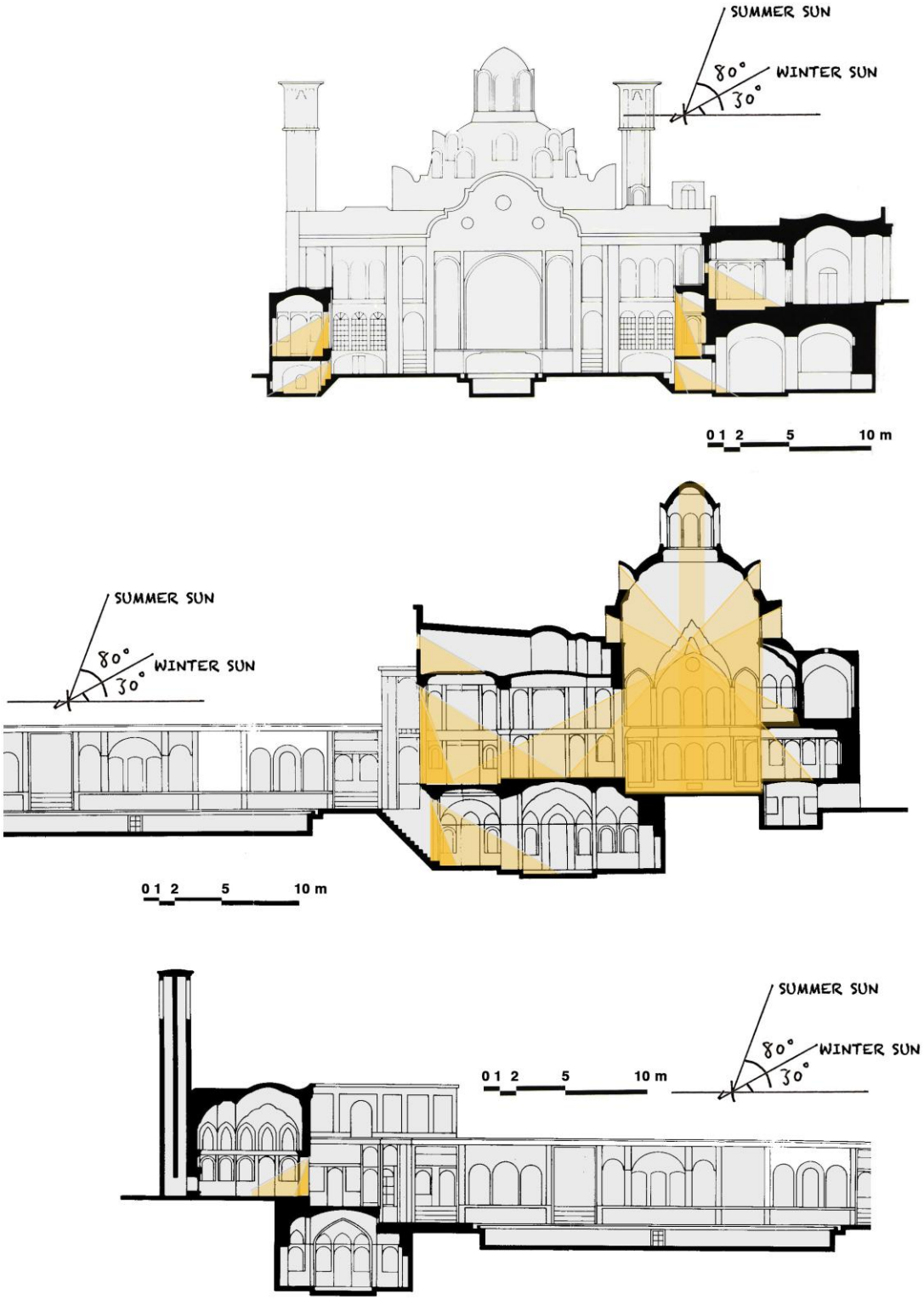


Fig. 3. The flow of sunlight in the Borujerdi's complex, Kashan, Iran.Top: The summer zone Bottom: The winter zoneFig. 3. The flow of sunlight in the Borujerdi's complex, Kashan, Iran.Top: The summer zone Bottom: The winter zone

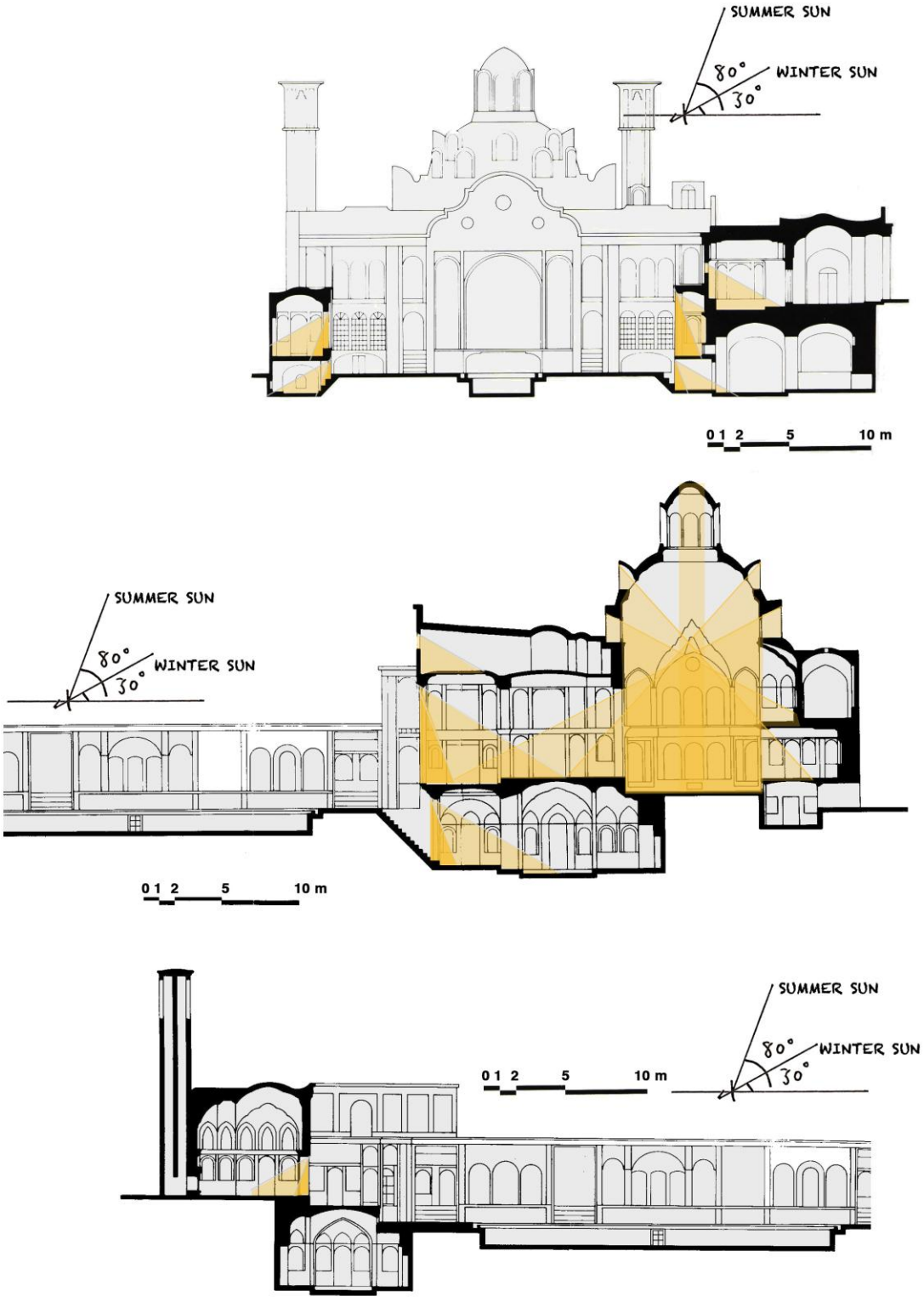


Fig. 4. The flow of sunlight in the eastern and western rooms of the Borujerdi's complex, Kashan, Iran. Fig. 4. The flow of sunlight in the eastern and western rooms of the Borujerdi's complex, Kashan, Iran.

Such buildings functioned as integrated systems whose performance relied on user awareness. Occupants intuitively understood spatial temperature gradients and

adapted behavior accordingly—an early manifestation of user-centered environmental control (Ratti et al., 2003).

5. Cultural Transformation and Decline of Passive Engagement

With modernization and globalization of construction methods, adaptive spatial behaviors have been supplanted by mechanical and automated systems. Buildings that once balanced climate through natural ventilation and daylight now depend on constant energy input (Givoni, 1998).

This shift represents a perceptual disconnection: users no longer sense environmental feedback. Curtains remain drawn, air conditioners run continuously, and naturally lit spaces are underused. The building's passive systems lose functionality, creating a cycle of energy overconsumption despite advanced technology (Al-Sallal, 2016).

Since the beginning of the Pahlavi II era in 1940 in Iran, along with changes in culture, economy, and social relations, most of these buildings have turned into museums, hotels, and tourist attractions. Traditional wind-catchers were mostly invaded by modern air conditioning systems, and also several connecting stairways were blocked for security reasons (see Figure 5). According to current occupants of the remaining buildings, it is not possible to eliminate detached modern air conditioners and the functional zones have been mostly reduced to the south-facing winter zones which were originally designed to catch most of the light and warmth in cold seasons.



Fig. 5. Destructive changes in functionality of traditional houses, Kashan, Iran. Fig. 5. Destructive changes in functionality of traditional houses, Kashan, Iran.

Although the summer hall remains architecturally intact and ideally designed to shield occupants from direct sunlight and extreme heat during hot days, contemporary use patterns have reversed its purpose. Today, people predominantly occupy the winter zone throughout the year—a space originally intended for colder seasons. As a result, substantial energy is expended on cooling these rooms, curtains remain closed to block excessive heat, and artificial lighting has replaced the abundant natural daylight once utilized. This decline in climatic responsiveness reflects not a failure of design but a breakdown in the social and perceptual context of use. The once highly functional architecture has become environmentally inefficient due to a diminished capacity among occupants to recognize and respond to variations in sunlight intensity and duration.

As illustrated in Figure 6., a former summer hall in an inhabited building now serves merely as a storage area. Despite its favorable microclimate—naturally cooler than the adjoining garden and adequately illuminated without heat gain—it remains unused. According to current residents, the absence of a roofed connecting corridor discourages passage through the open courtyard, leading to the abandonment of this otherwise comfortable and energy-efficient space.



Fig. 6. An abandoned summer residence in Kashan traditional houses, Kashan, Iran. Fig. 6. An abandoned summer residence in Kashan traditional houses, Kashan, Iran.

Re-establishing environmental literacy through design education and interactive systems can reverse this pattern and restore the human-environment reciprocity essential to sustainable performance.

6. Reintegrating Perception into Modern Building Systems

The evolution of sustainable architecture necessitates a paradigm shift from mechanistic optimization toward an integrative ecological intelligence—one that couples passive environmental strategies with perceptual and behavioral feedback systems. Future green-building technologies must not only regulate thermal and luminous conditions through automated control, but also cultivate human attunement to the dynamics of natural light and climate. Advanced interfaces such as smart façades, daylight-responsive dashboards, and adaptive interior illumination provide real-time sensorial cues that reveal the energetic consequences of occupants' actions (Kim et al., 2021). Through such mediated awareness, users become active participants within the environmental system, co-producing comfort rather than merely consuming it.

Embedding behavioral interaction into building-management frameworks thus transforms occupants from passive recipients into integral agents of environmental performance, aligning subjective comfort with systemic efficiency (Gunay et al., 2019). In hot-arid regions, where thermal differentials and solar exposure are extreme, this synergistic model—merging passive climatic design with perceptually interactive technologies—constitutes a critical advancement toward a human-centered yet high-performance architectural ecology. It situates sustainability not merely in material or mechanical domains, but within the reciprocal dialogue between perception, behavior, and built form.

7. Conclusion

High-performance building systems are evolving toward a multi-scalar integration of environmental sensing, adaptive control, and human-centered interaction. Future sustainability will depend less on isolated technological efficiency and more on the synergistic interoperability of passive design, predictive analytics, and occupant-responsive feedback. When building envelopes, control systems, and behavioral interfaces operate as interlinked subsystems, the built environment becomes a living infrastructure capable of continuous optimization.

This integration requires data-driven frameworks that merge environmental simulation, Internet of Things (IoT) networks, and machine-learning algorithms with real-time occupant input. Such convergence can recalibrate energy models dynamically, refine predictive maintenance, and personalize comfort profiles—all while minimizing total energy demand and carbon emissions. In essence, sustainable performance will emerge not from any single technology, but from the systemic coherence among design intelligence, operational analytics, and user perception. The fusion of passive bioclimatic principles with active, perceptually informed control architectures defines a pragmatic pathway toward next-generation, low-carbon, adaptive building ecosystems—

where technological precision and human awareness collectively drive environmental resilience.

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