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# A BEACON through the walls: AI-assisted tacit knowledge extraction from built environments

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**Introduction:** The rapid urbanization of contemporary society has created environments that often overlook the human needs of their inhabitants. This paper presents BEACON (Built Environment Architecture Cognitive Ontology Network), a comprehensive multi-layer ontological framework to support reasoning about the gaps between practical urban design and the requirements that emerge from social, cognitive and neuroarchitectural findings concerning urban living.

**Methods:** BEACON integrates seven analytical layers: physical, experiential, social, normative, behavioral, cognitive, and neural—a systematic network with descriptions ranging from physical design elements to individual neural responses.

**Results:** Integrating those layers addresses critical limitations in current neuroarchitecture research by providing: (1) a formal ontological structure for organizing complex environmental-neural relationships, (2) a practical methodology for extracting tacit knowledge from built environments, applying it to an analysis of Pachino's central square in Sicily, comparing historical (1910) and contemporary (2025) configurations to reveal how architectural modifications cascade through all analytical dimensions, and (3) an example design of an immersive XR platform for both research and applied urban planning, enabling real-time, multi-sensory analysis of urban environments.

**Discussion:** This transdisciplinary integration envisages a paradigm shift from post hoc environmental analysis to proactive design optimization.

## KEYWORDS

neuroarchitecture, neurosymbolic AI, ontology design, urban cognition, extended reality, built environment, neural response

## 1 Introduction

Neuroarchitecture makes us understand and design urban environments by applying neuroscientific principles to investigate how built environments impact human neural dynamics, perception, and overall experience (Jeffery, 2019). Its extension into “neurourbanism” encompasses the design of healthier, more sustainable urban environments informed by objective neuroscientific findings beyond formal design principles (Küçük and Yüceer, 2022).

As urbanization accelerates globally, with projections indicating that over 68% of the world's population will reside in cities by 2050 (United Nations, 2018), the imperative for

scientifically-informed, human-centered design approaches becomes increasingly critical. This shift recognizes that rapid urbanization has frequently overlooked the psychological and neurological needs of city dwellers, resulting in various physical and mental challenges for urban residents (Küçük and Yüceer, 2022).

Research in neuroarchitecture has established clear relationships between environmental features and neural responses across multiple domains. In the domain of spatial cognition and navigation, human wayfinding exploits an evolved brain system dedicated to processing navigable space, which also supports episodic memory formation (Jeffery, 2019). Key neural components include place cells that fire in context-dependent manners, head direction cells providing directional information, and grid cells involved in distance-measuring processes sensitive to environmental boundaries.

Poorly designed layouts, particularly those with rotational symmetry, can increase disorientation and cognitive burden, especially for older adults who struggle with landmark-based disambiguation (Jeffery, 2019).

Djebbara et al. (2022) introduced the neural basics for behavioral modulation in built environments, pointing to the neural structures and processes involved. Their reconstruction is used as a neural basis for our ontology framework (Section 5).

Karandinou and Turner (2017) advanced this understanding through portable Electroencephalography (EEG) studies, demonstrating that different architectural features elicit distinct patterns of brain activity related to attentional engagement and cognitive load during wayfinding. Their research revealed that specific visual cues in urban environments can either facilitate or impede cognitive mapping and orientation, with the brain's response being dynamic and influenced by the sequential experience of moving through environments rather than static perception alone.

The visual characteristics of urban environments profoundly influence human emotional states through measurable neural mechanisms. Brielmann et al. (2022) identified fractal geometry as particularly significant, demonstrating that environments incorporating multiple fractals with optimal dimensions—D values between 1.3 and 1.5, common in natural scenes—reduce stress and mental fatigue while inducing positive aesthetic experiences. This “fractal fluency” appears to be evolutionarily hardwired, with the human visual system efficiently processing natural fractal patterns through “effortless looking” that reduces physiological stress.

Complementing this research, Banaei et al. (2017) established through EEG studies that curvilinear spaces generate significantly higher pleasure and arousal ratings compared to rectilinear forms, correlating with increased activity in the anterior cingulate cortex (ACC). Remarkably, this ACC activation occurs within 50 milliseconds of stimulus onset, indicating rapid, unconscious processing of architectural forms that influences emotional states before conscious awareness.

The concept of Attention Restoration Theory, originally proposed by Kaplan (1995), is supported in contemporary neuroarchitecture research. Ohly et al. (2016) and Ancora et al. (2022) conducted systematic literature reviews demonstrating that complex urban built environments offer fewer capacities for cognitive recovery and restoration, leading to directed attention fatigue (when you spend extended periods engaged in tasks

that require concentrated mental effort, depleting the brain's capacity for focused, voluntary attention). Built environments consistently activate brain regions associated with higher-order visual processing, episodic memory, spatial navigation, and stress responses, including the amygdala and areas related to directed attention fatigue (Adolphs, 2010). Conversely, natural environments promote attentional restoration by engaging simpler, bottom-up attentional processes that require fewer mental resources. These environments activate brain areas associated with basic visual processing, visuospatial perception, sensorial integration, and emotional control, including the anterior cingulate cortex and precuneus, supporting restorative experiences.

## 1.1 Limitations and Research Gaps

Despite these advances, current neuroarchitecture research faces significant limitations (Rad et al., 2023) that hinder its practical application.

First, neuroscientific data are not easy to associate with urban situations (Marquardt et al., 2024): selected studies offer insights into the neuroarchitectural clockwork, but simulations of design choices with their neuroscientific counterparts are not available off-the-shelf.

Second, neuroarchitecture suffers from a lack of integrated frameworks (Wang et al., 2022). Current research tends to focus on specific aspects of urban experience rather than comprehensive frameworks simultaneously addressing multiple scales and dimensions. Most studies examine individual features or limited sets of variables, while we need to simulate complex interactions between physical, social, and cognitive factors in urban environments (Makanadar 2024). The field seems to lack a “systematic framework” (Mahdavi et al., 2023; Salingaros, 2024) for modelling the complex relationships between environmental features and human responses.

Third, many studies rely on laboratory settings or simplified virtual environments that may not capture the complexity of real urban experiences (Lee et al., 2022). While Mobile Brain/Body Imaging (MoBI) studies (Delaux et al., 2021) enable measurement during real-world navigation (Kühn and Gallinat, 2024), the volume and breadth of data required to train robust, generalizable models remain limited.

## 1.2 Our Contribution

We introduce BEACON (Built Environment Architecture Cognitive Ontology Network), a multi-layer formal ontology framework to analyze urban environments across seven integrated layers, from physical elements to neural responses. We represent it by using the OWL Description Logic (World Wide Web Consortium, 2012), enabling computational reasoning about complex environmental relations. We apply the Polanyi method (De Giorgis et al., 2025) for automatically extracting tacit (a.k.a. implicit) knowledge (Polanyi, 1966) from built environments, integrating multimodal data acquisition and representation (Tupayachi et al., 2024) with ontology-augmented knowledge graph generation (Gangemi and Nuzzolese, 2025). Furthermore, we present an extended reality

model designed to enable real-time, immersive multi-sensory environmental analysis (Hajrasouliha, 2024).

We demonstrate BEACON through a detailed analysis of Pachino's central square in Sicily, revealing how architectural design functions as a social engineering device that shapes neuro-cognitive development and community dynamics across historical periods. This approach moves beyond descriptive research toward design tools that can actively improve urban environments for human wellbeing.

## 2 Theoretical foundations

The complexity of urban environments demands a systematic methodology for extracting the *tacit knowledge* (Polanyi, 1966) embedded within their design. The architecture and formal representation that we contribute integrates multiple analytical perspectives, assuming that much of the knowledge associable with built environments operates below conscious awareness—inhabitants may not articulate why certain spaces feel comfortable or oppressive, yet these feelings arise from discoverable relationships between environmental features and human responses. Three foundational research paradigms have been singled out, which accommodate our need for transdisciplinary links between architecture (Pattern Language), cognitive neuroscience (Predictive Coding), and computational methods (Ontology Design Patterns). Finally, we have taken advantage of the soft analytic flexibility provided by Generative AI to implement simulations of a system based on the three foundations. The implementation enables a customised conditioning for ontology-augmented knowledge graph generation for multilayer analysis of built environments.

### 2.1 Christopher Alexander's pattern language as a theoretical bridge

Christopher Alexander's seminal work on pattern languages (Alexander, 1977; Alexander, 1979; Alexander, 2001) provides a theoretical foundation that bridges traditional architectural intuition and contemporary neuroarchitecture research. Alexander introduced the novel concept that successful built environments emerge from interconnected best practices ("patterns") operating across multiple scales, from regional planning down to architectural details.

Alexander's insight aligns with current neuroscientific findings about measurable human responses to environmental features. For example, spaces that feel "alive," "whole," or "comfortable" can now be understood through objective measures of stress reduction, attention restoration, and positive neural activation patterns documented in contemporary neuroarchitecture research (Jeffery, 2019; Brielmann et al., 2022).

Alexander identified 253 patterns, ranging from large-scale "Distribution of Towns" to specific details like "Window Place." Each pattern describes a design problem and its solution in terms of spatial relationships, human activities, and environmental qualities. They operate through "morphogenetic sequences," where smaller patterns combine to generate larger coherent structures

that support human flourishing.<sup>1</sup> This hierarchical organization parallels BEACON, where physical design elements cascade through experiential, social, and behavioral layers to influence cognitive and neural responses. Alexander's emphasis on pattern interconnectedness provides theoretical support for understanding how modifications at one scale create ripple effects throughout the entire environmental system.

Contemporary neuroarchitecture research provides empirical validation for many of Alexander's intuitive observations. His patterns emphasizing natural light and human-scaled proportions correspond directly to documented neurocognitive benefits of biophilic design and fractal geometry (Brielmann et al., 2022). Alexander's advocacy for spaces with "positive outdoor space" and "gardens at multiple levels" aligns with research demonstrating stress reduction and attention restoration through exposure to natural elements (Ohly et al., 2016). Similarly, Alexander's patterns addressing spatial configuration such as "Sequence of Sitting Spaces" and "Intimacy Gradient" reflect principles now understood through research on spatial cognition and social behavior in built environments (Karandinou and Turner, 2017).

Alexander's methodology contributes several key concepts relevant to multi-layer environmental analysis. His emphasis on "diagnosis before design" parallels the systematic assessment approaches required for understanding complex environmental systems across multiple analytical dimensions. The pattern language focus on "forces" acting within design situations provides a framework for understanding how different layers of environmental influence interact and sometimes conflict. This perspective supports understanding how modifications at one analytical layer create effects that propagate through other layers, ultimately influencing overall human experience in ways that cannot be predicted from examining individual components in isolation. Alexandrine principles are being used to ground automated evaluation of built environments (Salingaros, 2025).

### 2.2 Neuroscientific foundations

BEACON builds upon established neuroscientific principles demonstrating how environmental features influence brain functions, in particular about neural processing of space, experiential embodiment, predictive coding, fractal proportions, natural elements, and urban density. The brain processes environmental information through parallel pathways operating at different scales—from basic visual processing in occipital regions to complex social-spatial integration in temporoparietal networks (Messanvi et al., 2023).

Environmental experience is fundamentally embodied, with spatial navigation, social positioning, and cognitive processing intimately connected through shared neural substrates. Kühn and Gallinat (2024) synthesized research demonstrating that architectural features directly influence neural activity patterns—high ceilings activate brain regions involved in visuospatial exploration, open rooms are universally preferred

<sup>1</sup> See <https://patterns.architecture.net/doc/az-cf-173160> for a wide variety of morphogenetic sequences.

over enclosed ones, and large symmetrical spaces positively affect users' emotional states. Even subtle elements like window shapes significantly influence cortical activity, with pleasant shapes showing larger effects in the left hemisphere. This embodied perspective underscores that our physical movement through space fundamentally shapes our cognitive and emotional responses.

The brain continuously generates predictions about environmental features based on prior experience, with architectural regularities shaping these predictive models over time. This predictive processing process (Friston, 2010) helps explain why certain design patterns feel intuitively “right” or “wrong”—they either align with or violate our learned expectations about how spaces should function. Regular exposure to specific spatial configurations strengthens neural pathways associated with those patterns, creating deeply ingrained responses that operate largely below conscious awareness.

Specific architectural features consistently influence neurocognitive responses in measurable ways. Classical architectural proportions, recognized as statistical fractals, demonstrate positive effects on visual perception, attention, and emotional responses (Briellmann et al., 2022).

The integration of natural elements, including sunlight, water, vegetation, and natural geometries—collectively termed biophilic design—activates brain areas associated with basic visual processing, visuospatial perception, sensorial integration, and emotional control (Briellmann et al., 2022). The presence of natural elements appears to engage different neural processing pathways than built features, promoting restoration through bottom-up attentional processes that require fewer cognitive resources.

Urban density represents another critical factor linking environmental design to neural responses. Research has established clear connections between urban density and neural stress responses, with overcrowding acting as a social stressor that activates amygdala regions related to fear and negative affect (Ancora et al., 2022). Urban upbringing and current city living are associated with altered neural social stress processing and increased risk for mood and anxiety disorders. Environmental diversity emerges as a critical factor for positive affect and individual wellbeing, suggesting that monotonous urban environments may contribute to psychological distress through understimulation of neural reward systems.

## 2.3 Ontology design and multi-agent simulation

BEACON employs formal ontology design patterns (Hitzler et al., 2016) to structure the complex relationships between environmental features and human responses (see Section 5). This formalization serves multiple purposes: enabling computational reasoning about environmental-human relationships, providing a consistent vocabulary for interdisciplinary communication, and facilitating the integration of diverse data types within a unified analytical structure.

Following pattern-based design (Blomqvist et al., 2010), an established agile method for designing and evaluating computational ontologies using *competency questions* (what an expert would ask an ideal knowledge-based agent or AI to assist in regular or creative work), and *reusable best practices* (known

generalised solutions to model a schema that would create the possibility to answer those questions), we started by acquiring requirements from the analysis of neuroarchitecture literature, and the needs emerged therein to link multistratified knowledge.

Since we are acting in exploratory/creative mode, and in absence of previous established practices or elicitation methods, we decided to condition multiple state-of-the-art Large Language Models (LLMs) (Naveed et al., 2025) with an agentic approach (Acharya et al., 2025) that we call “Mixture of Experts Simulation” (MES). Each simulated agent represents the expertise in one of the background knowledge areas to discuss and collectively map inter-area relationships. The simulation involved expertise in Urban Design History, Architectural Phenomenology, Social Geography, Sociology, Behavioral Psychology, Cognitive Neuroscience, and Systems Integration, each contributing domain-specific insights while collaborating to understand systemic interactions.

Through structured discussions, MES artificial experts produced insight requirements for each area, and about inter-area relationships. The Urban Design Historian emphasized how physical structures embody temporal layers of social intention. The Architectural Phenomenologist explained how spatial volumes create experiential hierarchies transcending mere physical measurement. The Social Geographer demonstrated how spatial experience directly translates to social positioning through proximity regulation. The Sociologist revealed how spatial-social arrangements become codified into self-reinforcing normative expectations. The Behavioral Psychologist showed how spatial arrangements compel behavior through multiple mechanisms including affordances and observational learning. The Cognitive Neuroscientist explained how habitual behaviors create measurable neural changes through preferential synaptic strengthening. The Systems Integration Specialist synthesized these insights into integrated requirements, revealing how each layer both constrains and enables adjacent layers.

This collaborative agentic approach proved essential for understanding how modifications in any knowledge area create cascading effects throughout the system, making it emerge the bridging requirements, and identifying critical junctures where small changes produce impacts. The resulting requirements are explained in the next Section 3.

## 3 Multi-layer requirements

The architecture emerging from MES includes seven knowledge layers that ultimately connect physical environmental features to neural responses. The architecture is meant to address the limitations of traditional environmental psychology approaches, which often focus on isolated variables without considering their complex interactions. The architecture has been used as requirements to design the ontologies applied in the conditioning of LLMs for environmental tacit knowledge extraction.

### 3.1 Layer architecture

Seven layers represent distinct but interconnected levels of analysis, each capturing specific aspects of the environment-human

relationship while contributing to an integrated understanding of spatial experience.

Layer 1: Physical Environment constitutes the foundational level, encompassing tangible architectural and urban design elements. This layer includes structural elements such as buildings, boundaries, and materials; spatial relationships including proximities, heights, and sightlines; and environmental conditions such as light, sound, and movement pathways. These measurable, objective features of the built environment can be documented through traditional architectural methods and enhanced through contemporary techniques such as photogrammetric reconstruction and material analysis. The physical layer provides the substrate upon which all other experiential layers are built, yet its influence extends far beyond mere constraint—the specific configuration of physical elements actively shapes possibilities for experience and behavior.

Layer 2: Experiential Environment captures the translation of physical features into possibilities for action and sensory experience. This layer encompasses spatial affordances and constraints, sensory experiences including visual hierarchies and acoustic qualities, and movement possibilities and limitations. It bridges objective physical properties with subjective human experience, operationalizing Gibson's concept of "affordances"—the action possibilities offered by the environment (Gibson, 1979). For instance, the height differential between civic buildings and common structures does not merely represent a physical measurement but creates experiential hierarchies of prominence and dominance that profoundly influence how people navigate and understand the urban space.

Layer 3: Social Dynamics addresses how spatial configurations enable and constrain social interactions. This layer includes access regulations both explicit and implicit, visibility and surveillance dynamics, as well as opportunities and limitations for status display. Built environments contain social activities but also actively shape them through visibility patterns that determine who can see whom, proximity regulations that govern social distances, and territorial demarcations that establish group boundaries. As spatial experiences directly translate to social positioning, a piazza becomes not simply a void between buildings but a carefully calibrated arena where social proximity and distance are regulated through architectural means.

Layer 4: Normative Regulation captures the implicit and explicit rules governing behavior in different spatial contexts. This layer encompasses behavioral expectations that vary by location, ritual and ceremonial scripts embedded in spatial design, and the boundaries and consequences of transgression. These norms emerge from the interaction of cultural values with spatial affordances, creating location-specific behavioral codes that become self-reinforcing through visibility and social enforcement. When spatial-social arrangements become codified into normative expectations, the physical environment functions as a silent educator, continuously instructing inhabitants about appropriate conduct.

Layer 5: Behavioral Manifestation documents the observable behaviors emerging from the interaction of spatial affordances, social dynamics, and normative expectations. This layer includes habitual movement patterns that develop through repeated navigation, frequencies and qualities of social interaction shaped by spatial configuration, and the performance of social roles in spatially

appropriate ways. It represents the actualization of behavioral possibilities within environmental constraints, where spatial arrangements compel behavior through multiple mechanisms including affordances that make certain actions easier, constraints that make others difficult, and observational learning facilitated by visibility patterns.

Layer 6: Cognitive Processing addresses the mental processes engaged by environmental features. This layer encompasses how spaces direct attention through visual hierarchies and focal points, facilitate memory formation and association through distinctive features and regular patterns, and reinforce mechanisms of personal and social identity through repeated exposure to status-confirming spatial arrangements. The cognitive layer represents the interface between environmental stimuli and conscious experience, where automatic processing of spatial information shapes thoughts, memories, and self-concept.

Layer 7: Neural Activation is the brain activity that underlies all other layers—it's the biological foundation for how we experience and respond to our environment. This includes three key brain processes: spatial navigation (involving brain cells that help us understand location and movement), social awareness (particularly in brain regions that process social situations), and emotional responses (pathways that connect environmental features to our feelings). When we repeatedly experience certain places or situations, our brains literally rewire themselves through neuroplasticity, strengthening the neural connections associated with those experiences. These brain changes often happen without our conscious awareness, creating automatic responses to environmental cues that can last a lifetime.

### 3.2 Inter-layer relationships

The explanatory power of those requirements adds value from understanding their interconnections. Each layer both constrains and enables adjacent layers through specific bridging mechanisms that create cascading effects throughout the system.

The relationship between Physical and Experiential layers demonstrates how material properties and spatial configurations create affordances and sensory experiences. Architectural elements such as ceiling height, room geometry, and material textures do not merely exist as neutral features but actively create perceptions of volumes, boundaries, and relationships. A narrow doorway does not simply restrict physical passage but creates an experiential transition that heightens awareness of moving between spaces (Radvansky and Copeland, 2006). The acoustic properties of hard surfaces *versus* soft furnishings shape the auditory environment, influencing whether a space feels intimate or exposed (Barron, 1993).

The Experiential to Social transition reveals how sensory experiences and movement possibilities shape patterns of social encounter. Spatial configurations that create natural gathering points through comfortable microclimate conditions or attractive views facilitate certain types of social interaction while discouraging others. The regulation of social proximity through architectural means—such as the width of pathways determining whether people must acknowledge each other when passing—demonstrates how experiential features translate directly into social dynamics (Hall, 1966).

The crystallization of Social patterns into Normative expectations represents a crucial transition where repeated behaviors become codified rules. When certain spatial arrangements consistently produce specific social configurations—such as hierarchical seating in religious buildings—these patterns transform into expectations about appropriate behavior. The visibility of norm compliance or violation, facilitated by spatial design, creates self-reinforcing systems where social pressure maintains behavioral standards without explicit enforcement.

The Normative to Behavioral relationship encompasses how internalized rules guide actual behavioral choices. This influence operates through multiple channels: affordances that make norm-compliant behavior easier, constraints that make violations more difficult, and the observational learning that occurs when behavioral models are visible to others. The spatial environment thus functions as a behavioral script, continuously cueing appropriate actions through its configuration.

The progression from Behavioral patterns to Cognitive schemas represents the internalization of spatial experience into mental models. Habitual movement patterns shape cognitive maps not merely of physical space but of social space—understanding where one belongs and how to navigate social hierarchies embedded in spatial form. Regular behaviors in specific locations strengthen associations between places and activities, creating cognitive schemas that automatically activate when entering similar spaces.

The final transition from Cognitive processing to Neural activation represents the biological encoding of environmental experience. Repeated cognitive patterns, such as processing social hierarchies in spatial terms when navigating status-marked environments, create preferential neural pathway strengthening. The convergence of spatial and social information in brain regions such as the temporoparietal junction illustrates how architectural experience becomes neurologically embedded, creating structural brain changes through neuroplasticity that persist long after leaving the environment.

These relationships operate bidirectionally, creating feedback loops that allow higher-level processes to influence lower-level configurations. Social movements advocating for accessible design, for instance, originate in cognitive recognition of exclusion (Layer 6), manifest through collective behavior (Layer 5), challenge existing norms (Layer 4), alter social dynamics (Layer 3), demand new experiential possibilities (Layer 2), and ultimately result in physical modifications such as ramp installations (Layer 1).

These system-driven requirements should also account for temporal dynamics, since environmental influences operate across multiple timescales. Immediate responses, such as the rapid activation of the Anterior Cingulate Cortex (ACC) when encountering curvilinear *versus* rectilinear forms (Banaei et al., 2017), occur within milliseconds. Medium-term adaptations, such as the development of cognitive maps and behavioral routines, unfold over days to months. Long-term impacts, including the neural architectural changes associated with chronic environmental exposure, may develop over years or decades. Our ontological structure must therefore incorporate temporal operators that can represent these varied timescales and their interactions.

## 4 Case study: pachino's central square

An application of the analytic requirements in Section 3 to Pachino's central square in Sicily intends to demonstrate how architectural design functions as social engineering, shaping not merely behavior but neural development itself. The analysis is performed across two time periods—1910 and 2025—revealing how design modifications continue to influence human experience across all analytical dimensions.

### 4.1 Historical context

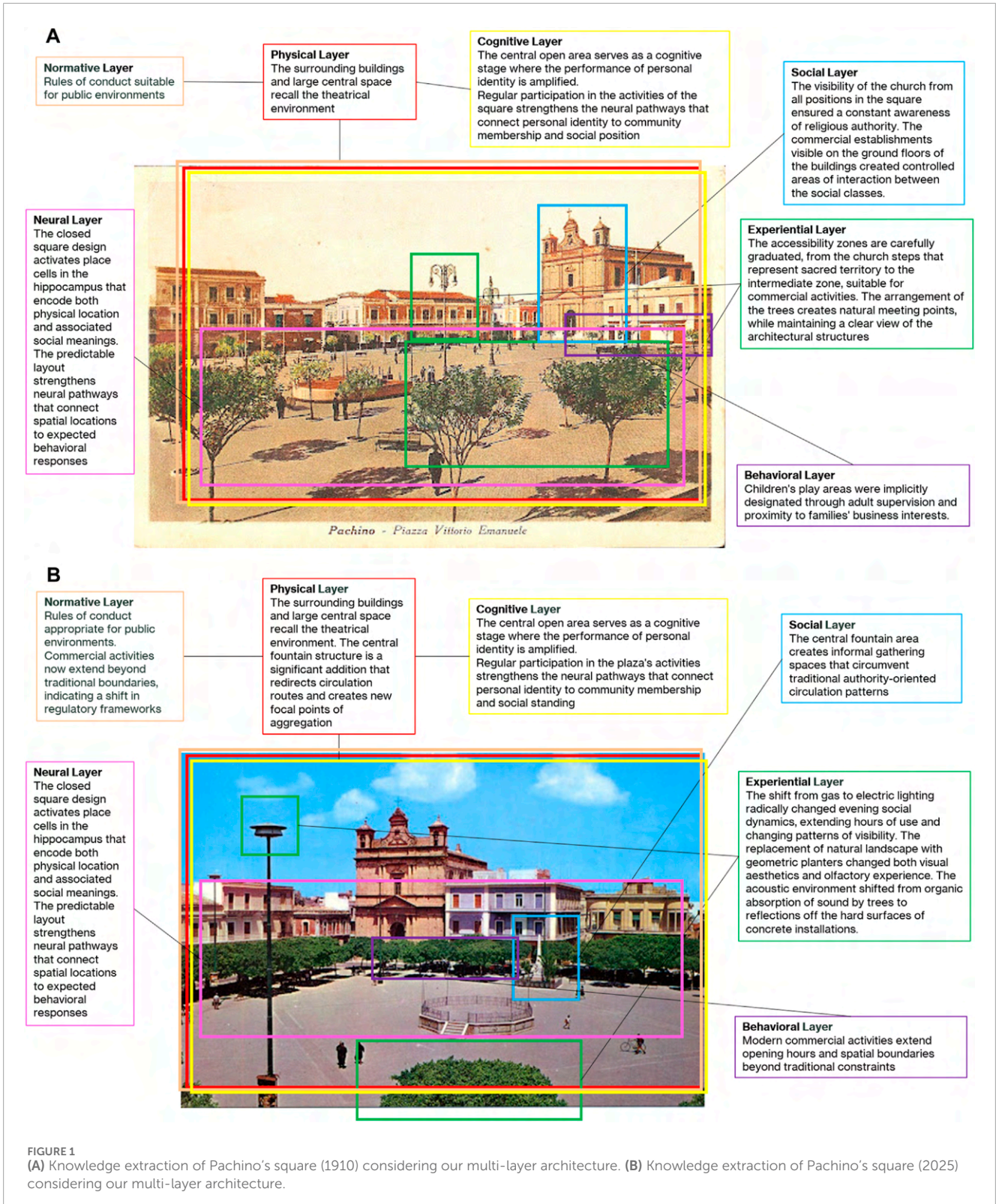
Pachino's central square, established in the 18th century, exemplifies the deliberate encoding of social hierarchy through architectural means. The square's carefully orchestrated layout—positioning the Town Hall, Chiesa Madre (Mother Church), aristocratic homes, and commercial establishments around a central void—created what we might now recognize as a sophisticated apparatus for social control and identity formation. This was not merely a gathering space but a three-dimensional diagram of power relations made manifest in stone and space.

The square operated as what Foucault (1979) might have termed a “disciplinary mechanism,” though predating his analysis by centuries. The design created a spatial panopticon where visibility ensured behavioral compliance without constant active surveillance. Citizens moving through the square necessarily performed their social roles under the watchful presence of institutional architecture. The centralization of civic, religious, and economic power around a single space ensured that daily life continuously reinforced existing hierarchies. Regular gatherings for market days, religious festivals, and civic ceremonies transformed abstract social relations into embodied experiences, with each person's position in the square reflecting and reinforcing their position in society.

### 4.2 Multi-layer analysis

A detailed analysis across the seven requirement layers shows a complex system where physical design elements cascade through multiple processing layers to shape individual and collective experience. The comparison between 1910 and 2025 configurations demonstrates both continuity and change in these multilayered influences (Figure 1).

Layer 1: Physical Environment Analysis (what are the fundamental tangible architectural and urban design elements?). In the historical configuration of 1910, the Chiesa Madre's positioning as the dominant architectural anchor was no accident—its elevated position and ornate facade created an unavoidable focal point from any position within the square. The municipal investment in ornate street lighting, visible in period photographs, indicates recognition of the square's role as civic theater. The rectangular perimeter of three-story buildings created an enclosed environment that focused attention inward while establishing clear boundaries between public and private space. Contemporary modifications include the replacement of organic landscaping with standardized concrete planters, altering the square's microclimate and sensory qualities. Modern lighting systems extend usable hours but change



the quality of evening illumination from the warm, variable glow of gas lamps to uniform electric brightness.

Layer 2: Experiential Environment Analysis (how physical features translate into possibilities for action and sensory experience?). The historical configuration's carefully graduated

zones of accessibility created what Alexander might term an "intimacy gradient"—from the sacred threshold of the church steps through the commercial middle ground to the informal edges. Natural tree placement created comfortable microclimates while maintaining visual connections to authority structures,

balancing comfort with surveillance. The elevation changes between different areas established natural viewing hierarchies that reinforced social stratification through embodied experience. Contemporary modifications have fundamentally altered these experiential qualities. The transition from gas to electric lighting extends activity hours but eliminates the temporal rhythms created by the labor of lamplighters and the gradual dimming of fuel-based illumination. Geometric planters provide less shade and seasonal variation than trees, reducing sensory richness while increasing visual uniformity. The acoustic environment has shifted from organic sound absorption to hard surface reflections, creating a more reverberant space that may increase stress through noise exposure.

**Layer 3: Social Dynamics Analysis** (how spatial configurations enable and constrain social interactions?). Historical photographs from 1910 demonstrate clear spatial segregation patterns, with formal dress indicating elite presence near institutional buildings while working-class figures occupy peripheral positions. This was not merely customary but architecturally enforced—the design created natural territories that would feel inappropriate to transgress. The visibility of the church from all positions ensured constant awareness of religious authority, creating what we might term “architectural conscience.” Ground-floor commercial establishments provided controlled interaction zones where different classes could engage in necessary economic exchanges within defined spatial and behavioral parameters. Contemporary patterns show significant democratization, though subtle hierarchies persist. Economic barriers replace some spatial ones—outdoor café seating creates new forms of territorial exclusion based on consumption rather than birthright. Tourist presence introduces unprecedented diversity in behavioral norms and spatial usage patterns. The central fountain area enables informal gatherings that bypass traditional circulation patterns focused on institutional buildings, creating new possibilities for social formation outside established hierarchies.

**Layer 4: Normative Regulation Analysis** (what rules govern behavior in different spatial contexts?). Historical religious processions followed routes that physically enacted theological hierarchies—the path from Chiesa Madre through the square created a sacred geography that participants bodily experienced. Market activities were spatially confined with implicit rules about appropriate commercial behavior varying by location within the square. Dress codes and deportment expectations created invisible boundaries more powerful than physical barriers. The positioning of civic buildings enabled surveillance while church bells provided temporal regulation, structuring daily rhythms through acoustic signals that penetrated private space. Contemporary norms show relaxation of formal restrictions while maintaining underlying respect patterns. Tourism introduces negotiation between local expectations and visitor behaviors, creating dynamic normative landscapes. Commercial activities now extend beyond traditional boundaries both spatially and temporally, indicating fundamental shifts in the regulation of economic life.

**Layer 5: Behavioral Manifestation Analysis** (how spatial affordances translate into observable behaviors?). Historical promenading patterns followed prescribed routes that displayed social status while respecting institutional boundaries—a “passeggiata” was not random wandering but choreographed social display. Religious observances created predictable gathering and

dispersal patterns tied to liturgical schedules, with the square’s design facilitating efficient crowd flows during major festivals. Commercial interactions followed temporal rhythms aligned with agricultural cycles and religious calendars. Spatial analysis describes how people maintained appropriate distances from authority structures while maximizing visibility within acceptable zones. Contemporary behaviors show increased informality though persistent structural influences. Tourist photography introduces new spatial practices—the search for optimal viewpoints creates novel circulation patterns. Extended commercial hours and relaxed spatial boundaries reflect changed economic structures. Yet respect for religious space boundaries persists, suggesting deeply internalized spatial norms resistant to surface modernization.

**Layer 6: Cognitive Processing Analysis** (how the square shapes mental processes across time periods?). The Chiesa Madre’s architectural prominence creates automatic attentional capture, priming religious consciousness regardless of conscious intention. The symmetrical building arrangement guides visual scanning in patterns that continuously return attention to institutional structures (Yarbus, 1967). The central void functions as a cognitive stage where personal identity performance becomes heightened through visibility. Landmark buildings serve as spatial anchors for episodic memory formation, with personal experiences becoming intertwined with institutional presence (Janzen and van Turenout, 2004). Regular participation in square activities strengthens neural pathways connecting personal identity to community membership. The predictable spatial layout facilitates cognitive mapping while embedding social hierarchies within spatial memory structures.

**Layer 7: Neural Activation Analysis** (what are the biological substrates of spatial experience?). The enclosed square design activates hippocampal place cells that encode not merely physical location but associated social meanings—neural maps that integrate “where” with “who belongs where” (Tavares et al., 2015). The predictable layout strengthens neural pathways connecting spatial positions to behavioral repertoires through repeated activation patterns. Proximity to authority structures triggers amygdala activation related to social vigilance, creating embodied respect through mild stress responses (Adolphs, 2010). Mirror neuron systems activate through observation of others’ spatial behaviors (Rizzolatti and Sinigaglia, 2004), facilitating rapid social learning of appropriate conduct. Positive experiences during community celebrations create dopaminergic reinforcement, associating the space with social reward and belonging (Bhanji and Mauricio, 2014). The integration of spatial and social processing in regions like the temporoparietal junction illustrates how architectural experience becomes neurologically embedded (Saxe and Kanwisher, 2003). Regular exposure from childhood literally shapes neural architecture, creating lifelong predispositions that persist even as conscious beliefs may change.

The Pachino analysis demonstrates how architectural design creates environments where abstract social concepts become lived neural realities. The square functions as a machine to influence people—citizens whose neural pathways have been shaped by repeated exposure to spatial hierarchies. The comparison between historical and contemporary configurations shows persistence and change. While surface behaviors may appear modernized, continuing influences of spatial structure on social dynamics and individual experience are still present. Physical modifications create

new possibilities while earlier patterns leave traces in collective memory and learned behaviors.

The social engineering impact of Pachino's spatial configuration lies not merely in its physical persistence but in its capacity to create self-reinforcing systems across multiple analytical layers. Even as contemporary modifications introduce new elements—electric lighting, concrete planters, tourist flows—the fundamental spatial grammar established centuries ago continues to organize experience. This is a principle for urban design: architectural interventions create cascading effects that persist far beyond their original context, embedding themselves in neural structures, social practices, and cultural memory in ways that resist simple modernization. The square thus serves as both historical artifact and living laboratory, revealing how built environments function as active agents in the continuous production of human consciousness and community life.

## 5 BEACON: a formal ontology network of environmental experience

We have translated the systematic requirements from Section 4 into BEACON (Built Environment Architecture Cognitive Ontology Network), a formal ontology network<sup>2</sup> that serves multiple functions. It enables computational reasoning about environmental-human relationships, provides a rigorous vocabulary for interdisciplinary communication, and establishes logical foundations for integrating different data types. We use the Web Ontology Language (OWL, W3C, 2009), ensuring compatibility with knowledge graph technologies and knowledge representation standards. The agile, pattern-based methods described by Hitzler et al. (2016) have been applied to design ontologies that follow domain and task requirements, as explained in the previous sections.

### 5.1 The ESBM ontology: a neurocognitive foundation

The Environment-Sensorimotor-Behavior-Modulation (ESBM) ontology provides the neurocognitive foundation for neuroarchitectural knowledge extraction. It formally models the low-level neurophysiological mechanisms that link an agent's perception of the environment to their automatic, sensorimotor-driven behaviors. It focuses on the “how” of human-environment interaction from a predictive processing (Friston, 2010) and enactive neuroscience perspective.

#### 5.1.1 Core ontology patterns

The ESBM ontology is structured around a few core ontology patterns that represent agents with their neurocognitive architecture and the immediate stimuli they encounter (Figures 2–5):

1. Agent as Substrate: At the center is `dul:Agent`, imported from the DOLCE Ultra Lite foundational ontology (Presutti

and Gangemi, 2016)<sup>3</sup>. The core axiom establishes that an agent is inextricably linked to its own neurocognition: every `esbm:NeuralStructure` (e.g., `esbm:Pulvinar`) is axiomatically defined as something that `dul:isPartOf` some `dul:Agent`, which `dul:isParticipantIn` a `esbm:NeuralProcess` (e.g., `esbm:PredictiveProcess`), and a `esbm:NeuralStructure esbm:isSubstrateFor` a `esbm:NeuralProcess`.

2. Stimulus-Response Pattern: This pattern models the immediate interaction with the environment. An `esbm:EnvironmentalFeature` represents a distinct aspect of the environment that `esbm:elicits` an `esbm:SensorimotorResponse`, the core class representing a neuro-body reaction.
3. Predictive Coding Pattern: This pattern models the brain's predictive mechanisms. A `esbm:Prediction` is an `esbm:NeuralRepresentation` that is compared against an incoming `esbm:SensorySignal`. This comparison possibly `esbm:generates` a `esbm:PredictionError`, which in turn `esbm:updates` the original `esbm:Prediction`, completing the error-correction loop. Predictions are the neural grounding of conceptual *frames*, i.e., situation schemas that are used to anticipate and interpret environmental situations (`esbm:Prediction esbm:isShapedBy` a `framester:Frame`).
4. Thalamic Integration Pattern: This pattern represents the role of thalamic nuclei in processing information. Since the ontology distinguishes neural structures from the processes they host, `esbm:Pulvinar` structures do not directly modulate activity, but `esbm:Pulvinar esbm:isSubstrateFor` a `esbm:NeuralProcess` which, in turn, `esbm:modulates` neural oscillations like `esbm:AlphaRhythm`. This structure-process distinction, combined with detailed property hierarchies (e.g., making `esbm:regulates` and `esbm:modulates` sub-properties of a general `esbm:influences` property), creates a more verifiable and precise model.

ESBM is a reusable foundational model of the low-level machinery that allows an agent to perceive and automatically react to their environment, grounding higher-level descriptions (*frames*) of the experience (*frame occurrences*) of environmental features in plausible neurophysiological processes.

### 5.2 The BEL ontology: modeling the multi-layered environmental experience

The Built Environment Layers (BEL) ontology represents how built environments shape human experience. It imports ESBM to ground built environmental experience analysis across seven distinct but interconnected layers. Where ESBM focuses on the low-level “how,” BEL provides the structure for the higher-level “what” and “why.”

#### 5.2.1 Core patterns

BEL represents an experience as a hub that connects components from the analytical layers described in previous sections (Figure 6):

<sup>2</sup> <https://github.com/aldogangemi/builtenvironmentexperience>

<sup>3</sup> <http://www.ontologydesignpatterns.org/ont/dul/DUL.owl>

1. The `bel:EnvironmentalExperience` Hub: This is the core class of the BEL ontology. It is a subclass of `framester:FrameOccurrence`, conceptualizing an experience as a specific, active, contextualized instantiation of a conceptual frame. Axioms enforce that every `bel:EnvironmentalExperience` must have a `dul:Agent` as its `bel:hasExperiencer` and must involve components from all seven aspects: `bel:involvesPhysicalElement`, `bel:involvesAffordance`, `bel:involvesSocialPattern`, `bel:involvesNormativeRule`, `bel:involvesBehavioralPattern`, `bel:involvesCognitiveProcess`, and `bel:involvesNeuralResponse`.
2. The Causal Chain Pattern: The primary structural pattern in BEL is the causal flow of influence between the layer aspects, modeled with a chain of object properties. A `bel:PhysicalElement` `bel:enables` an `esbm:Affordance` (the experiential aspect); this `esbm:Affordance` then `bel:shapes` a `bel:SocialPattern`, which `bel:crystallizesInto` a `bel:NormativeRule`. The `bel:NormativeRule` `bel:guides` a `bel:BehavioralPattern`, which `bel:influences` a `bel:CognitiveProcess`. Finally, the `bel:CognitiveProcess` `bel:activates` an `esbm:SensorimotorResponse` (the neural aspect). This flow is enforced through axioms, making the dependency chain explicit.
3. Temporal Dynamics and Measurement: The BEL ontology incorporates time and measurement to enable diachronic analysis and empirical grounding. Temporal classes like `bel:HistoricalConfiguration` and `bel:ExperientialMoment` allow for modeling across different timescales. Data properties such as `bel:hasFractalDimension` and `bel:hasAttentionDuration` provide hooks for associating quantitative data with conceptual entities, linking the formal model to measurable real-world phenomena.
4. Grounding in ESBM: The BEL ontology ensures its higher-level concepts are grounded in neuroscience by linking them directly to ESBM classes. For instance, `bel:CognitiveProcess` is a subclass of `esbm:NeuralProcess`, and the experiential and neural aspects are directly represented by `esbm:Affordance` and `esbm:SensorimotorResponse`, respectively.

BEL's `bel:EnvironmentalExperience` with the causal flow between its constituent parts, provide a transdisciplinary theory to represent and reason about how built environments shape human and social life.

### 5.3 The SIM ontology: modeling the dynamics of active inference

The Active Inference Simulation (SIM) ontology provides the vocabulary and formal structure needed to simulate the dynamic, cyclical process of an agent's enacted cognition. While the BEL and ESBM ontologies describe the “what” (the layers of experience) and the underlying “how” (the neurocognitive machinery), the SIM ontology models the “when” and “why” of the agent's actions over time. It makes the steps of the active inference loop—perception, belief updating, prediction, and action—explicit and traceable.

#### 5.3.1 Core patterns

The SIM ontology is designed with patterns that represent the stateful and probabilistic nature of agents' interaction with their environment (Figure 7).

**The State Chain Pattern:** The simulation's timeline is modeled as a sequence of discrete `sim:SimulationState` individuals, linked by the `sim:precedesState` property. Each state represents a snapshot of the simulation, containing the agent's observations, beliefs, and the outcomes of its inferences at that moment (`sim:atTimeStep`).

**The Stratified Prediction Pattern:** A crucial distinction is made between two levels of prediction. The high-level, conceptual `sim:Prediction` (e.g., predicting a social event) is formally linked to the underlying neurocognitive machinery that implements it via the `sim:isRealizedBy` property, which points to an `esbm:PredictiveProcess`. This explicitly connects the cognitive stratum to the neural stratum.

**The Probabilistic Belief Pattern:** The agent's cognitive state is represented as a probabilistic landscape. A `sim:AgentBeliefState` `sim:hasBelief` in multiple `sim:Belief` individuals. Each `sim:Belief` is a qualified statement about a state of affairs (`sim:aboutState`) and is associated with a specific `sim:hasProbability`, representing the agent's confidence.

**The Policy Selection Pattern:** Active inference frames action as selecting the best `sim:Policy` from a set of possibilities. Each policy is annotated with its calculated `sim:withExpectedFreeEnergy` (EFE) and a resulting `sim:hasSelectionProbability`. The agent selects the policy that is most likely to minimize EFE, and this choice is recorded in the state chain via the `sim:hasSelectedPolicy` property.

By formalizing these dynamic and probabilistic patterns, the SIM ontology makes BEACON move from the static description of an environment to a dynamic simulation of an agent enacting its experience within that environment.

Figure 8 provides an interlayer diagram for the main classes and properties from the three ontology modules.

### 5.4 The pachino ontology: a case study

The Pachino ontology serves as a concrete instantiation and proof-of-concept for the ESBM and BEL modules of BEACON. It translates a qualitative description of a built environment—the main square of Pachino, Sicily—into a formal, machine-readable knowledge graph. Its purpose is to validate the theoretical models and to create a dataset that can be queried to generate insights and answer complex questions.

The ontology primarily consists of individuals (entities, relations, facts) that are instances of classes defined in BEL and ESBM. It models two main scenarios, each represented as a distinct individual of type `bel:EnvironmentalExperience`: `pachino:PachinoExperience_1910` and `pachino:PachinoExperience_2025`. Each experience is linked to a `dul:Agent` (e.g., `pachino:HistoricalCitizen_Generic`) and a temporal configuration (e.g., `pachino:PachinoTime_1910`).

Components from each layer are instantiated and linked to their respective experience. For example, for the 1910 experience:

1. Physical: The “dominant architectural anchor” is instantiated as `pachino:PE_ChiesaMadreAnchorage_1910`

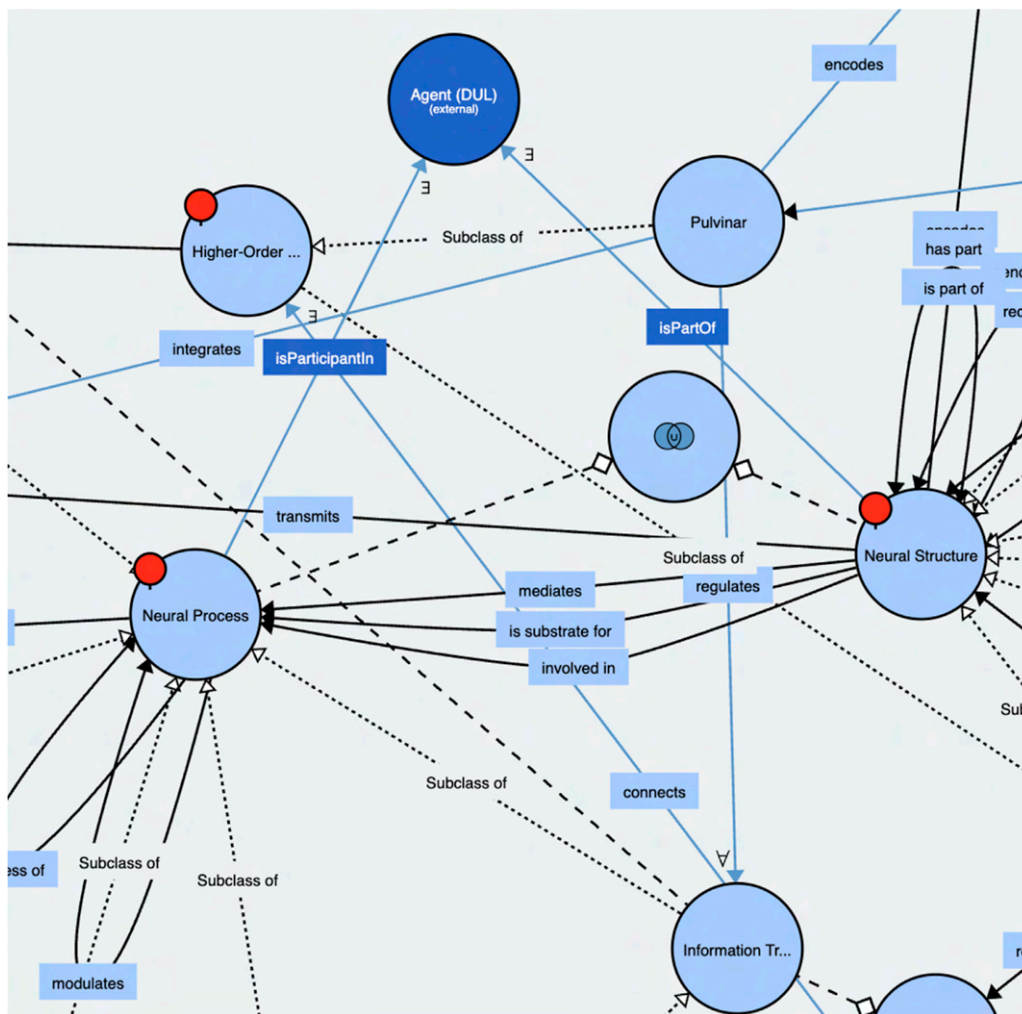


FIGURE 2  
ESBM: Agents and their neural structures as substrates of processes.

(a bel:PhysicalElement) and linked to the experience via bel:involvesPhysicalElement.

2. Experiential: This physical element bel:enables the pachino:EA\_GraduatedAccessibility\_1910 affordance.
3. Social: This affordance, in turn, bel:shapes the pachino:SP\_SpatialSegregation\_1910 social pattern.
4. Normative, Behavioral, Cognitive, and Neural: The causal chain is instantiated layer by layer, connecting individuals like pachino:NR\_SacredProcessionsRoutes\_1910, pachino:BP\_FormalPromenading\_1910, pachino:CP\_AttentionalCaptureChiesa\_1910, and finally a specific neural impact like pachino:NR\_AmygdalaActivation\_Authority\_1910 (an esbm:SensorimotorResponse). Each is connected to the pachino:PachinoExperience\_1910 and to the prior element in the chain, making the flow of influence explicit at the instance level.

The same process is repeated for the 2025 configuration, creating a parallel set of instances that allows for direct comparison. The Pachino knowledge graph exemplifies how to make the ESBM and

BEL testable, allowing researchers to formally trace a path from a design decision to its predicted neural impact.

### 5.5 A neurosymbolic simulation of an enacted environmental experience

The static descriptions provided by the ESBM and BEL ontologies, even when instantiated as a rich knowledge graph like pachino.owl, represent a snapshot in time. To provide an embodied foundation for tacit knowledge extraction, we also simulate the dynamic coupling between an agent and its environment, using the SIM ontology. The active inference component, which underpins the ESBM ontology, requires a predictive or generative engine (Parr et al., 2024) to anticipate plausible futures and to guide behavior. While a full probabilistic implementation is not in the scope of this paper, we can effectively simulate a generative Bayesian engine using a Large Language Model (LLM) as a “neurosymbolic oracle” tasked with generating plausible knowledge graph updates that represent the agent’s predictions. The

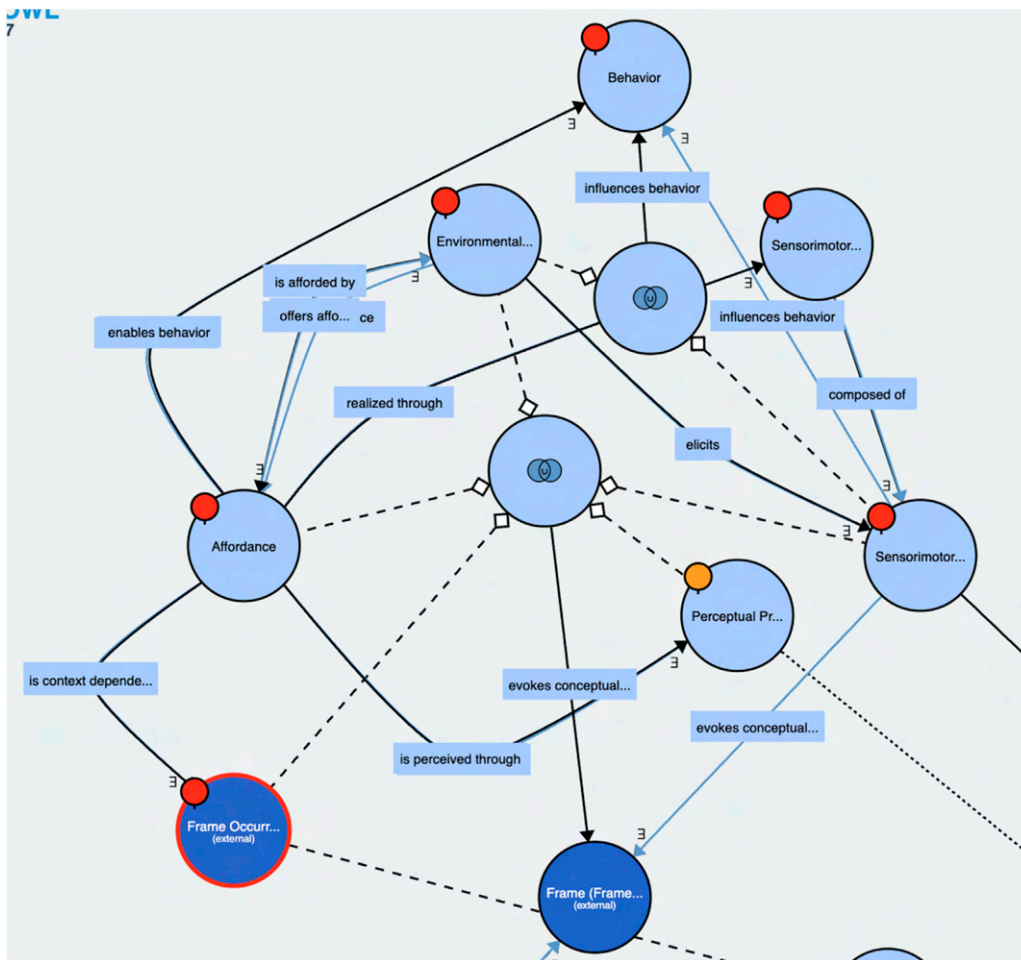


FIGURE 3  
ESBM: Sensorimotor responses elicited by environmental features.

process unfolds as a cyclical loop, moving from the current state of the knowledge graph to an LLM-generated prediction, which then informs an action that updates the knowledge graph for the next cycle.

### 5.5.1 Simulation flow: a minimal case from Pachino (2025)

Let's consider a minimal case: a `dul:Agent` (e.g., a modern tourist) begins its `bel:EnvironmentalExperience` in the contemporary Pachino square (`pachino:PachinoExperience_2025`). We will represent the dynamic simulation as a series of states.

State  $t = 0$ : Initial Perception and Prior Beliefs.

- Knowledge Graph State (KG<sub>t0</sub>): The simulation begins with an initial state. The knowledge graph contains the agent, their ongoing experience, and their first key observation.
  - `pachino:ModernTourist_Generic` `rdf:type` `dul:Agent`.
  - `pachino:Pachino Experience_2025` `bel:has` `Experiencer` `pachino:ModernTourist_Generic`.

- `pachino:Pachino Experience_2025` `bel:involves` `Physical Element` `pachino:PE_Central Elevated Structure_2025`.

- The Generative Task (LLM Conditioning): We provide this initial KG state to the generative engine (the LLM). The conditioning asks the LLM to act as the agent's internal generative model, based on the ESBM and BEL ontologies.

“You are an agent situated in an environment described by the following knowledge [a serialization of KG<sub>t0</sub>]. You have just perceived the `pachino:PE_CentralElevatedStructure_2025`. Based on the causal patterns in the BEL ontology, generate a “Predicted KG” that represents the most plausible affordances and social patterns this observation predicts.”

State  $t = 1$ : Prediction Generation (The LLM as Generative Engine).

- Knowledge Graph State (KG<sub>predicted</sub>): The LLM, leveraging its understanding of context and the patterns embedded in our

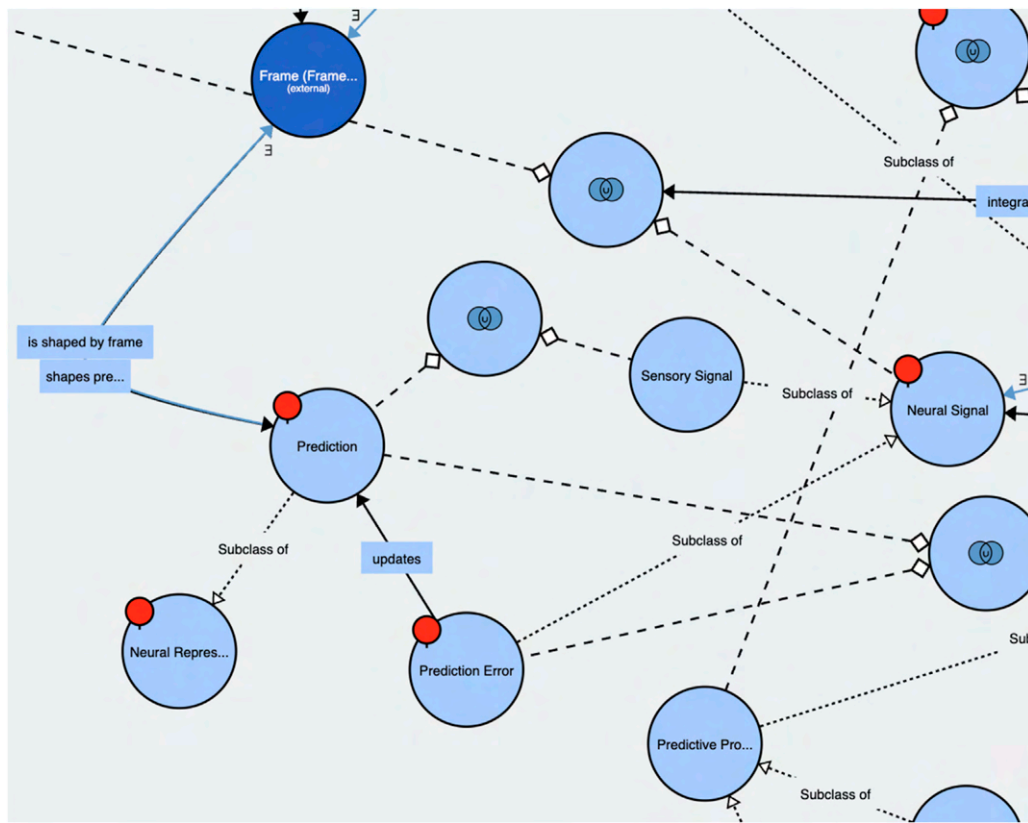


FIGURE 4  
ESBM: The error-correction loop: predictions as frames, compared against sensory signals.

ontology training, generates a new set of triples representing the agent’s prediction. This is the simulation of the agent sampling (predicting) from their internal model of the world. The output is not a single value but a plausible future state of the KG.

- pachino:PE\_CentralElevatedStructure\_2025 bel:enables pachino:EA\_InformalGatheringAffordance\_2025.
- pachino:EA\_InformalGatheringAffordance\_2025 bel:shapes pachino:SP\_InformalGatheringsFountain\_2025.
- Probabilistic Interpretation: While the LLM outputs explicit probabilities, its choice to generate these specific individuals over others (e.g., predicting “informal gathering” instead of “formal promenading”) represents a higher implicit probability for that future state, given the observation of a modern central fountain. This generated KG<sub>predicted</sub> serves as the agent’s expectation that needs to be fulfilled.

State t = 2: Action Selection and KG Update.

- The Generative Task (LLM Prompt): The agent must now select an action (esbm:Behavior) to minimize the “free energy” (the biological grounding of prediction error in Active Inference theory, cf. Friston (2010)) between its prediction and the sensed world state. In our simulation, this means choosing an

action that makes the KG<sub>predicted</sub> coherent with the external situation.

“Your prediction is that the central structure enables informal gatherings. To make this prediction a reality and maintain a coherent experience, which action from the set of possible behaviors should you select?”

- LLM Action Selection: The LLM selects the most coherent action. For instance, it generates a new individual:
  1. Pachino:ApproachesFountainBehavior rdf:type esbm:Behavior; rdfs:label “Approaches central fountain for social interaction”.
- Knowledge Graph Update (KG<sub>t1</sub>): The loop is closed by updating the main knowledge graph with the outcome of the inference cycle.
  1. Action Enactment: The selected action is formally added to the KG and linked to the agent and the experience, creating a record of their enacted choice: pachino:ModernTourist\_Generic esbm:influencesBehavior pachino:ApproachesFountain Behavior.
  2. Belief Update: Because the agent acted to confirm its prediction, the predicted states are now inferred



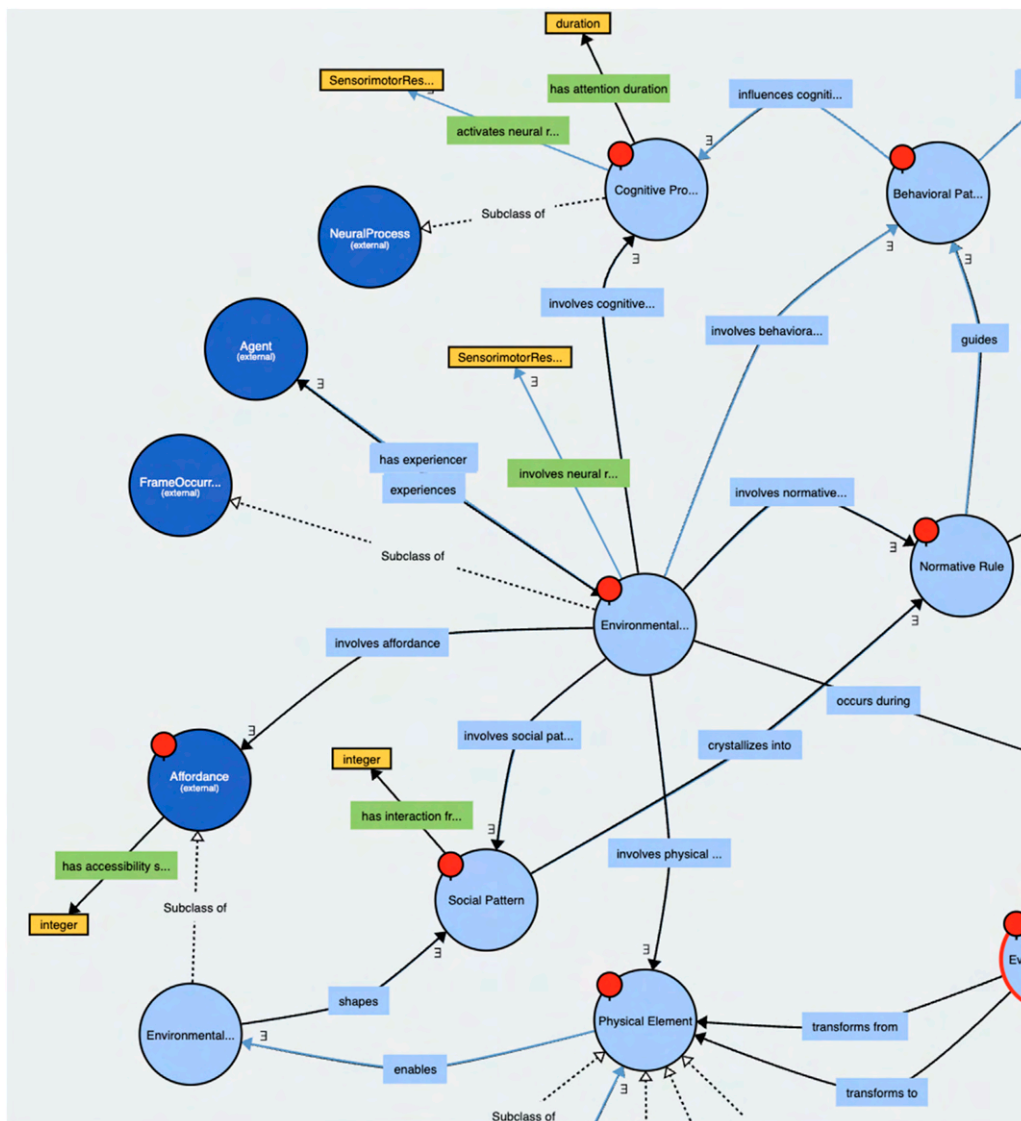


FIGURE 6  
BEL: Environmental experience situations, with affordances, rules, and social/behavioral patterns.

provide environmental tracking with sufficient precision for accurate overlay registration, while LiDAR sensors enable precise depth mapping essential for correct spatial positioning of virtual elements. Eye-tracking sensors serve dual functions, both providing contextualized information delivery based on gaze direction and gathering data about visual attention patterns for validation.

The proposed implementation integrates predictive capabilities with immersive simulation technologies. This enables proactive design optimization and real-time assessment of environmental modifications, moving beyond descriptive research toward prescriptive design tools that can actively improve urban environments for human wellbeing. The integration of augmented reality technologies could represent a significant advancement over current methodological approaches, providing unprecedented opportunities for both research and practical application in

urban design and planning contexts. Here, the idea is to integrate BEACON into wearable technologies like the AR glasses equipped with:

- Camera, to allows users to capture pictures based on an egocentric vision
- Audio with bone conduction, to receive a private verbal communication that grantee the privacy
- Eye-Tracker, to provide contextualized information in real-time

The following workflow presents a schematic representation of the integration between BEACON and wearable technologies starting from users' perspective (Figure 9).

The picture below (Figure 10) shows the application through smart glasses technology, where different analytical layers are

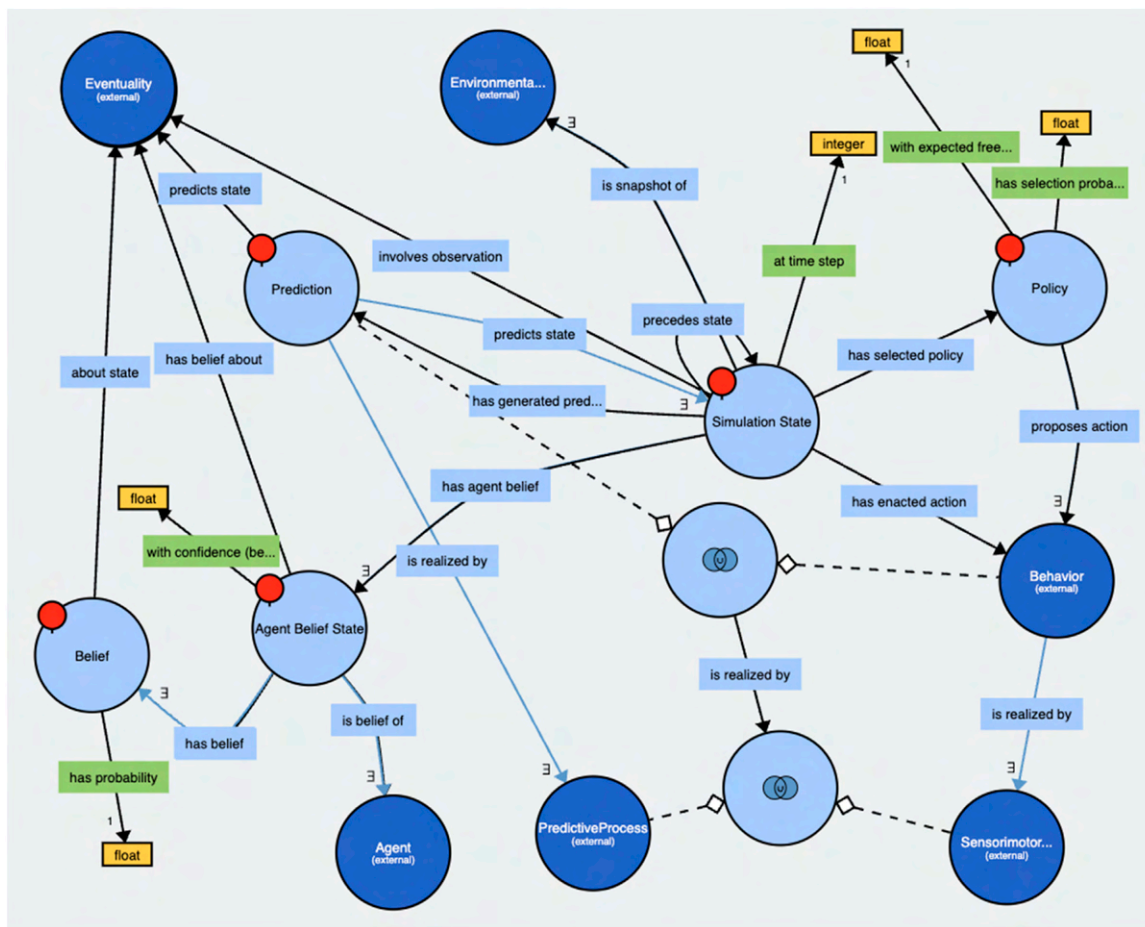


FIGURE 7  
SIM: Agents' interaction with their environment through ordered simulation states with social prediction and policy selection.

superimposed onto the real-world environment, based on the eye-tracker records. The implicit and explicit knowledge will be shared using verbal communication (audio system). The integration of ear-free conduction audio ensures private communication while maintaining environmental awareness, allowing users to receive detailed analytical information without disrupting their natural spatial experience or social interactions with others in the space.

Our system moves beyond static analysis to offer dynamic, context-responsive insights that adapt to individual users and changing environmental conditions.

Through this implementation, users gain a comprehensive understanding of urban environments across multiple analytical dimensions simultaneously.

## 7 Discussion

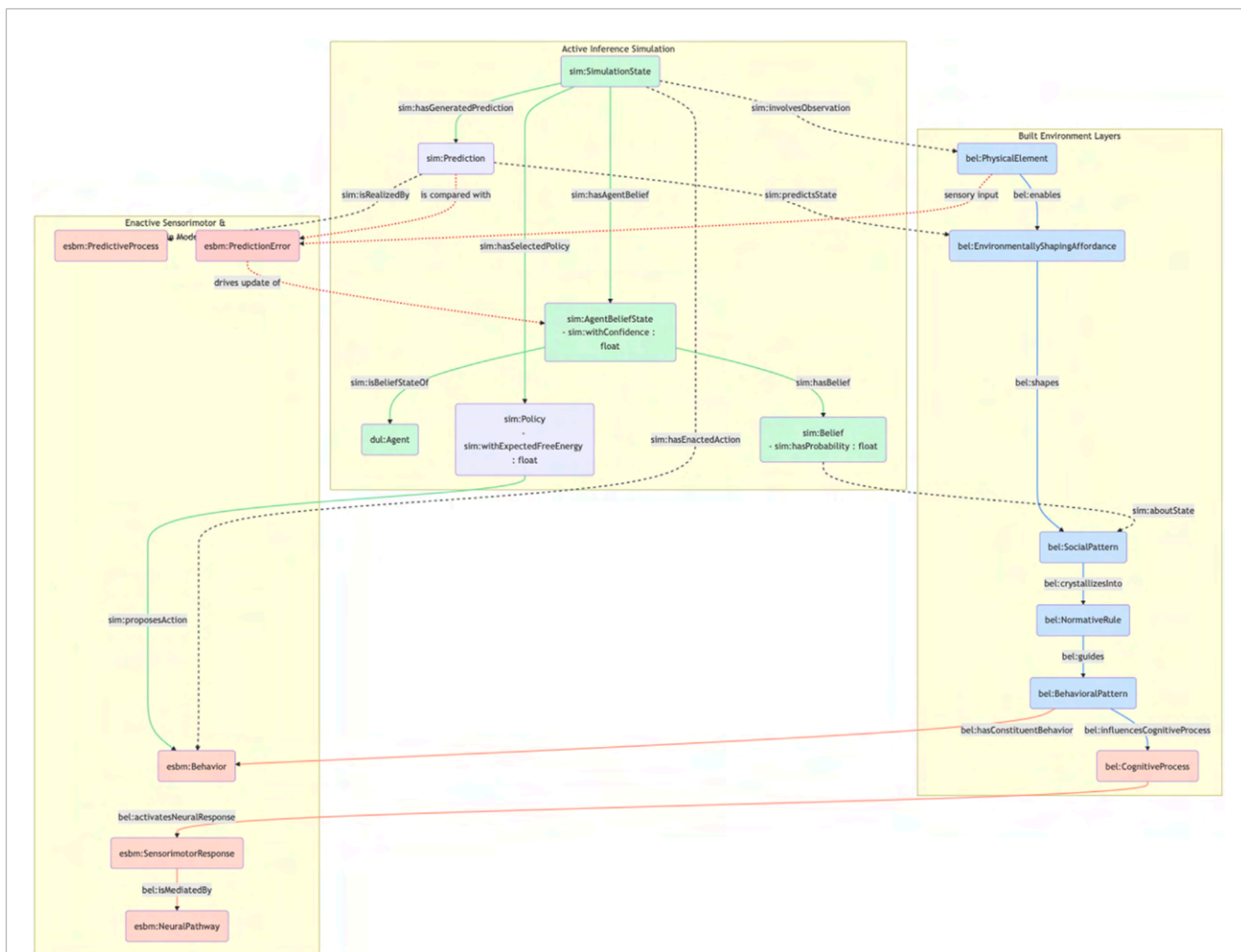
The multi-layered ontological framework presented in this study is both a theoretical advance and a practical tool for understanding and optimizing built environments. Its development and application can reveal insights extending neuroarchitecture to broader questions about human-environment interaction, interdisciplinary integration, and the role of technology in urban planning.

## 7.1 Theoretical contributions

BEACON advances neuroarchitecture theory with the systematic integration of seven analytical layers and moves beyond the fragmented approach characteristic of much environmental psychology research. Rather than studying isolated variables—lighting conditions, spatial configuration, or material properties—in isolation, it facilitates the extraction of how these elements interact systemically to produce emergent effects. This systemic perspective aligns with contemporary understanding of complex adaptive systems while remaining grounded in empirical neuroscientific research.

The transdisciplinary bridge across layers addresses a challenge in environmental research: the integration of objective measurement with subjective experience. By tracing pathways from measurable physical properties through experiential affordances to neural activation patterns, BEACON provides a conceptual structure for understanding how objective environmental features produce subjective experiences. This integration draws on Gibson's ecological psychology, Alexander's pattern language, and contemporary neuroscience to create a unified analytical approach.

The formal ontological specification enables computational reasoning about environmental-human relationships, transforming



**FIGURE 8** BEACON: Prediction-error loops enact behavioral/social predictions from simulation states involving observations of (possibly designed) physical elements, which enable affordances that shape social patterns, eventually predicted by high-level predictions. Prediction-error loops drive updates of belief states about social patterns that can crystallize into normative rules guiding behavioral patterns influencing cognitive processes. Simulation states select policies enacting actions leading to constitutive behaviour of behavioral patterns that on their turn activate sensorimotor responses mediated by neural pathways.

informal observations into logical structures amenable to automated analysis. This formalization serves multiple purposes beyond enabling XR implementation. It provides a precise vocabulary for interdisciplinary communication, reducing misunderstandings arising from disciplinary differences in terminology. The ontological structure enables systematic comparison across case studies, identifying universal patterns while accommodating cultural variation. Perhaps most importantly, it creates a foundation for accumulating knowledge over time, with new findings integrated into the existing structure. BEACON’s formal treatment of temporal dynamics represents another contribution by incorporating multiple timescales—from immediate perceptual responses to generational changes in spatial culture.

## 7.2 Practical implications

BEACON’s practical applications extend across multiple domains of environmental design and urban planning. In urban planning

contexts, the ability to predict how design modifications cascade through social and cognitive layers enables evidence-based decision-making. Planners can evaluate proposals not merely for traffic flow or economic impact but for their comprehensive effects on human wellbeing. The Pachino case study simulates how seemingly minor modifications—replacing trees with planters, changing lighting systems—may create cascading effects through all analytical layers.

Heritage preservation gains new analytical tools for understanding and communicating the significance of historical environments. Beyond preserving physical fabric, the framework reveals how historical spaces encoded social relationships and shaped community consciousness. This deeper understanding can inform preservation strategies that maintain not just buildings but the experiential qualities that made spaces meaningful to their communities. The AR implementation enables immersive heritage interpretation that conveys this multilayered significance to contemporary audiences.

Therapeutic design applications emerge from explicit connection between environmental features and neural responses. Healthcare facilities can be optimized not through intuition but

**TABLE 1** Detailed bridging across the seven layers by mapping between the high-level, symbolic concepts of experience and their underlying neurophysiological implementations.

Layer (from BEL)	Cognitive/Behavioral stratum (The “what”)	Bridging property/Mechanism	Neural stratum (The “how” - ESBM grounding)
1. Physical	A symbolic representation of a real-world object or space, e.g., pachino:PE_ChiesaMadreAnchorage_1910	esbm:elicits	The physical entity is transduced into raw esbm:SensorySignals in the agent’s nervous system
2. Experiential	The agent’s recognition of a meaningful opportunity for action, e.g., the esbm:Affordance of pachino:EA_GraduatedAccessibility_1910	bel:isPerceivedThrough	The affordance is recognized via a bel:PerceptualProcess, which involves the brain integrating sensory signals with predictions
3. Social	The agent’s inference of an abstract social context, e.g., the bel:SocialPattern of pachino:SP_SpatialSegregation_1910	bel:hasNeuralCorrelate	This high-level social inference corresponds to a specific esbm:NeuralActivityPattern in brain regions associated with social cognition
4. Normative	A stored belief about “correct” behavior in a given context, e.g., the bel:NormativeRule of deference to authority	esbm:isShapedByFrame	The rule is encoded as a strong prior within the agent’s generative model, represented by a framerster:Frame that shapes ongoing esbm:Predictions
5. Behavioral	A holistic, observable, and goal-directed action in the world, e.g., the bel:BehavioralPattern of pachino:BP_FormalPromenading_1910	sim:isRealizedBy	The observable behavior is the emergent result of a sequence of low-level esbm:SensorimotorResponse instances (i.e., patterns of motor commands)
6. Cognitive	A discrete, high-level mental event, like a “change of mind” (sim:BeliefUpdateEvent) or a moment of focus (bel:CognitiveProcess)	sim:isTriggeredBy	This cognitive event is precipitated by the accumulation of many underlying esbm:PredictionError signals, which drive synaptic plasticity and belief updating
7. Neural	The direct, subjective feeling associated with a neural event (the “what it is like” to have that response)	Identity/Direct Realization	The esbm:SensorimotorResponse itself, e.g., pachino:NR_AmygdalaActivation_Authority_1910. This is the foundational neurophysiological event

**TABLE 2** Summary of key stratified concepts: the core conceptual pairs enabling the representation of the multi-scale active inference model.

High-level concept (cognitive/Behavioral stratum)	Bridging property	Low-level implementation (neural stratum)	Description of bridge
The Situation (bel:EnvironmentalExperience)	bel:hasNeuralCorrelate	The Brain State (esbm:NeuralActivityPattern)	A high-level, inferred social situation is encoded as a specific pattern of physical brain activity
The Prediction (sim:Prediction)	sim:isRealizedBy	The Predictive Machinery (esbm:PredictiveProcess)	A conceptual prediction about the future is the emergent result of the underlying neurocognitive machinery of predictive coding
The “Aha!” Moment (sim:BeliefUpdateEvent)	sim:isTriggeredBy	The Error Signal (esbm:PredictionError)	A conscious change of belief is triggered by the accumulation of low-level neural signals indicating a mismatch with reality
The Action (esbm:Behavior)	sim:isRealizedBy	The Motor Command (esbm:SensorimotorResponse)	A meaningful, goal-directed action is physically realized by a complex sequence of neural motor commands

through systematic analysis of how design elements influence stress, attention, and emotional regulation. BEACON’s grounding in neuroscience provides empirical justification for design decisions that might otherwise seem subjective. Educational environments benefit similarly, with classroom designs optimized

for sustained attention and positive emotional associations with learning.

BEACON may also enable community empowerment through environmental literacy. By making visible the usually hidden influences of built environments, communities may become more

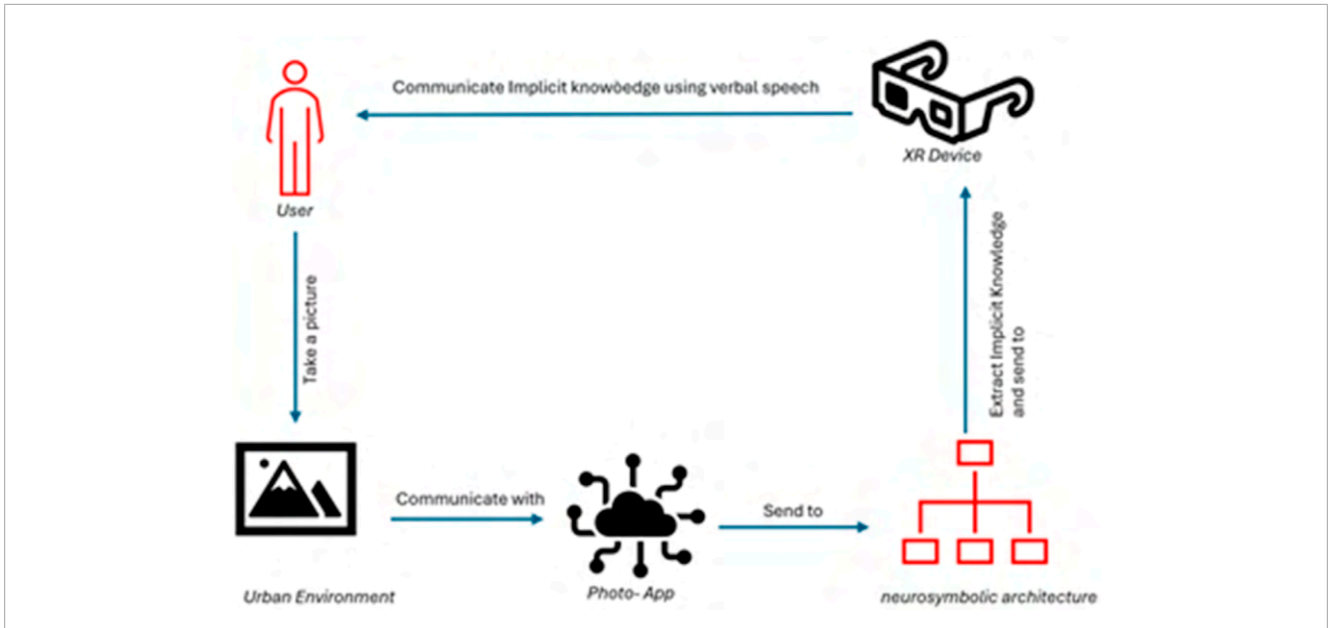


FIGURE 9 A schematic representation of the integration between BEACON and wearable technologies.



FIGURE 10 A practical application of BEACON through smart glasses technology. The red-highlighted area identifies the Physical Layer, focusing on the Chiesa Madre’s architectural elements; The green-highlighted zone represents the Experiential Layer, encompassing the outdoor dining and social gathering areas; The yellow-highlighted area indicates the Social Layer, focusing on access patterns, visibility dynamics, and implicit social hierarchies within the space.

aware of their personal and social effects. The AR implementation may be useful in this regard, transforming abstract concepts into immediately perceivable experiences that facilitate public discourse about environmental quality.

### 7.3 Methodological innovations

Our approach introduces several methodological innovations that contribute to environment-behavior research.

The “Mixture of Experts Simulation” method used to elicit negotiated requirements for BEACON design offers a model for interdisciplinary collaboration in complex domains. By structuring expert interaction around specific inter-layer relationships, the method enables knowledge integration while respecting disciplinary expertise.

The formal ontology network provides a sharable conceptual basis for semantic and data interoperability, and can be evolved in a transparent way. It also provides a conditioning ground for LLMs, leaving room for dynamic tacit knowledge extraction and modular ontology extension (De Giorgis et al., 2025).

BEACON's predictive capabilities enable hypothesis testing before implementation. It can also reduce costly mistakes in urban development while identifying beneficial interventions.

## 7.4 Limitations and future directions

Besides these contributions, some limitations warrant acknowledgment.

While BEACON supports various user types, its intended use within different communities of practice needs adaptation considering the different backgrounds and levels of expertise. Anyways, the neurosymbolic knowledge-driven methods are supposed to be not necessarily in the foreground of final users' applications.

BEACON's comprehensive analysis requires extensive data collection that may prove resource-intensive for routine application. Data collection and its reverse engineering, as well as the evaluation methods of knowledge graphs depend on specific tasks and reasoning habits within specific communities, which need to be tackled on purpose.

While the XR implementation can operate with limited data, realizing its full analytical potential requires multimodal documentation across extended time periods. Future research should develop streamlined assessment protocols that capture essential information with reduced resource requirements to deal with raising costs. There are other limitations like technological barriers, and uneven access across different regions, which might be mitigated in future technological infrastructures, and provisionally accommodated by using more traditional devices.

Cultural variability in spatial interpretation presents ongoing challenges. While BEACON's structure appears universal, the specific meanings associated with spatial configurations vary significantly across cultures. The elevated religious building that signifies authority in Catholic Sicily might convey different meanings in Buddhist Thailand or secular Sweden. Future development should incorporate cultural calibration mechanisms that adjust interpretations while maintaining structural consistency.

Incorporating neural and cognitive data into urban design raises ethical issues (e.g., surveillance, data ownership, cognitive profiling), which will require cybersecurity solutions and adherence to local regulation, e.g., GDPR and AI Act in the EU.

Empirical validation across diverse contexts remains incomplete. While the Pachino case study demonstrates analytical and simulation power, validation across different cultural contexts, urban scales, and building types is needed. Experimental studies manipulating specific environmental features while measuring responses across all seven layers could refine understanding of inter-layer relationships.

## 8 Conclusion

This paper has presented a comprehensive multi-layer ontology network, BEACON, that bridges the gap between neuroscientific research and practical urban design. Through systematic connection of physical design elements to neural responses via intermediate layers of experience, social dynamics, normative regulation, behavior, and cognitive processing, we provide both theoretical understanding and practical tools for creating human-centered urban environments.

Starting from a theoretical integration of requirements to analyze environmental influence while maintaining fidelity to empirical research findings, BEACON has been formalized in the OWL knowledge representation language for computational reasoning. The Pachino case study applies BEACON modeling to demonstrate how architectural design functions as social engineering, shaping not merely behavior but the neural architecture of inhabitants across generations. The augmented reality implementation transforms abstract analysis into immersive experience, enabling diverse stakeholders to perceive and understand multiple layers of environmental influence.

As global urbanization accelerates, the need for scientifically-informed, human-centered design intensifies. BEACON provides the integration of formal ontology, neuroscience, and immersive technology offering a new hybrid paradigm in urban design to recognize built environments as active participants in shaping human experience.

## Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: <https://github.com/aldogangemi/builtenvironmentexperience>.

## Author contributions

AG: Writing – review and editing, Writing – original draft. CL: Writing – review and editing, Writing – original draft.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Generative AI statement

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