

The Empathic Instrument:
Phenomenology, Neuroscience and EEG in
Architectural Design Development



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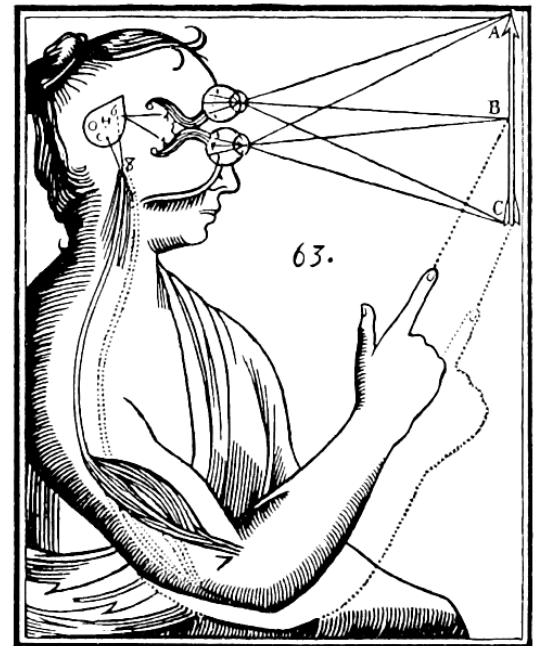
Introduction:

Our experience of space is enacted by our bodies in motion. The body continuously attunes itself, immediately and wholly, to all that shapes a space. This process is mostly unconscious. Perception is not a mental act performed upon the world but a bodily condition of being within it (Merleau-Ponty, 1945). The environment in return is a field of affordances, in relation and inseparable from the body that encounters it. It is a field of possibilities, continuously soliciting the body's response (Rietveld & Kiverstein, 2014). This relation between perception, body and the environment was first articulated by phenomenology in the mid-twentieth century and would find its empirical foundation in neuroscience by the century's end.

Architectural phenomenology and cognitive neuroscience developed in relative isolation from one another, yet they arrived at a remarkably similar understanding of the relationship between body, mind, and space. Architectural phenomenology, originating in the philosophical foundations of Merleau-Ponty (Merleau-Ponty, 1945) and articulated through the works of architects and theorists such as Norberg-Schulz and Pallasmaa, argued that architecture and bodily experience are inseparable conditions of one another (Norberg-Schulz, 1979; Pallasmaa, 1996). These philosophical arguments found their empirical ground through neuroscience. Most influentially, the discovery of mirror neurons first observed by di Pellegrino et al. in 1992 and later named mirror neurons by Gallese et al. in 1996 provided a neurological ground for what phenomenology had long argued philosophically. The formal convergence of neuroscience and architecture was established in 2003 with the founding of the Academy of Neuroscience for Architecture (ANFA), marking the emergence of neuroarchitecture as a recognised field that has since grown rapidly in the two decades (Eberhard, 2009; Zhao et al., 2025).

Central to this growth was the electroencephalogram (EEG). First described, it translates the brain's electrical activity into readable signal through electrodes placed on the scalp (Borck, 2018). Among available brain imaging modalities, EEG is preferred for the study of embodied spatial experience, as its sensors are light enough to allow near-complete freedom of movement of the head and body, and its time resolution is sufficient to record brain activity on the timescale of natural motor behaviour (Makeig et al., 2009).

These qualities have established EEG as the primary instrument of neuroarchitecture research, with published studies growing substantially since 2015 (Zhao et al., 2025). However, this growth in research has not been evenly distributed in different stages of architectural design process. A systematic review of EEG-aided architectural design research conducted on studies published between 2013 and 2023 reveals a distinct disparity in where neurophysiological data has been applied across the architectural design process. Filtering 42 studies from an initial pool of 1305 and organising them into three broad application categories of design guideline, design

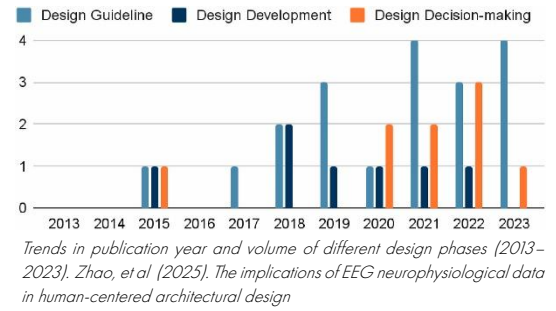


Drawing from René Descartes' (1596-1650) in "Treatise of Man" supposing the function of the pineal gland.

review, and design development, twenty-six studies address design guidelines, ten address design review, and only seven address design development (Zhao et al., 2025). Furthermore, while development of EEG neurophysiological data applied in design guideline phase shows a distinct and continuous growth since 2015 and its application within design review processes began to expand more markedly after 2020, integration within the design development phase remains moderate and has not demonstrated comparable rapid growth yet (Zhao et al., 2025).

The aim of this thesis is to examine the reasons for the limited and uneven adoption of EEG research in the design development phase compared to other architectural design phases, and to ask how EEG-based neurophysiological feedback can be more effectively integrated into architectural design development.

By tracing the historical and philosophical foundations from which neuroarchitecture emerged, this thesis argues that the field has developed a sufficiently robust theoretical and methodological base to support integration across all design phases. It then examines the role and limits of neuroscience in architectural practice, arguing that its most meaningful contribution lies not in the production of universal standards but in extending the empathic reach of the designer toward the specific inhabitants and conditions that their own embodied experience cannot fully access. While the limitations of the existing research are real and deserve serious consideration, they apply equally across all phases and do not account for a gap specific to design development. If neither the theoretical foundations nor the critical limitations of the field explain the disparity, the explanation must be sought in the nature of the research itself, in what design development research requires of its practitioners and why those requirements have so far limited its growth. By categorising the forty-two studies identified by Zhao et al. according to their computational complexity, this thesis identifies a clear and phase-specific pattern. The technical demands of design development research are categorically distinct from those of guideline and review research, placing it consistently beyond the reach of the tools and expertise available to most architectural researchers and designers. The gap is largely technical and infrastructural, suggesting that the field's most meaningful next step is the development of accessible tools and pipelines that bring neurophysiological knowledge into the conditions of real architectural practice, at the specificity and scale that design development requires.



Chapter 1:

From Body to Brain to Building

When I return to myself from an excursion into the realm of dogmatic common sense or of science, I find, not a source of intrinsic truth, but a subject destined to the world.

Merleau-Ponty, Phenomenology of Perception, Preface

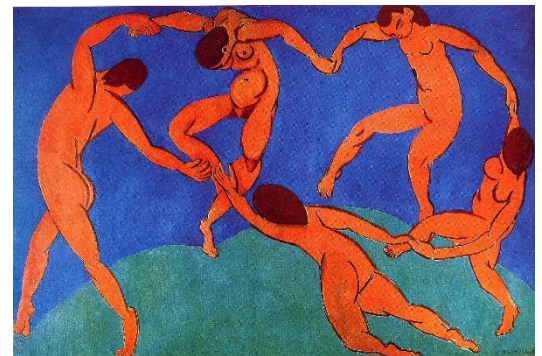
1.1-Phenomenology:

In 1641, René Descartes, determined to doubt everything he could doubt, arrived at the only certainty that doubt itself could not dissolve. "Cogito ergo sum— I think, therefore I am." Stripping away the testimony of the senses and the existence of the external world through methodical doubt, he found his only certainty to be the act of doubting itself. What remained after this reduction was a purely thinking self while the body was placed on the side of the physical world. A purely mechanical arrangement of matter as any other object, governed by physical laws. In this view, the experienced reality is reinstated in the Cogito, simply labelled 'thought of' the world.

Kant gave this separation its most systematic form, making consciousness the condition under which experience becomes possible at all. The subject does not encounter a world already formed but imposes upon the sensations, structures of space, time and causality through which the world becomes coherent. In both cases, as Merleau-Ponty identifies, Descartes and Kant detached the subject by implying that one could not possibly apprehend anything as existing unless one first experienced oneself as existing in the act of apprehending it. This presents 'the consciousness as the condition of there being anything at all, and the act of relating as the basis of relatedness'(Merleau-Ponty, 1945). Analytical reflection, in both its Cartesian and Kantian forms, starts from our experience of the world and retreats to the subject as a condition of possibility distinct from that experience, and in doing so offers a reconstruction of the world rather than an account of it. The body remains part of the physical world that the subject constitutes rather than inhabits.

This is the philosophical frame that Merleau-Ponty, writing in *Phenomenology of Perception* in 1945, sets out to challenge. Starting from Husserl's founding directive to return to the things themselves, he refuses to treat the world as the product of a constituting subject. It would be artificial to claim the world results from syntheses linking sensations and perspectives when both the sensations and the perspectives are themselves products of analysis, with no prior reality of their own. "The real has to be described, not constructed or formed' (Merleau-Ponty, 1945). The world is the field for all thoughts and all perceptions. As such, perception is not a deliberate act or taking up of a position but the condition from which all acts proceed, presupposed by each of them.

The consequences of this change in order of perceiving the world are immense. The body is not an assemblage of different



Henri Matisse's The Dance (1910)- The body is not placed in space but constitutes it through movement.

organs placed in space, but a unified system oriented toward the world. The body inhabits space and it is the condition from which spatial orientation, spatial meaning, and spatial experience become possible at all (Merleau-Ponty, 1945). To attend to the body is to attend to the source at which experience itself originates. Merleau-Ponty's insistence on returning to the body is an insistence on returning to lived, embodied engagement with the world.

For architects this bodily understanding of perception demands an understanding of the body and by extension the mind as part of the body and its responses to space. This marks a shift of focus from aesthetics and the features of places as individual and disconnected physical realities to a focus on how these relate to and are perceived by the embodied mind.

This understanding of embodied spatial experience found its way into architectural theory in the second half of the twentieth century, most significantly through the work of Christian Norberg-Schulz and Juhani Pallasmaa. In *Genius Loci* (1979), expanding on Heidegger's account of dwelling, Norberg-Schulz argued that the fundamental purpose of architecture is not the production of space in an abstract or geometric sense but the creation of places — spaces in which we orient ourselves and identify with our surroundings. To dwell is not to occupy a space but to be in a meaningful relationship to a place, a relationship which is lived and embodied. This distinction between abstract space and lived place suggests a shift in architectural theory away from proportions toward the quality and realities of lived human experience. The body, as the nexus of this experience, therefore, demands the attention of the architect as it is where architectural meaning originates.

Juhani Pallasmaa extended this position, first in *The Eyes of the Skin* (1996) and his subsequent works. In *The Eyes of the Skin* he identified and critiqued the way architecture was taught, conceived, and practiced in modern architectural culture by identifying the dominance of vision and the suppression of all other senses. Every meaningful encounter with architecture is multisensory, and the body is the locus of reference, memory, imagination, and integration (Pallasmaa, 1996). Expanding on this position in 2013, he argues that the experienced meanings of architecture are not primarily rational or verbalised but arise through embodied and unconscious projections, identifications, and empathy. We are mentally and emotionally affected by buildings before we understand them (Pallasmaa, 2013). What neuroscience and phenomenology share, and what makes their combination in neurophenomenology productive, is that both insist that the body and its pre-reflective responses are the origin of architectural experience.

Phenomenology had offered architecture a framework of embodied experience, but it remained on descriptive and philosophical grounds, from which it would later draw on neuroscience to back its claims empirically.



Woman Reading a Letter, Johannes Vermeer, c. 1663
The body is the point through which light, space, and time converge into a single experience.

1.2-Neuroscience:

Dark room of the Psychiatric Clinic in Jena. Double doors shut out noises from the outside. A path-breaking discovery is about to be tested that Professor Dr. Hans Berger, director of the Psychiatric University Clinic in Jena, has successfully performed. It involves the recording of thoughts in the form of a jagged curve, the electric script of the human brain.

– *Stadt-Anzeiger Dusseldorf, 6 August 1930, cited in Borck (2018).*

The empirical ground confirming the theoretical frame of phenomenology began to emerge in the early 1990s with developments in cognitive neuroscience that ultimately pointed to the same conclusion.

In 1992, a class of premotor neurons in the macaque brain was observed to be activated both when the animal executed an intentional action and when it observed the same action being performed by another (di Pellegrino et al., 1992, cited in Freedberg & Gallese, 2007). The significance of these neurons, named mirror neurons by Gallese et al. in 1996, stems from what this discovery implies. The body is motorically engaged with and resonates with the world it perceives before any conscious response takes place. This confirms what phenomenology had described as motor intentionality. Observation and action, perception and response, are not sequential processes mediated by cognition but share the same neural substrate. The boundary between self and world, at the level of the nervous system, is more porous than what Descartes had assumed foundational.

The second development was the proposal of enactive cognition by Francisco Varela, Evan Thompson, and Eleanor Rosch in *The Embodied Mind* (1991). The prevailing computational model of the mind understood cognition as the processing of internal representations. They argued that cognition is not a process solely in the brain but is enacted through the ongoing interaction between a living body and its environment. The mind is not the processor of the body's inputs but is instead constituted through bodily action in the world. This account of cognition, which had been one of phenomenology's central claims, was now stated in the language of cognitive science and grounded in biology.

Vittorio Gallese brought these findings together into a unified theoretical framework he termed embodied simulation. The body schema, the brain's unconscious map of the body used to control movement, and the body image, our conscious awareness of the body, are handled by the same neural circuits, and damage to them disrupts both motor control and conscious awareness simultaneously (Gallese, 2005). The body's dual nature as both a sensing subject and sensed object is what allows us to recognise others as individuals and the world as a field of meaningful experience. In this, Gallese draws explicit parallels to Merleau-Ponty and Husserl, suggesting that neuroscience gives empirical grounding to these philosophical intuitions (Gallese, 2005).

Phenomenology and neuroscience had subsequently established that space is experienced through the body and that this experience has a measurable biological basis. If the body's responses to the built environment are neurologically grounded and therefore measurable, then architecture, as a field engaged with that response, has both the reason and the means to engage with neuroscience directly. If the relationship between body, brain, and built environment could be described philosophically and verified empirically, it could also be studied systematically. Neuroarchitecture was the institutional recognition of that possibility.

1.3-Neuroarchitecture:

The formal institutional recognition of neuroarchitecture was marked in 2003 with the founding of the Academy of Neuroscience for Architecture in San Diego. ANFA aimed to promote and advance neuroscientific knowledge and research relating to understanding human responses to the built environment. We spend more than ninety percent of our waking hours inside buildings, but the discipline responsible for designing those buildings had largely proceeded without systematic knowledge of how they act on the brain and body (Eberhard, 2009). Neuroarchitecture emerged as a field to empirically study the neurological and physiological mechanisms through which the built environment shapes human experience.

Central to the methods of achieving this goal has been the electroencephalogram, or EEG. First described by Hans Berger in 1929, EEG records the brain's electrical activity through electrodes placed on the scalp, translating neural dynamics into readable signal with millisecond temporal resolution (Borck, 2018). This allows the recording of the body's response to a specific event or stimulus. EEG sensors are light enough to allow near-complete freedom of movement of the head and body, and this mobile property combined with sufficient time resolution to record brain activity on the timescale of natural motor behaviour makes it the preferred instrument for neuroarchitectural research (Makeig et al., 2009). As architecture is experienced through a body in motion, the portability and temporal sensitivity of EEG has made it the ideal tool for studying the brain's responses to spatial experience in movement, in real or simulated environments. The field grew rapidly following its institutional founding, with published studies accelerating substantially after 2015, driven in particular by the development and increasing commercialisation of mobile brain/body imaging devices (Zhao et al., 2025).

Chapter 2: The current landscape

In the recent decade, studies at the intersection of neuroscience and architecture have received increasing attention. Architecture needs to be understood not only as an artifact but in its biological and ecological context, and the tools for doing so are now available (Pallasmaa, 2013). Many aspects of architecture which previously were not rationally analysed and measured can now be empirically explored through neuroscience (Gallese & Gattara, 2015). What the field of neuroarchitecture possesses today is a layered account of the relationship between body, brain, and built environment; one layer being the philosophical language to describe that relationship and the other the empirical methods to investigate it.

The goals of neuroarchitecture stem directly from this possibility. As the body's responses to the environment are neurologically grounded and measurable, many design decisions can now be better understood and anticipated. The aspiration to not rely solely on individual intuition but to be supported by verifiable knowledge of how spaces affect our wellbeing has been shared by an increasing number of architects. This aspiration is reflected in Rietveld and Kiverstein's landscape of affordances: to design a space is to design the field of possibilities it makes available to the bodies that will encounter it (Rietveld & Kiverstein, 2014). The affordances a space offers are not fixed properties of that space but emerge from the encounter between the capacities of the skilled body and the material configuration of the environment. Neuroscience can identify the causal biological chains between the properties of the built environment and the cognitive, emotional, and physiological states of the people who inhabit it (Albright, 2015). Architecture is most precisely human-centred when design decisions are informed by knowledge of what the body and brain actually need, respond to, and are shaped by.

However, the growth in neuroarchitectural research has not been evenly distributed across the full scope of the architectural design process. A systematic review and bibliometric analysis of Zhao et al. (2025) give a comprehensive picture of how the neuroarchitectural research stands today. Covering studies published between 2013 and 2023 by using search strings combining electroencephalography, architecture, and design across five major academic databases, 1,316 papers were retrieved. Following a multi-stage screening process assessing type, language, subject, topic, stimuli, and tool, this was reduced to 34 studies, to which 8 additional papers were manually included for their significance in the field, resulting in a final selection of 42 studies for analysis (Zhao et al., 2025). These were then categorised across three phases: design guideline, design review, and design development. Twenty-six studies, representing 62 percent, address design guidelines, ten address design review, and only seven, representing seventeen percent, address design development, the phase in which neurophysiological data would be most directly integrated into the act of designing itself. Most studies and reviews focused on

pre-design phase and on informing the selection of elements such as spatial layout, form, color, and material (I. Bower et al., 2022; Cruz-Garza et al., 2022a; Shemesh et al., 2021; Vavrinsky et al., 2019), but application of neuroimaging tools throughout other phases of architectural design, especially the design phase remains limited. Furthermore, the disparity is not only in the volume but in the trends of the research. The application of EEG in the design guideline phase has shown a distinct and continuous increasing tendency since 2015. Design review research began to develop substantially after 2020. Design development, by contrast, has remained at a moderate level since its first appearances and has not demonstrated comparable growth in either period (Zhao et al., 2025). To uncover the reasons for this disparity, we first need to investigate the role and limitations of neuroscience in architecture and the critiques surrounding it and ultimately by analysing the body of research done so far.

Chapter 3: The Role and Limits of Neuroscience in Architecture

'The disciplines of neuroscience and architecture intersect in their understanding of and obligation to their subject: the embodied human being, a being who can exist only in relationship – relationship to the places we inhabit, to each other, to the world'

Sarah Robinson, 2015

Chapter 3.1: Empathy and the Social Dimension

So far, we have established that cognition is not generated internally by the brain processing the external world but is enacted through the body's entanglement with its environment. And this environment is not a neutral container but is instead a field of possibilities that emerges from the encounter of a skilled body, on the basis of its abilities, with the material configuration of the world around it.

With this understanding of the relation of embodied human being to the places it inhabits, what remains is the relation to others — the social dimension.

Expanding on the discovery of mirror neurons, Vittorio Gallese developed the theory of intersubjectivity, understood first and foremost as intercorporeality: 'the mutual resonance of intentionally meaningful sensorimotor behaviours' (Gallese, 2023). Our understanding of others is not exclusively dependent on cognitive reasoning but also on the relational nature of our bodies. What he names embodied simulation proposes that our social interactions acquire meaning by means of reusing our own mental states and processes in functionally attributing them to others. When we perceive others expressing emotions or sensations, the same brain areas are activated as when we experience those same states ourselves. Furthermore,

this non-conscious, pre-reflective functional mechanism of the brain-body extends beyond social interaction. It is equally triggered during the experience of spatiality around the body and during the contemplation of objects. Therefore, our rich and diverse experiences of space, objects, and other individuals are all made possible by this characteristic of the brain itself and on the basis of our capacity to empathize with them.

Empathy, in this light, is not a sentiment brought to design but the embodied mechanism through which design, at its most meaningful, becomes possible.

Yet empathy is not a dissolution of the self into the other.

'In my non-primordial experience I feel, as it were, led by a primordial one not experienced by me but still there, manifesting itself in my non-primordial experience' (Stein, 1917, p. 11).

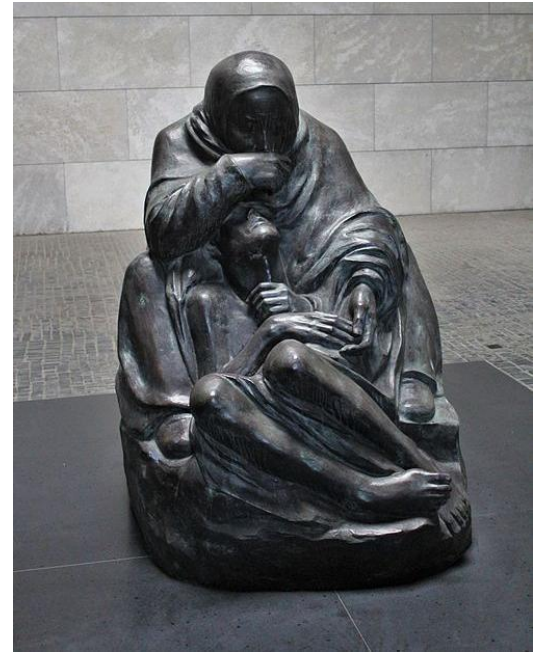
Even in the deepest emphatic engagement, the distinction between self and the other remains (Stein, 1917). Therefore, the quality of our empathic engagement with others is determined by our common ground, and when our shared experiences grow distant, that common ground becomes harder to tread.

'We emulate the physiognomy of a space through our unconscious sense of identification, muscular imitation, and empathy' (Pallasmaa, 2013, p. 7).

The architect's craft is unavoidably constituted in an embodied manner of existence. A space is inhabited by the architect's imagination before it is inhabited in the world. Memories, accumulated feelings, and procedural skills together reshape the architect's imagination and therefore the design process (Arbib, 2013). This lived, existential knowledge, the intuition and embodied imagination is fundamentally different from methodically formalised knowledge and is not reducible to it. (Pallasmaa, 2013). This constitutes most precisely where neuroscience is at its most effective in architecture, not as a correction or replacement of intuition, but as its extension.

As the designer's bodily and cultural conditions becomes more distant to that of the users, the empathic engagement of them inevitably weakens. Neuroscience then acts as bridge or a helping guide strengthening the link between the designer and users. In working with Alzheimer's patients, Zeisel demonstrated that neuroscientific informed architectural decisions produce outcomes of direct clinical value: anxiety and aggression are reduced in settings with greater privacy and personalisation; social withdrawal is reduced where common spaces are limited in number and each carries a distinctive identity; agitation is reduced in environments that are more residential than institutional in character (Zeisel, cited in Albright, 2015, p. 200). The spatial experience of Alzheimer's disease, the disorientation and the erosion of environmental memory is difficult to grasp in the imagination of the designer however attentive.

The neuroscientific evidence then acts as a supplement to the



Mother with her Dead Son, Pietà, 1937, Kathe Kollwitz

designer's empathic imagination by providing an understanding of the causal biological links between the properties of the built environment and the cognitive, emotional, and physiological states of the people who inhabit it. Understanding how cognition is neurologically wired allows designers to make more informed design decisions that are grounded and serves the specific neurological reality of the inhabitants. This understanding can become crucial in environments designed for the most vulnerable.

NICUs, the intensive care units that specialize in the treatment of ill or premature newborn infants are a clear example of how neuroscientific knowledge is and should change the architects' design decisions. twelve percent care in NICUs have a higher chance of developing disabilities, such as cerebral palsy and learning difficulties than other children. Eberhard describes three stages of early neurological development, the third of which is almost entirely driven by responses to stimulation from the architectural setting, whether that be the mother's womb or its surrogate in the NICU (Eberhard, 2015, p. 132). It is in this third stage that the cortex forms its new connections, making the quality of the architectural environment constitutive to the developing brain. Disruption to the critical auditory period, which begins approximately eight weeks before birth and continues till the second year of life, can permanently impair the infant's ability to distinguish between sound frequencies. The neural relationships that govern the perception of lines, shapes, and spatial form are established in the first months after birth and are irreversible once the window closes (Eberhard, 2015, p. 133). Traditional NICUs were designed around the need of doctors and nurses without considering some neurological needs of the infants. Windows providing sunlight did not account that the eyelids of premature infants offer no adequate protection against daylight, whose intensity far exceeds that of artificial lighting by several orders of magnitude (Eberhard, 2015, p. 133). High levels of background noise from cooling equipment and communications systems in the NICU have been shown to have major long-term negative effects causing difficulties in discriminating between frequencies in later stage of infants' lives. These failures do not stem from negligence but designers lack of knowledge and embodied empathy that stem from designing for users whose neurological reality is inaccessible to the designer's own embodied experience.

Both cases reveal the same condition that Stein's account of empathy anticipates that the quality of empathic engagement is bounded by shared experience, and where that shared experience is most limited, the contribution of neuroscience in architectural practice is most meaningful.



Manager, Mr. E.M. Bayliss and nurses attending babies in the Baby Incubator exhibit on the Pike at the 1904 World's Fair

Chapter 3.2: The Risk of Generalisation

The role of neuroscience in architectural practice has not been without critique, and the research produced so far carries limitations that deserve serious consideration. From the final 42 studies reviewed, Zhao et al. note that participant numbers across the reviewed studies range from as few as seven to as many as 479, this significant disparity in research design could potentially affect the generalisability and applicability of results. Furthermore, the majority of studies have focused on student populations, raising questions about the applicability of findings across different demographic groups, as gender, cultural background, and age can all influence how individuals perceive and respond to architectural spaces. Studies also largely isolate single architectural elements, but as our emotional and behavioural responses are complex in nature, this may significantly alter the effects when other elements are present (Zhao et al., 2025).

'The quality of the whole permeates, affects and controls every detail, and the attempt to grasp a complete experiential entity through its isolated elements is doomed to inadequacy'

(Pallasmaa, 2013, p. 13, citing Dewey).

At its current state, the field remains caught between scientific inquiry and practical application, not yet fully satisfying the demands of either (Zhao et al., 2025, p. 32).

Architectural meaning exists fundamentally in the experience, which is unique, situational and individual. Neuroscience should not be used as a universal standard that reduces the diversity of human experience into biological averages but as a tool for specific, contextual, and population-sensitive inquiry (Pallasmaa, 2013, p. 9). The neurological investigation of architectural experience 'has to be based on a deep dialogue between scientists and the makers of architecture' (Pallasmaa, 2013, p. 21), a dialogue oriented not toward generalisation but toward specific inhabitants and specific places they inhabit at each design.

Given the advantages and limitations of neuroscientific knowledge for architecture mentioned above, the most meaningful contribution of such knowledge lies not in the production of universal standards but in extending the reach of empathic design judgment toward the full diversity of embodied human conditions that architecture is obliged to serve.

As established in Chapter 2, the current body of neuroarchitectural research is heavily concentrated in the design guideline phase, which accounts for sixty-two percent of the reviewed studies, while design development research accounts for only seventeen percent and has shown no comparable growth trajectory (Zhao et al., 2025). The growth of design guideline research has been a meaningful and necessary development for the field, establishing verifiable relationships between architectural elements and neurophysiological responses, building an empirical foundation for the growing



Ad Parnassum, Paul Klee (1932)

'...the attempt to grasp a complete experiential entity through its isolated elements is doomed to inadequacy'

neuroarchitectural research of today. It is on this foundation, that the case for design development research now stands. The knowledge that guidelines have produced about how the body and brain respond to space could become more practical when brought directly into the design process itself, applied in a specific context, for specific inhabitants. It is here, in the integration of neurophysiological knowledge into the act of designing rather than the evaluation of its results, that the field's most meaningful contribution to architectural practice remains to be made. What precisely stands in the way of that integration, and what the research that has attempted it reveals about the nature of those obstacles, is the question the following chapter sets out to answer.

Chapter 4: Analysis of the Identified research

To understand the complications and reasons for the uneven adoption of EEG based neuroscientific research in architecture it is necessary to examine the research identified previously by the systematic review and bibliometric analysis of Zhao et al.

By categorising the forty-two studies reviewed by Zhao et al. by computational complexity, comparing the technical demands of design guideline, design review, and design development research, a pattern of technical complexity can be identified. A three-level framework of computational complexity is applied to each of the forty-two studies as an analytical tool developed for this thesis. Level 1 encompasses studies requiring only statistical analysis, commercial applications, and proprietary tools. Level 2 encompasses studies using standard signal processing techniques such as filtering, Fast Fourier Transform, and Power Spectral Density through established open-source toolboxes such as MATLAB EEGlab, combined with statistical analysis. Level 3 encompasses studies requiring machine learning, deep learning, neural networks, real-time data streaming, brain-computer interface systems, reinforcement learning, or custom algorithm development.

Three studies were excluded from the analysis on the grounds of insufficient methodological reporting. The remaining corpus is twenty-four guideline studies, ten review studies, and six development studies.

Applied across all three phases, the complexity framework

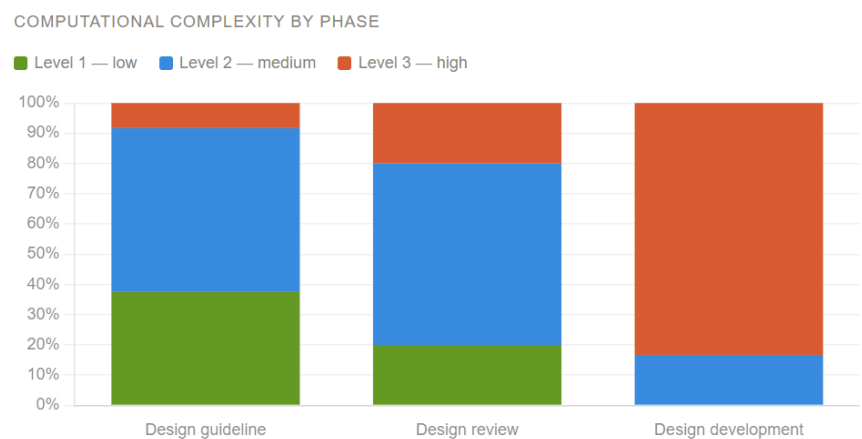


Figure 1. Computational complexity distribution across all three design phases (author's analysis of studies in Zhao et al., 2025).

Complexity level	Guideline (n=24)	Review (n=10)	Development (n=6)
Level 1 — low	9 (37.5%)	2 (20.0%)	0 (0%)
Level 2 — medium	13 (54.2%)	6 (60.0%)	1 (16.7%)
Level 3 — high	3 (12.5%)	2 (20.0%)	5 (83.3%)
Level 1 + 2 combined	91.7%	80.0%	16.7%

Table 1. Full complexity classification. Three studies excluded due to insufficient methodological reporting (Erkan, 2023; Ergan et al., 2019; Jain et al., 2023).

produces the following distribution. High-complexity research increases from twelve percent in the guideline phase to twenty percent in the review phase to eighty-three percent in the design development phase. Inversely, studies accessible to researchers without specialist computer science training fall from ninety-one percent in the guideline phase to sixteen percent in the design development phase — a gap of seventy-five percent. Design development research has no studies at Level 1 complexity (Figure and table 1).

The five design development studies at Level 3 complexity make the nature of these demands clear. Nguyen et al. (2019) transmitted EEG data in real time to Grasshopper, allowing architectural forms to be manipulated live by the brain data stream. Yang et al. (2021) built a pipeline combining EEGLab, OpenVibe, MATLAB machine learning, and Grasshopper for real-time parametric geometric design. Xu et al. (2018) developed a reinforcement learning model implemented in TensorFlow and Python that automatically adjusted the colour of a space based on participants' EEG alpha power. Kachhia et al. (2020) developed a brain-computer interface for 3D printing, translating EEG signals through deep learning into physical architectural form. Zhang et al. (2022) integrated EEG data with Grasshopper using a genetic algorithm to drive parametric design generation (Table 2).

The most frequently occurring keyword in these studies, alongside electroencephalography, is machine learning and deep learning — a finding Zhao et al. describe as revealing 'the close disciplinary integration of computer science with neuroarchitecture' that design development demands (Zhao et al., 2025).

The seventy-five percentage point gap between accessible tool usage in guideline research and design development research reveals that design development requires a categorically different technical infrastructure, one that demands expertise at the intersection of computer science, neuroscience, and architecture simultaneously — a combination that lies outside the standard training of architectural researchers and beyond the infrastructure of most research teams (Figure 2).

The development of these methods necessitates advanced expertise in computer science, and their application remains largely confined to basic architectural forms rather than comprehensive architectural design — suggesting a substantial distance to cover before widespread implementation in architectural practice (Zhao et al., 2025). Yang et al. (2021) built a pipeline combining EEGLab

KEY COMPARISON: ACCESSIBLE VS HIGH-COMPLEXITY RESEARCH



Figure 2. Accessible (Level 1 + 2 combined) versus high-complexity (Level 3) research by phase. The seventy-five percentage point gap between guideline and development research is the central finding of Chapter 4.

Table 2. Complexity classification of design development studies

Study	Subject	Key technical demands	Level
Nguyen et al. (2019)	BCI-VR design	Real-time EEG to Grasshopper via UDP, CNN, ANN, machine learning	Level 3
Yang et al. (2021)	BCI geometric design	EEGLab, OpenVibe, SVM machine learning, Grasshopper, UDP streaming	Level 3
Xu et al. (2018)	Responsive environments	Reinforcement learning (PPO), TensorFlow, Python, autonomous agent decision-making	Level 3
Kachhia et al. (2020)	BCI for 3D printing	Hybrid CNN-LSTM deep learning, BCI pipeline, CAD to physical form	Level 3
Zhang et al. (2022)	Spatial optimisation	EEG integrated with Grasshopper, NSGA-II genetic algorithm, parametric generation	Level 3
Ducao et al. (2018)	Urban street mapping	Custom Multimer system, Hilbert transforms, bandpass filtering, spatial analysis	Level 2

Note: Three studies excluded from analysis on grounds of insufficient methodological reporting (Erkan, 2023; Ergan et al., 2019; Jain et al., 2023).

Conclusion

Tracing the theoretical, critical, and empirical dimensions this thesis attempted to understand the reasons of why despite the growing presence of EEG based neurophysiological research in architecture, this research remains concentrated in the design guideline phase and has not found comparable adoption in design development. This disparity is not rooted in philosophical or theoretical inadequacy but in the technical and infrastructural demands that design development research places on its practitioners, demands that the field has not yet developed accessible and adequate tools to meet.

The critique of generalisation examined in Chapter 3 sharpens rather than undermines this conclusion. Neuroscientific knowledge in architecture is most valuable when it extends the architect's embodied empathic reach toward those whose embodied conditions differ fundamentally from their own, when spatial experience cannot be accessed through the designer's own body and imagination. This knowledge is specific, contextual, and population sensitive. It is knowledge most meaningfully generated when neuroscience is brought into the act of designing itself, in direct response to the specific inhabitants and context at hand.

The path forward is therefore instrumental. As design guidelines have blossomed from the commercialisation of mobile EEG devices (Zhao et al., 2025), design development now requires tools and pipelines designed to address the complexities of this integration and which are accessible to designers.

One example of such tools comes from my own experience developing a neurological feedback system for architectural design. The system captures brain activity from people

experiencing virtual architectural spaces, automatically processes the raw EEG signal, and classifies emotional response into categories that architects can read and act on. The ambition is not to replace the architect's judgment but to extend it, to give the designer access to the neurophysiological voice of the people they are designing for, at the moment when that voice can still shape what is being made.

That experience has also shown me how much remains to be explored. The technical demands of building an accessible pipeline are considerable, and the distance between a working prototype and a tool that architectural practice can adopt at scale is significant. What the field would benefit from is more accessible infrastructure, open and representative datasets that allow researchers to develop and validate systems without building entirely from scratch, and a growing attention to the practical conditions under which architects actually work.

Ultimately, whether neuroscience will find its place in the act of designing depends on the degree to which the field turns its attention toward building the accessible tools, pipelines, and shared datasets that make this integration possible.

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