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Rethinking historical analogues between body and structure, expanding this analogue with new body concepts from cognitive neuroscience to enrich structural analogical design thinking.

# Analogue structure: structural analogies in the context of evolving body concept

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The structure-body analogy has a long history. In the eighteenth century, Jean-Rodolphe Perronet compared the Gothic church's organisational structural logic to the skeletal forms of animals.[1] In his study of the science of the human body, engineer Thomas Tredgold also made a comparison between structural rationality and the body, arguing that the concept of the body and the system of relations and organisation between its parts were inextricably linked to the overall constitutive relationship between architectural structures and their artistic expression.[2] This way of thinking evolved into a significant nineteenth-century architectural trend known as 'Gothic Rationalism', which was founded on the belief that the beauty of Gothic churches stemmed from their absolute rationality and economy of structure, a functionalist approach to aesthetics.

This concept dates back to Aristotle, who believed that our perception of a creature's beauty is generated by a rational appreciation of its structure and function. He believed that each limb or distinct structure had a distinct purpose, and that parts were functional only in relation to the whole.[3] According to this functionalist view of aesthetics, the origin of our aesthetic is the essential, functional role of each limb and organ in the overall body's work. Thus, each architectural design component should serve a distinct and functional purpose.

This philosophical reflection on the relationship between part and whole found biological support in Georges Cuvier's later comparative anatomy. His research focused on the relationship between organs within the organism and how they came together to form a whole in terms of form and function. Cuvier argues that 'All the organs of one and the same animal form a single system of which all the parts hold together, act and react upon each other; and there can be no modifications in any one of them that will not bring about analogous modifications in them all.'[4]

The anatomical principle of the 'correlation of parts', directly influenced Eugène Viollet-le-Duc's use of anatomy as an analytical method to study the relationship between structure, function, and form in the Gothic church through analogies with the constitutive relationships of the body's structure.[5] Inspired by Cuvier, Viollet-le-Duc dissected the Gothic church's structure to reveal the inextricable interconnection between each structural element and the mechanics governing its organisation and synergistic relationships.[6] Viollet-le-Duc, inspired in particular by Nicolas Henri Jacob's exploded perspective of the human body for Jean-Baptiste Marc Bourgery's anatomical treatise,[7] employs a similar exploded analytical diagram to dismantle the Gothic church's various structural elements, visually demonstrating the static relationships between the various parts. Viollet-le-Duc contended that architecture's form is determined by structural rationality and organicity, and that, once the fundamental principles of structure and construction are established, form or 'style' will emerge naturally.[8] These analogy-based studies were instrumental in establishing structural rationalism and precipitating a subsequent wave of de-ornamentation. Similarly, Karl Bötticher coined the terms *Kernform* (*Core-form*) and *Kunstform* (*Art-form*) to refer to the material and static properties of architecture and the symbolic meaning conveyed by the static properties.[9] Bötticher analogises the relationship between the *Kernform* and the *Kunstform* in architectural structures to the relationship between 'bone' and 'flesh' in the human body. From this, he argues that only when the structural form is expressed similarly to the organism can an expressive *Kunstform* be constructed.[10]

Hendrik Petrus Berlage criticises this division of ontology and representation, arguing that the building's internal structure must be considered in conjunction with its decorative artistic expression to restore the indivisible 'full-body' analogy between body and structure.[11] Berlage's criticism is reminiscent of the Eiffel Tower controversy. Influenced by structural rationalism, the Eiffel Tower makes the best use of available materials to achieve the most efficient structural design. However, the term 'fleshless' or 'massless' generated

considerable controversy. Joseph August Lux criticises its structural expression: 'A railway bridge, an Eiffel Tower and similar pieces of engineering are all bare skeleton. It can satisfy my understanding, but it can never satisfy my heart. [...] I might use a metaphor: the human skeleton is surely the most perfect work of engineering. But for my eye, when it is in search of beauty, it is the blooming flesh that is decisive.'[12] Lux's argument is consistent with Berlage's assessment of the dualism perspective on structure and architecture as insufficient for a comprehensive evaluation and reference of structure and architecture. The analogy between architecture and the body presented here is mainly one-sided, emphasising the *Kernform* of the body at the expense of the *Kunstform* and other more complex bodily functions.

**Limitations of traditional biological analogies**

The Eiffel Tower's quest for structural authenticity and minimal materialisation exemplifies a moral attitude or virtue frequently found in the modern architectural movement influenced by functionalism. That is, the supporting structures of a building should be necessary, meaningful, functionally explicit, and exposed. There is an inherent and implicit recognition of utilising the fewest structural materials possible while remaining economically viable. It is not sufficient for each component to perform a distinct function; the structure must be well organised and expressed so that the function can be clearly read: similar to how some of the body's bones protrude from the skin.[13] Deciphering the logic that governs its operation provides us with intellectual and aesthetic satisfaction, which is why an authentic representation of the structure is required.

The Eiffel Tower demonstrates that the contradiction between the 'bone' and 'skin' of the architectural structure is essentially an analogical 'biological fallacy' to functionalist aesthetics.[14] An organism's physical characteristics are intrinsically linked to environmental variations, and its form must allow for a certain degree of plasticity in order to respond to external changes. Thus, while the 'bone' of a structure and its external 'skin' are inextricably linked, the 'skin' is not simply derived from the 'bone'. Allowing for some plasticity in the 'skin' is the body's norm. Thus, the two should have an interactive and dynamic relationship rather than a linear cause-and-effect relationship. Even Viollet-le-Duc's insistence that the Gothic church's distinctive 'style' is due to its necessary functionality and structural economy has been debunked.[15] As John Summerson has emphasised, the Gothic church's rational beauty does not derive from Viollet-le-Duc's pursuit of absolute economy and efficiency, but rather 'seeks to express its function dialectically – to offer a visible argument to the spectator.'[16] Heinrich Wölfflin has investigated how the structure is expressed in Gothic architecture. He argues that the Gothic church's 'tension' and impact are not limited to its physical order and structural rationality. Rather than that, it is the clear structural expression that conveys the embodied 'metaphor of force' through *Einfühlung* (*empathy*), thereby creating psychological stress and tension.[17] Wölfflin's extension of the structure-body analogy from Viollet-le-Duc's almost entirely mechanical viewpoint to a more comprehensive analogy between mind and body was accompanied by the historical evolution of the concept of the body.

As early as the seventeenth century, René Descartes argued for the existence of a dual entity composed of matter and spirit, or body and soul, through the now-famous maxim 'I think, therefore I am.' This dualism of mind and body has always greatly affected people's thinking on the relationship between mind and body, as it severed the connection between the two and reduced the cognitive process's reliance on the body. On the one hand, Descartes paved the way for the development of anatomy and medicine by dispelling religious taboos against the body through the separation of mind and body.[18] On the other hand, this perspective led to the study of the body as a machine, laying the foundation for a theory of organ and bodily system function based on purely mechanical principles.

This dualist perspective on mind and body influenced Cuvier's anatomical approach to the body as a mechanical system[19] and inspired Viollet-le-Duc's entirely mechanical and rational study of architectural structures. However, as with the controversy surrounding the Eiffel Tower, the dichotomy between skeleton and skin, or material and perception, is a static and one-sided quest for rationality and authenticity. Cuvier and Viollet-le-Duc make no reference in their analogy to the importance of other more fundamental body dimensions, such as the circulatory or nervous systems. Instead, they only emphasise the relationship between the physical dimensions of the skeleton in isolation, presenting an inadequate analogue.

On a philosophical level, mind-body dualism has also been questioned, and many thinkers have attempted to transcend the divisions between the two. Martin Heidegger coined the term 'Being-in-the-world'. He believes that existence and the world are inextricably linked; there is no distinction between subject and object and how we perceive the world emerges from our bodies' interactions with it.[20] Similarly, Maurice Merleau-Ponty asserted that the body is the subject of perception and that perception, the body, and the world are inextricably linked.[21] People interact with the world primarily through their bodies, not their minds, and perception and knowledge of the world arise due to the body's action on the objective world. This embodied perspective also explains why Wölfflin used empathy to interpret the Gothic church's 'tension'. Empathy is a term that refers to a person's capacity to comprehend and 'feel' other people and situations through the sympathetic projection of the body. In contrast to the physical perspective of anatomy, this analogy between the body and perceived structure is a perceptual or even irrational cognition based on bodily experience.



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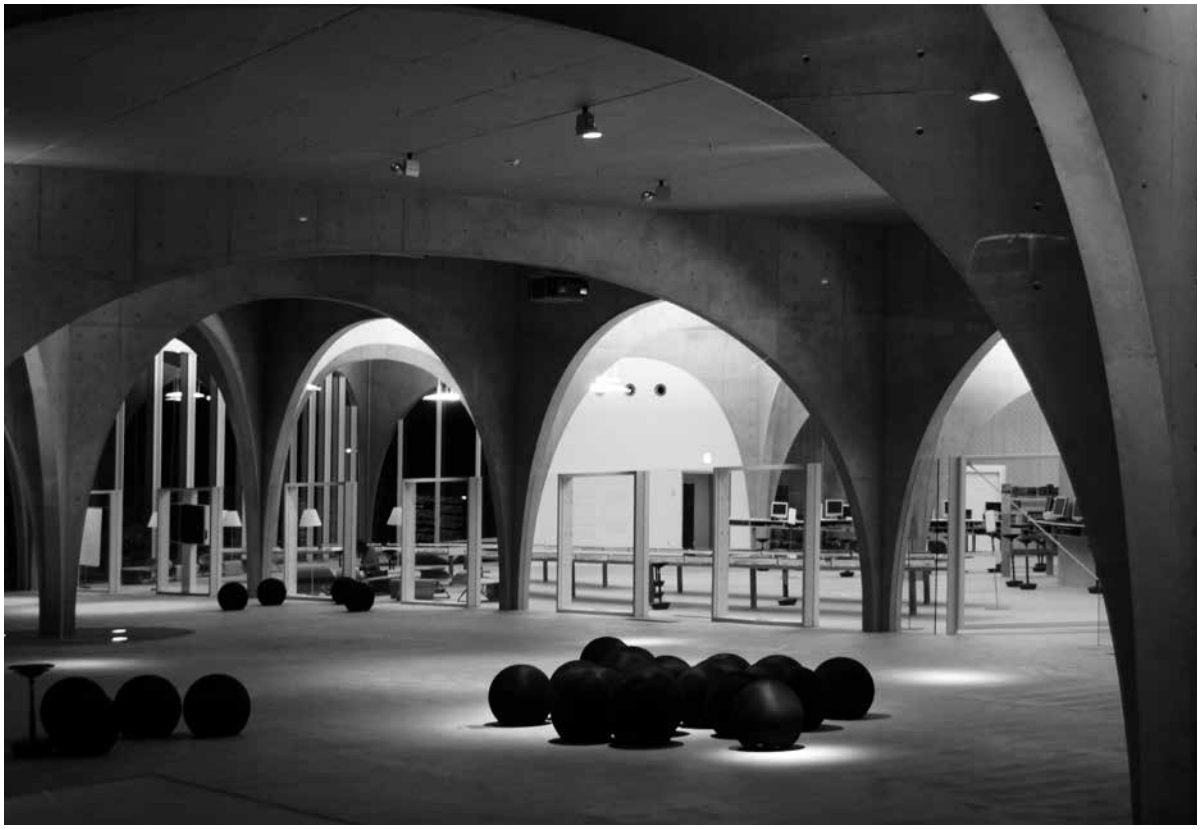

1 Tama Art University Library, Toyo Ito, Tokyo, 2007.

In his *An Analogical Architecture*, Aldo Rossi also emphasises the irrational dimension of analogy.[22] He quotes Carl Gustav Jung's description of analogical thinking: 'The "analogical" or fantastic thought is sensible, figurative and mute [...] Analogical thought is archaic, unconscious and practically inexpressible in words.'[23] Rossi considers analogy as a figurative expression of ideas and ways of thinking and as a method of architectural and urban design – a rationalisation of spatial experience into the production of space. This analogical thinking and empathy theory are complementary in that they both emphasise the unconscious or irrational dimension of perception, the neglected psychological dimension resulting from the separation of mind and body, and the humanistic dimension inherent in architecture but not included in previous structural analogies.

Along with the evolution of the concept of the body, recent advances in cognitive neuroscience have bolstered and expanded empathy and other cognitive theories, ushering in a new era of structural design analogies with the body.[24] Similar to how the developments in the biological sciences have historically inspired and facilitated structural design and thought, the findings in neuroscience can contribute to a more rigorous and scientific explanation of the analogy between structural design and the human body, thereby bridging the mind-body dualism's fragmented perception.

The following section will examine the traditional biological analogy's missing perspective and expand on its established argument through the contemporary new body conception. To complete the mental and experiential dimensions of the analogy, the cognitive neuroscience perspective is combined with a subversive examination of structural cognition. The main objective is to broaden our understanding of the body-structural analogy and to inspire new structural design thinking.

**Structural analogue and the physical body**

The primary difficulty with Viollet-le-Duc's dualistic interpretation of the analogy between body and structure, skeleton, and flesh, is the object of the analogy's singularity and static nature. Many structural analogies in this so-called rational perspective are naïve comparisons between the skeleton of the body and the supporting structures of architecture, such as columns, beams, or arches. Then non-weight-bearing enclosures such as screen walls or façades are used as a metaphor for the 'envelope'. This is an oversimplification and an incomplete understanding of the structural relationship between architecture and the body. As Pierre Patte has criticised analogies that arbitrarily use solid materials such as masonry to represent the Gothic church's skeleton, the balance of the structural relationship between the building and the body also includes the elastic living structure of muscles and skin.[25] If the body consisted solely of bones, it would be impossible to maintain structural stability and balance. While this analogy enables the structure to be more vivid, clear, and understandable, it also leads the design of structure into a one-sided



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pursuit of the minimum material and most economical 'structural rationalism' for a long period. This is because other structural systems are ignored in the body and structure analogy. The controversy surrounding the Eiffel Tower results from this pervasive misunderstanding of the 'rational image'.

The omission of other bodily systems caused people like Viollet-le-Duc to confine the analogy to a static stage. The body is composed of several dynamically balanced systems, and if the skeleton's structural role is preferred, then the rest of the body will naturally be considered 'decorated' and attached to the skeleton, but this is inaccurate. Just as the body is not a static 'machine' but a dynamic whole that interacts with the external, the balance of the body structure activates various bodily mechanisms in response to changes in the external context. As a result, it always maintains a dynamic correspondence, promoting balance and stability throughout the environment. The body is thus a malleable structure capable of change,[26] but it is not a binary distinction between 'functional' and 'decorative', but rather a function that manifests in response to various states.

Similarly, the building structure system must work cohesively to resist changing forces from various directions and properties. The structural resistance mechanisms activated by the overall relationship of the structure vary depending on the context (e.g., from tensile to compressive). This one-sided misinterpretation of the structure based on the skeleton's relationship alone has resulted in a disregard for the structure's overall relationship. This perception has significantly decoupled the structure from other building elements (such as the façade), depriving the functionality other elements can produce. As Berlage's critique of the cladding-frame dichotomy, the cladding should be related to the frame but not entirely dependent on the skeleton. The perceived beauty of the body is also influenced by the ambiguous relationship between skin and skeletal expression, which is more suggestive than the literal representation of the skeleton. Therefore, it is critical to maintain a modest relationship between structure and expression in analogy to the body.

For example, Toyo Ito's Tama Art University Library transforms the logic of a beam-column structure into a series of continuous arches *[1]*. It is not a dishonest structural expression, but a trans-formal structural logic that emphasises the building's intention by blurring and highlighting the body's perception of force. In this case, the arches achieve Toyo Ito's desired cave-like spatial expression, and the continuous curves formed by the continuous arches echo the sense of flow inherent in the original site.[27] These purposefully ambiguous or exaggerated expressions of structure do not prevent people from understanding the design intent because of their 'dishonest' expressions, but rather stimulate a strong propensity to perceive and comprehend the embodied expression of the structural concept on a more abstract or experiential level.

Thus, from the perspective of biological adaptation and active evolutionary selection, Viollet-le-Duc's Aristotelian fantasy of a perfect and formally explicit structure is unjustifiable. The body is a highly complex and intricate mechanism. The analogy with the body can inspire much structural thinking. However, it is essential to avoid falling into a one-sided functional determinism and becoming lost in pursuing a false 'authenticity'. The mechanisms by which the body's systems self-regulate in response to external changes have been improved through studies such as cybernetics and are now being applied to the regulation of complex systems in architecture.[28] Suppose these mechanisms in the body can be taught to predefine malleability or tolerance in addition to structural stability in response to environmental and functional changes, the structural system's possibilities can be significantly expanded, allowing the analogy between structure and body to become more complete and interconnected.

**Structural metaphor and bodily experience**

The analogy between body and structure emphasises only the physical dimension, inevitably relegating structures to the category of functional load-bearing machines. By omitting its perceptual and experiential dimensions, the structures generated by this thinking become a 'mental vacuum'. This unidirectional and dehumanising analogical perspective considers only the local and global relationships, but ignores the correspondence between the expression of these relationships and the subjective level of human perception. Furthermore, contemporary architectural design tends to reduce structural design to a purely intellectual activity unrelated to any specific bodily experience, thereby suffocating the bodily meaning of structure.[29] Thus, references to the body are also assignable in the design of structural expression or representation. The relationship between structure and body should not be a mechanical, bijective analogy, as Viollet-le-Duc thought, but rather a metaphor with a certain correlation. The metaphorical perspective slightly differs from the analogical perspective in that it retains a degree of redundancy and permits structural designs inspired by, but not limited to, the physical structure of the body.

However, the historical metaphor between art and formal expression of structure and the body was superficial and vague. This metaphor is prevalent in the renaissance in the geometric appearance of architectural structures concerning the equilibrium and proportions of the human body, in the narrow sense of correlating the configuration of a building to the parts of the body or applying the proportions between the human body's limbs to architectural elements.[30] This narrow reasoning is a mathematical and even mystical metaphor that does not adequately explain why people experience aesthetics. In the modernist period, this proportional metaphor eventually resulted in an investigation of purely geometric proportional



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systems, omitting any consideration of the human dimension. With the revolutionary conception of the body, embodied cognition of the body and mind gradually supplanted the previous dualistic view of the mind and body as distinct entities. The traditional cognitivist view of cognition as an abstract symbolic computational process occurring in the brain was deemed excessively narrow.[31] As a result, a purely mathematical interpretation of geometric forms and proportions as metaphor for structural expressions and bodily meanings is also inadequate. The argument that cognition, mind, and meaning-making are inextricably linked to the body has gained widespread acceptance in fields such as empathy and phenomenology, and has been expanded and subverted in recent years by cognitive neuroscience. This section will combine the recent emergence of different cognitive neuroscience contributions, such as mirror neurons, enactivism, and 4E, in order to clarify and expand the relationship between the body and structure and provide new perspectives for structural design.

Mirror neurons are a seminal discovery in neuroscience that has profoundly affected various fields of knowledge. Mirror neurons were discovered when scientists found that the neurons triggered by macaques' premotor and posterior parietal cortex both fired when touching and seeing a banana.[32] Therefore, the mirror neuron explains that the same neural structures involved in our own bodily experiences contribute to conceptualising what we perceive from the world both visually and corporally. Our understanding of the world is an unconscious process through mirroring others' experience and then evoking our memorised past corresponding bodily experiences and feelings. Additionally, the mechanism of mirror neurons are not restricted to the *social* realm: humans have the 'precognitive capacity to mirror the *tactile* values of all objects or forms in our environments, both living and non-living'.[33] And the significance of this critical mirroring mechanism in the metaphor of structure is that it demonstrates, on the one hand, that the traditional understanding of perception's dualism of mind-body separation is one-sided and inaccurate while also scientifically validating Wölfflin's idea of using empathy to read the Gothic church and explaining how architectural structures gain understanding through our own body and sensory-motor experience. For example, when people observe the Pisa tower, they understand and feel its tendency to capsize by recalling similar past bodily memories, which evoke the corresponding moods, such as unstable and unbalanced.

Furthermore, the notion of 'embodied simulation', proposed by Vittorio Gallese, extensively explains that human perception and cognition emerge from the active dynamic interaction and movement within the environment.[34] Embodied simulation demonstrates that embodiment is an active mode of interaction and experience in our bodies and that even static objects can be 'animated' when they are induced in the observer's brain.[35] This means that even static structural representations, when associated with the 'dynamics' of the body, can convey embodied motion to us.

The key findings of mirror neurons and related mechanisms of embodied simulation and research on sensory perception and emotion, among others, imply that our more fundamental corporeal responses primarily structure all our encounters with architecture.[36] This also redefines the relationship between perception, body, and structure from the perspective of embodied perception. To overcome the shortcomings of the above disembodied cognitive model, where body and mind are separated, Varela and others propose an enactive approach, which emphasises the concept that a living being is an autonomous agent that generates and maintains its cognitive domain through continuous reciprocal interactions between the brain, body, and environment.[37] The enactive approach views perception as 'an embodied coping with the environment'.[38] It contends that intelligence is not confined to the skeleton but resides in the interconnections between body, mind, and environment.[39]

These neuroscientific findings imply that metaphor is doubly embodied. First, as an unconscious experiential cognitive process; second, as an evocation and retrieval of previous bodily experiences and feelings.[40] And this cognitive perspective on the unconscious and empirical is strikingly similar to Rossi's attitude towards analogy's irrational and empirical dimensions as a guide for architectural design. This attitude also appears to fit Daniel Kahneman's proposed two modes of thought: fast and slow.[41] The fast bodily response originates primarily at the experiential level. This perspective establishes a direct link between analogical thinking and imagination and a theoretical foundation for the analogy between the structure's expressive dimension and the body.

Recently, many models and explanations further strengthen the link between organism and environment through the 4E approach to cognition, which refers to enactive, embodied, embedded, and extended.[42] Although this theory does not yet constitute a cohesive cognitive theory, it has been through a constant and open process of development and evolution, and increasing research has begun to illustrate its promise.[43] Several recent attempts have been made to adapt 4E to architectural design and instruction.[44] This enactive approach proposes that the relationship between neuroscience and architecture is less about answering scientific questions and more about discovering the systemic structure of architects' creative processes. Architecture becomes the design interplay between living organisms and forms.

From the conception of empathy to recent neuroscience discoveries, the expression and perception of the structure have taken on a more scientific and precise perspective at the level of bodily experience. This metaphor based on body



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experience reintroduces the human dimension to structural design, enabling structures to transcend the purely intellectual activity of 'computation' and achieve physical equilibrium while gaining a different dimension of design inspiration from an embodiment perspective. As a result of these new studies, the findings of neuroscience are extending the analogy between structural expression and the body from the formal level to the metaphorical level of experience and perception. In this regard, the neuroscience study of 'body schema' can provide us with some new references.

Body schema is a critical part of embodied perception. It describes an individual's capacity to unconsciously act coherently in the world and be aware of one's body.[45] It mixes and synchronises physiological information from somatosensory modalities, such as proprioception, kinesthesia, and haptics, into a sensory-motor modality as part of its involvement in motor control.[46] It refers to an unconsciousness and empirical reflection rather than a rational analysis of cultural and scientific knowledge.[47] At the same time, the body schema is distinct from Rudolf Arnheim's superficial symbolic metaphor of the body.[48] It refers to a dynamic internal representation of bodily parts that constrains and defines the movement of tendencies towards possible body actions. This introduces a dynamic and experiential dimension to the previously static analogy of sign or form. As with Rossi's unconscious analogy, the intentionality of movement and implied body movement that the body schema emphasises is a prereflective irrational reaction. It emphasises not only the intention and information associated with the body's movement but also the emotions associated with the bodily experience of it,[49] which is another critical aspect of the body that has been overlooked besides the rational analogy. For instance, the sensation we get when reading a tilted structure as if it were about to collapse can be interpreted as a memory of instability triggered by our bodies' increasing muscular tension as we tilt.

Recent research on the body's somatosensory system and motor system dimensions demonstrates that our sensorimotor knowledge constitutes our perceptual ability. Therefore, perception is not something that occurs to or within us but rather something we do.[50] This shifts the emphasis of the analogy between structure and body from form and proportion to movement and interaction. It also offers a fresh viewpoint on design and thinking at the level of structural expression and artistic expression.

The use of static structures to represent and suggest the dynamic body and its experiences seems a very abstract perspective. However, Body schema concretised our attention to the underlying motivations for action and attention. Similar to Arnheim's description of 'Immobile Motion',[51] the static structure's metaphor for the body's dynamics derives from the structure's tendencies to express an embodied movement on the one hand and from the possibility of bodily interaction with it on the other (e.g., by indicating climbing or leaning). In this case, the metaphor of structure and body becomes an allusion to the body's dynamics or action, an expression of the body's unconsciously dynamic relationship between balance and unbalance in response to changes in the external environment, rather than a formal analogy.[52] And both perspectives can be conveyed through the structure's organisation. By establishing connections between structural elements' parts and wholes, or between multiple structural systems, the expression of structure can shift and combine the implication and guidance of various body gestures.

It is important to note that structural design must not lose sight of the technical aspects of load-bearing while taking expression into account, which implies that structural design also seeks precision. Therefore, the historical analogy between structure and body should not be discarded, but rather reintegrated through the lens of neuroscience with the more perceptual aspects of the metaphor that had been previously separated from it, in order to evolve into a new structural analogy that combines rational and perceptual aspects. Through the incorporation of perceptual and experiential aspects into the structural analogy, structural design can also transcend the traditional requirement for a clear representation of structural systems. In the view of bodily experience, alienation or blurring of structural systems could instead reinforce the relationship between the human bodily experience and the structure.[53] As 'embodied simulation' emphasises, bodily experience and interaction are vital for meaning, and this structural metaphor for bodily experience stimulates communication with architecture to derive meaning from bodily experience.

One of the more prevalent methods is to alienate structures to disrupt the habitus of interaction between the structure and the body, amplifying the generation of bodily experience. Similar to how alienation or amplification of the static structural logic can activate the memory of a bodily experience for the experiencer in the physical analogy, this directly evoked movement of the body can also consciously activate the memory of a bodily experience. For example, in the Bahrain Pavilion in Dubai 2020, *[2]*, Christian Kerez constructed the building using a dense network of steel tubes with a diameter of only 12 cm, securing the façade while limiting the interior's spatial experience. The building's seemingly random structural rods are derived from precise structural calculations, partially as tension rods, partially as compression rods, and partially as spatially defined elements. Walking through them requires making sharp turns in body orientation due to the varying distances between the steel tubes; lowering or bending down the body frequently occurs due to the varying angles and combinations of structural elements. Sometimes people could lean on and hold them directly. This structural system acts directly on bodily schema, disrupting the



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2 **Bahrain Pavilion, Christian Kerez, Dubai, 2020.**



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3 Maison à Bordeaux, OMA, Bordeaux, 1998.

habituation and continuity use of the space, amplifying the bodily experience evoked by traversing it, stimulating the meaning of the body, and thus amplifying the potential of space.

Another strategy is to blur or obscure the structure's overall logic representation so that the experience is always limited to a portion of the structure's equilibrium system. For example, only reading or experiencing a part of a structure in two or more superimposed systems may cause a one-sided (or unbalanced) bodily sensation and then encounter a different one from another part. Only after experiencing the structure in its entirety can the fragmented representation achieve continuity and relevance at the conceptual level, resulting in the development of a psychological Gestalt and an understanding of the structural system. At this point, the structure as a whole can be compared to the synthesis of a series of bodily changes captured with a high-speed camera, whereas the partial representation of the structure is comparable to the communication of a single frame from this series of bodily changes; simply observing a single body pose or a partial body pose in a series of bodily changes does not achieve the structure's equilibrium and continuity at the conceptual level. Thus, our bodily experience conveys the implication of structure in terms of temporal continuity for bodily experience and movement tendencies.

For instance, Rem Koolhaas and Cecil Balmond collaborated on Maison à Bordeaux to design a 'floating' box that speaks to the site while providing the best view possible [3]. The building's sense of floating results from the distortion of the structural system, which enabled them to replace one side of the support with one suspended from above and panning the other side outwards to create a dislocation. The two structural systems are superimposed, leaving only an eccentric column with highly reflective material supporting a sizeable black box visible on the ground floor. From either side of the building, one can observe only a portion of the overall equilibrium system and thus cannot directly read the structure's load-bearing logic. The fragments of this equilibrium system can be conceptually pieced together and thus understood only by traversing the entire building. This fragmented structural representation is comparable to the presentation of a series of bodily motion fragments that can be rationalised from an embodied perspective only after they are combined. Additionally, the fragmented representation of structure in architecture arouses curiosity, encouraging more active exploration and interaction with structure, thereby aiding in the dialogue of architectural concepts.

This newly proposed structural-body analogy refers to using static structures to imply, guide, and even stimulate the body's dynamic tendencies via organisational relationships. It is a psychological expression of the body's dynamics through physical interaction. In contrast to the 'authenticity' sought by analogies historically focused on structural forms, the addition of a bodily experience dimension to analogies enables a rethinking of what is meant by structural authenticity: is formal or



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functional similarity genuine? If one wanted to use structure to convey feelings more closely associated with bodily experience, many structural choices undermine the structure's supposed clarity, inviting movement and exploration and thus eliciting increased metaphors of bodily interaction and dynamic experience. This could be another underappreciated aspect of bodily authenticity.

Notably, even though studies of mirror neurons have provided evidence from sensorimotor experience for cross-cultural sources of perception and opened the door to the possibility of other neurocognitive mechanisms,[54] the extent to which mirror neurons can explain perceptual behaviours such as empathy is still a matter of heated debate.[55] This article's discussion of structurally embodied perception is not intended to revert all explanations to a body-based perspective. As neuroscience research advances, it is hoped that the evidence found by mirror neurons between sensorimotor experience and perception will combine the physical and psychological aspects of the body with structural design and expression, opening a new door for innovative design methods based on analogies between the body and structure.

**Analogue as structural design**

The traditional view of the body affects not only the static body analogy but also the understanding of the design process. This analogy is not only about imitating natural forms but also about the process of natural evolution.[56] Because the body and the building structure are both malleable, structural design should be a subjective choice for the designer rather than a problem with a fixed solution. As the enactive approach has emphasised, structural design should be an active process rather than a reactive one. However, the current separation of the architectural and structural professions has transformed the structure into a problem-solving exercise to determine the optimal supporting building form. From a biological perspective, optimality is always a subjective choice rather than an objective outcome, and the Gothic churches lauded by Viollet-le-Duc can be viewed as a particular case in the evolutionary process rather than a universal truth.[57]

The classic Darwinian process of biological evolution presented a process of error correction, and imitating the process of structural design to this Darwinian perspective makes it difficult to ascribe any notion of 'design' to the structure, as the process is unrelated to any explicit purpose or outcome.[58] However, in practice, this optimising design thinking is easily constrained by oversimplification of the external environment, which increases the likelihood that the same errors will persist throughout the evolutionary process, ultimately leading to a relatively 'good solution'. Structural design is not merely a process of problem-solving. The analogical view of the body as a medium is the polar opposite of the traditional problem-solving approach to design. It provides a predictable course of action, liberating us from the self-optimising cycle of reactive problem-solving shackles. It enables us to be proactive in our design choices and decisions. Allowing structures' evolutionary processes to incorporate the evidence and principles of bodily experience as a consideration that structures can incorporate from the beginning. This analogical perspective on bodily experience also employs an iterative design process. It focuses not only on comparing the evolution of biophysical forms but also intends to introduce the psychological and experiential levels of adaptive evolution from an evolutionary psychological perspective into the analogical process of structural design.[59]

Regarding structural behaviour, we can use, for instance, Engel's classification of structural systems as a starting point for examining the expressive design potential of various structural systems.[60] In the translation of static bodily gestures into structures, the two structural systems, vector-active and section-active, which use topological combinatorial relations as their starting point, are well suited to describe the equilibrium between structures and body parts, thereby conveying embodiment. For the spatially oriented design of the overall relationship between structure and dynamic interaction and movement, form-active and surface-active, which emphasise a more three-dimensional compositional approach, are more likely to shape the translation of the body's dynamic experience. Height-active structural systems, on the other hand, permit a more integrated approach to static and dynamic structural expressions in the face of increasingly complex structural environments. These bodily perspectives appear to provide important new insights into the expressive dimensions of structural systems such as tensegrity and membrane structures.[61]

Regarding the design model, neuroscience-inspired structural design presupposes early iterative collaboration between the structural engineer and architect to define the design problem on both an emotional and rational level and to choose the design direction for the design's subsequent evolution. For instance, architects and structural engineers can incorporate our unconscious bodily experiences into the design process via hand drawing or physical models during the conceptual structure design phase. On the one hand, this facilitates communication by illustrating our bodily experiences; on the other hand, it incorporates bodily thinking into the design, thereby including the structure's humanistic expression.[62] Moreover, as suggested by Henry Francis Mallgrave, architectural design should not solely focus on the development of formal concepts, but should be a forum for rigorous interdisciplinary research.[63] Faced with uncertain future challenges, architecture as a discipline must broaden its scope and shift from an introspective structural design to a more compatible design of structures. In order to advance the future development of architecture



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and structures, these challenges require not only collaboration between architects and structural engineers but also a deeper collaboration with other disciplines, such as neuroscientists and psychologists. This collaboration should not be limited to the passive acceptance of neuroscientific knowledge but should also involve active participation in neuroscientific disciplines. It is believed that the numerous studies of architecture and structure can provide neuroscientists and other specialists with new insights and research topics.

The biological analogy between building and body has persisted throughout history, and discoveries in neuroscience have expanded the analogy's horizons. However, this is not the end of the story. The field of structure and architecture must remain open to new technical findings, actively compare and contrast thinking and innovation, and embrace new knowledge in the manner of the former sages to promote structure and architecture beyond the rationale of pure technique and into a perceptual level. This review and discussion of the analogue structure are not intended to focus exclusively on the body, but rather to reflect on a fundamental value of design – one that confronts the human instinct to perceive and think about space.

**Notes**

1. Martin Bressani, *Architecture and the Historical Imagination: Eugène-Emmanuel Viollet-le-Duc, 1814–1879* (Farnham, Surrey: Ashgate Publishing, 2014), p. 186.
2. Thomas Tredgold, *Elementary Principles of Carpentry* (London: Taylor, 1820).
3. Aristotle and William Ogle, *Aristotle on the Parts of Animals* (London: K. Paul, French & Co., 1882).
4. Michel Foucault, *The Order of Things: An Archaeology of the Human Sciences*, 2nd edn (London: Routledge, 2002), p. 289.
5. Aron Vinegar, 'Architecture under the Knife: Viollet-le-Duc's Illustrations for the Dictionnaire Raisonné and the Anatomical Representation of Architectural Knowledge' (unpublished Master's thesis, McGill University, 1995), p. 10.
6. Eugène-Emmanuel Viollet-le-Duc, *The Foundations of Architecture: Selections From the Dictionnaire raisonné*, ed. by George Braziller (New York, NY: G. Braziller, 1990).
7. Jacob deconstructs the body's unity through exploded diagrams and dismantles it into discrete elements in various body parts. It emphasises the dynamic and relational nature of perception, allowing the reader to more clearly interpret the relationships between the elements intellectually. For more details, see: *Atlas of Human Anatomy and Surgery: The Complete Coloured Plates of 1831–1854*, ed. by Jean-Marie le Minor and Henri Sick (Cologne: Taschen, 2008).
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11. Hendrik P. Berlage, *Gedanken über Stil in der Baukunst* [*Thoughts on Style in Architecture*] (Leipzig: Zeitler, 1905), p. 24.
12. Joseph August Lux, *Ingenieur-Aesthetik* [*Engineer-Aesthetics*] (Munich: Verlag van Gustav Lammers, 1910), pp. 3–4.
13. Philip Steadman, *The Evolution of Designs: Biological Analogy in Architecture and the Applied Arts* (London: Routledge, 2008), pp. 8–20.
14. Steadman, *The Evolution of Designs*, chs 13, 14.
15. Viollet-le-Duc's adamancy was later demonstrated to be exaggerated in subsequent experimental and theoretical analyses, such as Pol Abraham's criticism. For more details, see: Pol Abraham, *Viollet-le-Duc et le Rationalisme Médiéval* (Paris: Vincent, Fréal, 1934).
16. John Summerson, *Heavenly Mansions, and other Essays on Architecture* (New York, NY: Norton, 1998), p. 149.
17. Heinrich Wölfflin, 'Prolegomena to a Psychology of Architecture', in *Empathy, Form, and Space: Problems in German Aesthetics, 1873–1893*, ed. by Robert Vischer and Harry Francis Mallgrave (Santa Monica, CA: Getty Center for the History of Art and the Humanities, 1994), p. 150.
18. The body and soul were considered one in religion, and the study of the human body through dissection was therefore forbidden. Descartes' mind-body dualism liberated natural science from theological constraints, demythologises the body, and relegates its study to medicine.
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20. Dermot Moran, *Introduction to Phenomenology* (London: Routledge, 2000), pp. 222–45.
21. Maurice Merleau-Ponty, *Phenomenology of Perception* (London: Routledge & Kegan Paul, 1962).
22. Aldo Rossi, 'An Analogical Architecture', *Architecture and Urbanism* (a+u), 56 (May 1974), 74–6.
23. Carl G. Jung, in *The Freud/Jung Letters: The Correspondence between Sigmund Freud and C. G. Jung* (2 March 1910), ed. by William McGuire, trans. by Ralph Manheim and R. F. C. Hull (London: Penguin Twentieth Century Classics, 1991), p. 160.
24. Harry Francis Mallgrave, *Architecture and Embodiment: The Implications of the New Sciences and Humanities for Design* (London: Routledge, 2013). For other relevant works, see for example: Sarah Robinson and Juhani Pallasmaa, *Mind in Architecture: Neuroscience, Embodiment, and the Future of Design* (Cambridge, MA: The MIT Press, 2015); Shuaizhong Wang, Toni Kotnik, Joseph Schwartz, Ting Cao, 'Equilibrium as the Common Ground: Introducing Embodied Perception into Structural Design with Graphic Statics',



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*Frontiers of Architectural Research*, 11 (2022), 574–89.
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30. For more details, see: Peter Hugh Scholfield, *The Theory of Proportion in Architecture* (Cambridge, UK and New York, NY: Cambridge University Press, 2011).
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32. Giacomo Rizzolatti, Leonardo Fogassi, Vittorio Gallese, 'Mirrors in the Mind', *Scientific American*, 295:5 (2006), 54–61.
33. Harry Francis Mallgrave, 'Embodiment and Enculturation: The Future of Architectural Design', *Frontiers in Psychology*, 6 (16 September 2015), 1398.
34. See Vittorio Gallese, 'Embodied Simulation: From Neurons to Phenomenal Experience', *Phenomenology and the Cognitive Sciences*, 4 (2005), 23–48.
35. David Freedberg and Vittorio Gallese, 'Motion, Emotion and Empathy in Aesthetic Experience', *Trends in Cognitive Sciences*, 11 (May 2007), 197–203.
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37. Francisco J. Varela, Evan Thompson, Eleanor Rosch, *The Embodied Mind: Cognitive Science and Human Experience* (Cambridge, MA: London: MIT Press, 1991); Andrea Jelić and others, 'The Enactive Approach to Architectural Experience: A Neurophysiological Perspective on Embodiment, Motivation, and Affordances', *Frontiers in Psychology*, 7 (2016), 481.
38. Shaun Gallagher and Dan Zahavi, *The Phenomenological Mind: An Introduction to Philosophy of Mind and Cognitive Science* (London: Routledge, 2008).
39. *The Oxford Handbook of 4E Cognition*, ed. by Albert Newen, Leon De Bruin, Shaun Gallagher (Oxford: Oxford University Press, 2018).
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41. According to Kahneman's psychological framework, human thought patterns are classified as rational, conscious, and requiring a great deal of attentional resources; and those that occur subconsciously, are extremely agile and fast, and do not require attention. See Daniel Kahneman, *Thinking, Fast and Slow* (New York, NY: Farrar, Straus and Giroux, 2013).
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49. Matthew Bower and Shaun Gallagher, 'Bodily Affects as Prenoetic Elements in Enactive Perception', *Phenomenology and Mind*, 4 (2016), 78–93.
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51. Rudolf Arnheim, *Art and Visual Perception: A Psychology of the Creative Eye* (Berkeley, CA: University of California Press, 1974).
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56. Montgomery Schuyler, 'Modern Architecture', *Architectural Record*, 4 (July–September 1894), 1–13.
57. Thomas Tredgold, *Elementary Principles of Carpentry*, p. VIII.
58. Christopher Alexander, *Notes on the Synthesis of Form* (Cambridge, MA and London: Harvard University Press, 1964), p. 77.
59. Evolutionary psychology examines the evolution of mental functioning through the lens of evolution and environmental adaptation. It asserts that in response to environmental stresses, humans have evolved a number of distinct 'psychological modules'. These modules are 'domain specific' in that they employ a variety of adaptive



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strategies in response to a variety of environmental stresses.

60. According to different design orientation, Heinrich Engel divided structure systems into five categories: Form-active, Vector-active, Section-active, Surface-active, Height-active. For more information, see: Heino Engel, *Structure Systems* (Ostfildern: Hatje Cantz, 2013).
61. Obviously, structural design using the body as a medium frequently exceeds the limits of general structural types, and the combination of this with Heino Engel's structural system is intended to establish a potential link between the structural thinking presented in the article based on body analogies and the numerous structural systems already in existence.
62. For more related discussion, see: Juhani Pallasmaa, *The Embodied Image: Imagination and Imagery in Architecture* (Chichester: John Wiley & Sons, 2011); Or Calatrava's many practices and reflections on the use of hand sketches through the body as a source of structural design inspiration, see, for example: Javier Arnaldo and Santiago Calatrava, *Santiago Calatrava: Sculptures and Drawings* (Valencià: ALDEASA, 2001)
63. Harry Francis Mallgrave, *From Object to Experience: The New Culture of Architectural Design* (New York, NY: Bloomsbury Academic, 2018).

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The author declares none.

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