Wang, Shuaizhong; Kotnik, Toni; Schwartz, Joseph

Redefining Structural Art : A Neuroaesthetics Perspective on the Art of Structural Design

Published in:
Architecture, Structures and Construction

DOI:
10.1007/s44150-022-00027-y

Published: 09/03/2022

Document Version
Publisher's PDF, also known as Version of record

Please cite the original version:
Wang, S., Kotnik, T., & Schwartz, J. (2022). Redefining Structural Art : A Neuroaesthetics Perspective on the Art of Structural Design. *Architecture, Structures and Construction*, *2*(1), 3-16. https://doi.org/10.1007/s44150-022-00027-y

Architecture, Structures and Construction (2022) 2:3–16
https://doi.org/10.1007/s44150-022-00027-y

ORIGINAL PAPER

Redefining Structural Art: A Neuroaesthetics Perspective on the Art of Structural Design

Shuaizhong Wang[1] · Toni Kotnik[2] · Joseph Schwartz[1]

Received: 27 October 2021 / Accepted: 18 February 2022 / Published online: 9 March 2022

Abstract
Structural art should not be marginalised as an integral part of structural design. By reviewing historical understandings of structural art, this article discusses the ambiguous and neglected perspective of structural art on architectural design and human perception dimensions, concentrating the attention of structural art on the question of human aesthetic perception. Based on significant changes in how art is perceived due to recent neuroaesthetics research, this article introduces recent findings from cognitive neuroscience regarding embodied perception principles, sheds new light on the aesthetic experiences inherent in the built environment, and clarifies and expands previously held beliefs about structural art. Finally, while emphasising the significance of structural art, this article attempts to provide a body-informed perspective on structural art that can aid in incorporating human neuroaesthetic perception principles during the conceptual phase of the structural design process, thereby redefining the effect of structures on architectural space and aesthetics, thus redefining structural art.

Keywords Structural art · Structural aesthetics · Neuroaesthetics · Perception · Embodiment · Affordance

Introduction

Building structures are shaped by both their technical and artistic dimensions [1, 2]. From ancient Greek to Roman Thermae to Gothic Churches, these past architectural marvels result from a marriage of technology and art. However, by the mid-nineteenth century, the advances in science and technology render the prior art of architecture obsolete, bringing an end to the era of intuitive construction techniques [3]. The architect who mastered the entire architectural design process gradually relinquished control of the structural design and construction processes. Engineers are more concerned with the technical implementation of spatial structures, whereas architects are concerned with realising the relationship between architecture, art, and social function [4]. Structural thinking evolved into a tool for structural calculations and mechanical analysis in order to support the building's form, and "structural design" became "structural analysis." This separation of technology and art resulted in two interdependent static principles in structural design: mechanical and artistic.

However, architects and structural engineers have marginalised the aesthetic aspect of structural design to focus exclusively on the technical aspects [5]. And this is not an exhaustive description of structural thought. The relationship between architecture and structure has been the subject of considerable debate throughout the twentieth century. Many studies have been devoted to the design-oriented perspective on structural design.[1] As one of the most widely known definitions, David Billington's ground-breaking book, *The Tower and the Bridge*, proposed a definition of structural art in 1983 to explain further the significance of art and design in structural design. It had a sizable influence on subsequent generations of architects and structural engineers. Unfortunately, their discussions of structural art were frequently restricted to large-scale structures such as bridges, large-spanning structures, thin-shelled vaults/roofs, and towers [6]. However, structures are not simply large-scale

✉ Shuaizhong Wang
shuaizhong.wang@arch.ethz.ch

1 Department of Architecture, ETH Zürich, Zürich, Switzerland

2 Department of Architecture, Aalto University, Espoo, Finland

[1] For related research, see for example, Torroja, M. E., Polivka, J. J., & Polivka, M. (1958). Philosophy of structures. Berkeley: University of California Press; Nervi, P. L. (1965). Architecture, Aesthetics and technology in building. Harvard University Press, Cambridge, Mass.

infrastructures or public buildings; they are also intimate and small-scale elements that pervade our daily lives. Structural art is more like a concept than the artistic forms typically found in large structures [5]. The structural concept in small and medium-sized buildings also significantly impacts all aspects of the building space and daily life. Therefore, it would be irresponsible for a structural engineer to delegate the artistic aspects of structure to the architect, as this would significantly reduce the scope and degree of the structural designer's contribution of creativity and expression.

The purpose of this article is to bring attention to an often-overlooked aspect of structural art from an architectural design perspective. Compared to the existing structural art in large structures, this article focuses on structural art in architecture, which is more relevant to people's daily lives. Through a review and analysis of structural art in architectural design, the article focuses on the perception aspect of structure, especially embodied perception. In order to clarify the poetic and artistic perception principles of structure, the article introduces recent neuroscience findings on "neuroaesthetics". It elucidates the logic and methods behind the structural art found in selected buildings through the lens of neuroaesthetics' principle of aesthetic judgement. The article aims to dissolve the boundaries between architects and structural engineers and establish a new collaborative relationship that promotes artistic integration between the spatial and structural qualities of architecture.

The inadequate consideration of structural art

Already in 25BC, the Roman architect Vitruvius coined the terms *firmitas*, *utilitas* and *venustas* as the basis for architectural and structural design [7]. In the nineteenth century, many structural engineers were dissatisfied with the bland monotony of technical presentation and initiated their "A New Tradition: Art in Engineering" to recognise the importance of aesthetics. In 1812, British engineer Thomas Telford coined the term "Structural Art," defining it as the individual expression of structure within the discipline of material efficiency, construction economy, and final form appearance [4, pp. 3–24]. The Eiffel Tower (Fig. 1), designed by Gustave Eiffel in 1887, is the most emblematic example of this way of thinking. The Eiffel Tower successfully combines mechanics, structure, and aesthetics through steel, resulting in an artistic expression that combines grandeur, elegance, and lightness. It is worth noting that the Eiffel Tower's four arches are not integral to the overall structure but rather represent a compromise between visual security and aesthetic considerations for classical structural elements [8]. Thus, the design of the Eiffel Tower is influenced by mechanical and engineering considerations and cultural and artistic ones.

Fig. 1 The Eiffel Tower, Paris, 1889. Photo: Nikolija Grozdanovic

In 1983, American engineer David Billington developed the term "structural art" and gave recognition to many prominent structural artists [4]. He defined three disciplines of structural art as Efficiency, Economy, and Elegance, empathising this trend as a new type of art inspired by new technological innovations that are "entirely the work of engineers and of the engineering imagination [4, p. 4]." Later on, these criteria of structural art were complemented into three perspectives: scientific, social, and symbolic [6].[2] Billington and Garlock also pointed out that a work of structural art is always generated from one's ability to imagine and conceive a new structural form, visualising the final appearance, determining it by calculation, and formulating a method for constructing the structure [9]. However, this understanding of structural art is still confined to engineer-based projects such as bridges, towers, and high-rise buildings.

The master builders such as Eduardo Torroja, Pier Luigi Nervi, Heinz Isler, Sergio Musmeci, Felix Candela, and Frei Otto also practised similar concepts regarding structural art. They formed a group of engineers concerned with the architectural significance of structures that emerged in the mid-twentieth century, later dubbed "engineer-architects" [10].[3] For example, in *Aesthetics and technology in building*, Nervi presented the term "correctness," which refers to the bare minimum that should be attained in architecture, is

[2] Due to the environmental requirements, recent researches have also added ecological and ethical imperatives to Billington's three-E-principles. See J. A. Ochsendorf, "Eladio Dieste as Structural Artist," in Eladio Dieste: innovation in structural art, Princeton, Princeton University Press, 2004, p. 95.

[3] Relate articles see for example Nervi, Pier Luigi, Giuseppina Salvadori, and Mario Salvadori. 1956. Structures. New York: F.W. Dodge Corp; Chilton, J., & Isler, H. (2000). Heinz Isler. London: T. Telford; Otto, F., Schanz, S., & Robinson, M. (2001). Frei Otto, Bodo Rasch: finding form: Towards an architecture of the minimal. Fellbach: Edition Axel Menges.

defined further as stability, durability, and material selection according to their natural features as well as functional and economic efficiency [11]. He even emphasises that beauty transcends such “correctness.” While technology provides solutions and form, architecture is the result of adaptations to these proposals [12, p. 253]. Unlike previous structural art, which focused exclusively on the structure, engineer-architects have begun integrating structure with architectural function and space. They strive to balance their work between structural integrity, formal artistry, and architectural space. The form became a critical medium for achieving this balance: rather than accumulating materials, the form was used to create solid structures that became an expression of the designer’s aesthetic values and the container for the architectural space.

Since the 1990s, the pursuit of structural aesthetics has acquired a new dimension. The advancement of computer-aided design software and the emergence of new construction techniques have significantly increased structural technology and performance, thereby enriching architecture’s formal artistic vocabulary. This performance-driven structural thinking has driven the development of, for example, Performative Architecture [13]. This highly technical and performance-oriented structural art can be used almost quantitatively to assess or forecast a building’s function, stability, economy, and so on, and thus eliminate suboptimal results. For instance, topology optimisation has been extensively studied and practised in order to determine the form of a structure. Besides, there is no shortage of more subtle concerns and aesthetic explorations of the structure among adherents of the technical philosophy [14]. For example, many digital fabrication researchers have included artistic dimensions in their parametric explorations.[4] However, their explorations were limited mainly to experiments with novel materials and construction methods on small-scale structures, which can be interpreted as a further examination of engineer-architects’ thinking in the context of technological advancement. However, these extreme technical pursuits constrained the structure’s artistic or perceptual thinking.

Many of these constraints on structural art stem from engineers constantly being confronted with two widespread structural design myths: the belief that an efficient structure is inherently elegant and that a beautiful structure must be expensive [15]. H. Seymour Howard, for example, has elaborated on this point. He divides the structure into four categories: “minimal”, “adequate”, “formal” or “sculptural”, and “pretentious”. He emphasises the importance of both “visible” and “hidden” structures in terms of art and the emotional perception they impart on people, as well as their load-bearing efficiency and economics, in introducing these four types of structure. As a result, he stressed that “what is ‘best for the structure’ is not necessarily best for the building as a whole” [12, p. 255]. Meanwhile, an excessive emphasis on structural forms, such as “structure for structure’s sake,” is also inappropriate [16]. Schlaich points out that a structural form’s aesthetic expressions are not simply a desire to discover an ornamental form, nor is it a subordination of its technical function; otherwise, a building would be overdesigned and devoid of any semblance of structural art [17]. To fully realise the art of structure at all levels and scales, we must transform the structure into a synthesis of two aspects – technology and art – which can only be accomplished collaboratively between architects and engineers [18]. However, the structural art mentioned previously, distinct from the architect, is insufficient to achieve this balance.

Therefore, structural art can not be reduced to large-scale infrastructures such as bridges and towers or small-scale architectural vignettes defined solely in engineering efficiency and economics. Not only are structures used in engineering, but the art of structural design also plays a significant role in determining architectural space in everyday architecture. Howard has emphasised the importance of reintegrating structural techniques into the art of architectural design. Every aspect of the final structure must be considered during this early stage of development if the structure is to meet the art and societal requirements. Beauty cannot be added after practical considerations have been addressed, and the engineer should also be involved in preliminary studies [16]. Only when the art of structure is integrated with the art of architecture can designers think and design the art of structure holistically.

To balance the structure’s technical and artistic aspects, it is necessary to discuss what constitutes a “moderate” structure. Fritz Schumacher proposed the “dual truth concept” in this regard, which discussed the relationship between architectural art and structural technology on a rather abstract level. He believes that “technical truth” is the starting point for “artistic truth,” which is achieved through an emphatic or symbolic reinterpretation of “technical truth’s” characteristics [19, p. 228]. Nervi expands on this concept of ‘artistic truth’ by coining the term “Truth Plus” [12, p. 254]. He argues that the structure’s load-bearing function should serve as the inspiration and driving force for its form, which can be slightly adapted to aesthetic requirements and intuitive perceptions. Nervi divides the design process into two stages in this manner. The first stage is objective and deals exclusively with technical issues, whereas the second stage is subjective and cannot be governed by rules or logic. He argues that a structure can only be considered “correct” if

[4] For example, “the robotic touch” described by Fabio Gramazio and Matthias Kohler: Gramazio, F., Kohler, M., & Willmann, J. (2014). The robotic touch: how robots change architecture. Park Books, Zurich; or the construction experiments by Achim Menges: Menges, A. (2012). Material computation: Higher integration in morphogenetic design. Hoboken, NJ: Wiley.

both objective and subjective dimensions are balanced [11]. Thus, the efficiency of structures is discussed in terms of not only force and economy, but also perception and aesthetics. For example, Ove Arup calls this type of assessment "aesthetic accountancy", which seeks a balance between cost, functionality, and aesthetics [20, p. 242]. However, it will be challenging to judge aesthetic merit because the parameters must be weighed relative to cost and efficiency.

To better understand this "aesthetic accountancy" and to weigh them appropriately during the structural design process, it is necessary to understand the underlying principles of how people perceive structural art and the effect of structures on their aesthetic experience. While the load-bearing part of the structure can quickly be evaluated through efficiency and economy criteria, what about the structure's elegance or artistic aspect? Billington once stated, "Only when people begin to sense the emotion, the passion in a work of structure do they begin to recognise it as art [21]." He also questions doctrinaire structural honesty, arguing that we can think in the opposite direction, delving into the perspective that beauty is derived from form. He notes that, in addition to efficiently expressing force, Howard's "adequate structure" must communicate the concept of structural art in a way that the general public understands. The reason for considering the influence of form on the structure is to incorporate how people observe and perceive structural form into the design process—because the designed structure and its purpose must be comprehensible to the user [12, pp. 241–259].

The scholars mentioned above, such as Billington, are attempting to balance a moderate representation of structure from the structural engineer's perspective based on the criteria of efficiency and economy. However, the art of structure is not simply about utilising the least amount of material and constructing the lightest structure, nor a purely formal game. Various studies on the design and expression of structures have also been conducted throughout architecture's history. As Billington emphasises, the relationship between a structure's physical load-bearing structure and its artistic expression and how to achieve a balance between the two has always been a matter of perception—of how one perceives and understands the artistic dimension of the structure.

The question of structural expression

From an engineering standpoint, the Eiffel Tower is a masterpiece of structure art, conveying the structure's artistic properties while utilising as little material as possible in combination with steel, a novel material at the time. However, this choice of minimal materials sparked numerous debates at the time, with people expressing astonishment at the structure's "fleshless" or "massless" expression, while also raising serious doubts about the engineering minimalism's ability to meet the demands of the people: "…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." [22, pp. 3–4]." Some artists of the era even advocated for the tower's demolition [23]. The debate over the Eiffel Tower's structural expression is similar to Auguste Choisy's condemnation of the fan vaults of the Henry VII Chapel as a substitution of science for art. Choisy argued that good architecture could not rely solely on technique, but required a proper judgement of aesthetic effect, and that rational thinking about structure should not be interpreted as a structural form that obeys the laws of physics [24]. Similarly, while the Eiffel Tower satisfies some of the structure's technical requirements, it falls short of balancing many considerations of expression as a whole.

The relationship between ontology and representation in the "bone" and "skin" of the Eiffel Tower structure has been widely discussed throughout architecture history. For example, the *Kernform* and *Kunstform* (meaning core-form and art-form) from Karl Bötticher [25], or the Raiment theory from Gottfried Semper [26]. Eduard F. Sekler dismantles the tension that exists between them in his article *Structure, Construction, and Tectonics*. He defines structures as "the more general and abstract concept refers to a system or principle of arrangement destined to cope with forces at work in building [27, p. 89]." The structure is an "intangible concept" that is "realised through construction and visualised through tectonics [27, p. 92]." As a result, structures are constrained on the one hand by the construction technique and on the other by the perceptual representation of the tectonic form. And this intangible part of the structure, which is the other half apart from technology, demonstrates the critical nature of structural expression—the abstract structure can only be experienced as the materialised result of a tectonic expression. Sekler's emphasis on the "visual" dimension of structure elucidates the essential medium through which the structure is experienced—perception. Therefore, Sekler defines "construction" as the process by which an architect infuses his or her own emotions into the expression of the structure and stimulates his or her "plastic emotions" [27]. Along with this "intangible concept", Billington and Garlock also emphasised that a work of structural art is always the product of one person's ability to imagine and conceive a new structural form, to visualise the final appearance, to define it by calculations, and to develop a means of building the structure [28]. Pier Luigi Nervi also emphasises the indisputable physical and artistic aspects of structure and relates the art of structure to the subjective factors that generate aesthetic feelings [11].

While many architects (in collaboration with others) create art out of structural rationality to transcend it, history reveals that their motivations for illustrating the beauty of structural art are somewhat different and cannot be quantified in the same way as a structure's physical load-bearing capacity. Furthermore, structural design intentions should not be restricted to professionals; structures should communicate what ordinary people can perceive as well. The layperson's perception, on the other hand, is based on everyday experiences. Even engineers occasionally struggle to comprehend the behaviour of specific structures until they see drawings illustrating hidden members and details, ground anchors, or reinforcement [20, p. 247]. As a result, designers should limit themselves to structural forms that are comprehensible to those who are not trained in the discipline. In architectural contexts, structural art is complex, influenced by various historical, cultural, and contextual factors (scientific, social, and symbolic). The challenge then becomes how to construct a structural expression that is shared by individuals universally with varying levels of knowledge.

Harry Francis Mallgrave writes in the prologue to *Style* that Semper's study of reading internal forces in forms resulted in the sprouting of empathy in the fields of architecture and art towards the end of the nineteenth century [29, pp. 1–70]. Friedrich Theodor Vischer, influenced by Semper, believes that the human sense of form is a sympathetic projection of the environment [2]. And subsequently, his son Robert Vischer extended this projection into *Einfühlung* in his doctoral dissertation, which was later translated as empathy. Empathy is a term that refers to the capacity to comprehend and "feel into" other things. It is the primary reason for the unified human perception of form. Later on, Heinrich Wölfflin, an art historian, proposed a physiognomic method for empathy. He contends that "physical forms possess a character only because we ourselves possess a body … as human beings with a body that teaches us the nature of gravity, contraction, strength and so on, we gather the experience that enables us to identify with the conditions of other forms [30]." Wölfflin emphasised in his PhD dissertation that the principle of perception is not a mysterious visionary effect but a bodily mediating effect. This is because our body is capable of differentiating between the embodied form of architecture and its internal forces [30]. Wölfflin's study of "force" in Renaissance and Baroque architecture focuses on how the body has been employed as a "metaphor for force" to experimentally "experience" psychological tension and compression [30, 31]. He demonstrates that the "force" of structure exists not only on a physical level but also on a psychological level via empathy induced by embodiment. Sekler also draws a parallel between tectonics and artistic expression in his description of structural perception, arguing that structural expression is an empathy between the built environment and the human body [27], thereby intensifying one's experience of the internal forces manifested in structural forms.

The research on empathy and phenomenology, as well as their human body metaphor, all attempt to explain that the body is the most direct way for us to understand space, architecture, and the world [32]. These inextricable connections between architecture and body enable the integration of bodily perception and structural reasoning into a unified architectural design logic. Verticality (spatial orientation), gravity (forces), balance, and motion in architecture are defined mainly and constituted by architectural structures [33]. These structural elements imply, direct, and organise our perception of the function of space and how we might interact with architecture [34]. In this perspective, the body becomes a medium for perception, linking abstract meaning and the concrete world. The study of empathy has been tackled in many architectural designs and research throughout history, focusing on how humans psychologically and biologically perceive structures expressed through the human body. For instance, as Steen Eiler Rasmussen explains in *Experiencing Architecture*, it is not sufficient to "see" architecture to authentically experience and comprehend it; instead, it is necessary to experience the space holistically, integrating the senses of visual, tactile, and auditory [35]. And because this holistic spatial experience is organised by the human body and is inextricably linked to bodily behavioural patterns, the body may be viewed as the foundation for constructing the perception of architectural space. The perspective of embodied perceptions is closely associated with the development of phenomenology in the twentieth century. As phenomenologist Merleau-Ponty wrote that "the body is our general medium for having the world [36]", describes the way we are in the world is essentially through an embodied experience, rather than the visual stimuli alone. The bodily movement is a spontaneous construction of intentionality of the external, and a spontaneous experience and reaction to the external, which is independent of any conscious representation of the external [36]. This means the intentionality of human experience is always addressed to the relationship and interaction between the body and the external object, not the external object itself. However, technology-oriented formalism has been the primary driver of empathy theory since the early twentieth century. What was lacking in structural design was a scientific foundation for explaining or demonstrating the principles underlying how humans read and respond to structural expressions [37]. Notably, recent neuroscience research can more clearly and methodically corroborate these embodiment-related ideas and hypotheses about the relationship between structures and the body. In Cognitive Neuroscience, similar to the theories of empathy, the embodiment is the central and indispensable awareness.

The Neuroaesthetics perspective of structural art

Neuroscience research has shown an increasing interest in art and aesthetics over the last decade. Modern brain imaging techniques (such as fMRI) have revolutionised our understanding of aesthetics. Semir Zeki is a neuroscientist who pioneered this field by coining the term "neuroaesthetics" [38]. Which is a study of the brain-body system to better understand what aesthetic work means intrinsically to humans [39]. In this context, the term "aesthetics" is used primarily in the bodily sense, as derived from the Greek *aisthesis*; it refers to the sensorimotor and affective properties of our perception of things. These aesthetic components are a physical manifestation of the multimodal perception available to our body. The experience of architecture can be deconstructed into its bodily grounding elements through the application of experimental aesthetics [40].

The mid-1990s discovery of mirror neurons bolsters this body-based aesthetic perspective [41]. It has been shown those mirror neurons in macaques' premotor and posterior parietal cortex fire when an action is observed and executed [42]. This mirror neuron system (MNS) also exists in the human ventral premotor cortex and the posterior parietal cortex. Based on these findings, the human brain is active in both first- and third-person experiences of motor actions and emotions. So this explains the feelings of empathetic involvement with architectural actions. Furthermore, it shows that the traditional understanding of human perception is biased and inaccurate [43]. This embodied thinking can scientifically support the discussions of embodied perception in empathy theory and phenomenology.

Gallese proposed the concept of "embodied simulation" based on mirror neurons to explain further how humans not only "see" the built environment but also feel and simulate emotions and actions within it via the body [44]. Embodied simulation is a functional mechanism that enables us to make a pre-reflective sense of others' behaviour, emotions, and feelings. Through this mechanism, the actions, emotions, and feelings we observe activate our internal representations of the bodily states associated with these social stimuli, as if we were performing similar actions or experiencing comparable emotions or feelings [45]. Gallese thus links action, perception and cognition into a unified and interconnected domain. Additionally, recent research indicates that our embodied simulations are not restricted to the social world. Humans possess the "precognitive capacity to mirror the tactile values of all objects or forms in our environments, both living and nonliving [46]". This establishes a robust theoretical foundation for design thinking that uses the built environment to influence how humans perceive space. Embodied simulation appears to be a fundamental feature of our brain, enabling a rich and varied experience of space, objects, and other people; it also underpins our capacity for empathy. Recently, it has been suggested that the term 'empathy' be replaced by the concept of embodied simulation [46].

Fig. 2 The twisted column in Rome Lateran cloister. Archbasilica of Saint John Lateran, Rome, 1735. Photo: Kodiak

Mirror neurons function by retrieving memories of previous bodily experiences and emotional states. They evoke the past bodily experience and mood associated with that bodily gesture directly and unconsciously, demonstrating our capacity to read into things. This may account for the perceptual similarity between a structural engineer and a non-structural person – they share a nearly identical physical structure. Following the unconscious impression, the structural engineer's or other people's knowledge will manifest in the conscious and analytical reading of the structural system.

The finding of embodied simulation is based on the premise that perception and cognition are fundamentally dependent on an organism's interaction with its environment [47, 48]. It argues that embodiment is an active mode of movement and experience for our bodies, an active "experiential understanding" of our environment [44, 49]. And it is precisely these activations of embodied mechanisms of simulated action, emotion, and bodily sensation that underpin an aesthetic experience of art. Furthermore, Freedberg and Gallese emphasise that embodied simulation can be motivated by both static and dynamic artistic representations [40]. For example, when the viewer is confronted with a twisted Romanesque column, the visual perception of the twisted column's form can also induce a corresponding state of tension in the body's muscles (Fig. 2) [50]. Thus, they believe that the embodied perspective on aesthetic experience can be divided into two parts: first, the relationship between the observer's empathic feelings induced by embodied simulation and the expression (of the actions, intentions, objects, emotions, and feelings depicted in the painting, sculpture, or architecture); and second, the relationship between the observer's empathic feelings induced by embodied simulation and the visible traces of the making process (e.g. brush strokes and traces of movement in a painting or in the composition of an object) [40].

To further illustrate the aesthetic relationship between human embodied principles and architectural space, it is necessary to understand what motivates us to have an embodied action. As Gallese stated, "The primordial quality turning space, objects, and behaviour into intentional objects is their constitution as objects of the motor intentionality that our body's motor potentialities express [51]." Thus, the specific intentional interactions that objects specify—that is, how they are intended to be manipulated and used—constitute a substantial part of their representational content, regardless of whether they are artificial or not.

Gibson coined the term *affordance* to refer to the potential usability, interactions, and meanings that the action possibilities of things may provide for people [52]. Similar to Heidegger's central tenet that our primary mode of being is essentially a pragmatic, action-oriented encounter with our environment [53], affordances are intended to describe the potentially valuable modes of interaction that emerge from people's potential perceptual behaviour. The inherent structure of people's experiences of architectural environments, according to affordance, is determined by their adaptability and ability to move and act. Recent research has also revealed a strong correlation between openness and the desire to move through space [54], and a tendency for people to perceive open spaces as more beautiful [55]. This can also be interpreted as an aesthetic experience triggered by the increased affordance and interaction possibilities created by openness. It proves what Lipps has suggested, this motor simulation mechanism, combined with the emotional resonance it elicits, is a critical component of the aesthetic experience of architectural objects: even a still-life can be "animated" by the embodied simulation it elicits in the observer's brain [50].

Thus, starting with the premise that architecture is a design for affordance, we can argue that the possibility of embodied action intrinsically shapes people's experience of architecture. More precisely, architectural-body communication can be defined as the conceptual connection between bodily patterns and the "enacted" affordances of the built environment [48]. Thus, the experience of architectural space is formed through the interaction of our bodies with the affordances of space.

The concept of neuroaesthetics is clarified through the lens of affordances. It elaborated on how aesthetics arises from everything that contributes to our capacity for meaningful experience [56, 57]. For example, if the verticality and mass of the architectonic structure are in harmony with the body, they will be perceived as a pleasant disposition [58]. Aesthetics, in this sense, are derived primarily from bodily connotation, bodily enactive processes, and bodily experience. Thus, the primary goal of architectural aesthetic expression is to establish a predicted connection between bodily systems and architectural spaces [59]. Similarly, aesthetic evaluation can be defined as the process of judging and making sense of an object's gesture or action in relation to the body and motor system [48]. Thus, architectural experience and aesthetic quality can be broken down into their "grounding bodily elements [60, p. 164]." This is one of the primary reasons we find symmetrical, well-proportioned, and regular objects more aesthetically pleasing than irregular and asymmetrical objects [61]. Neuroscience research has extended the previous superficial analogy of bodily proportions and geometric relationships to the bodily experience.[5] That is, the consideration of bodily sensations and balance related to the body experience should be a core part of the structure-oriented design. In comparison to the previous passive perspective of understanding architecture through the body, neuroscience reverses the relationship between architecture and the body, encouraging us to consider architecture through the body's lens actively and to incorporate the body's experience into the structure's design from the beginning, thereby influencing its possible artistic expression.[6] As more attention is paid to the relationship between architecture and neuroscience, more concrete and practical applications will be tackled by future research.

Along with neuroaesthetics, the neural activation of our bodily aesthetic experience is equally significant and complex [62]. The purpose of embodied activation is to elicit an empathic response/engagement from the building's observer and to align the architect's intended targeted motions to elicit an embodied simulation concerning the design intention.

Varela et al. argue that our perception results from active and dynamic interactions with our environment [48]. This is referred to as an *enactive* approach. Similarly, the embodiment can be regarded as the crucial factor for the emergence of cognition, which seeks to exist in meaningful relationships with its environment. It is modulated by how sensory-motor patterns are memorised through past bodily experience, which portrays perception as an active process rather

[5] For more details about the relationship between bodily proportion and architecture, see Scholfield, P. H. (1958). The theory of proportion in architecture. Cambridge: University Press.

[6] For an example of a graphical method for actively involving embodiment in structural design, see: Wang, S., Kotnik, T., Schwartz, J., & Cao, T. (2022). Equilibrium as the common ground: Introducing embodied perception into structural design with graphic statics. *Frontiers of Architectural research.*

than something that happens to us passively [63]. Therefore, the enaction could emerge only by labelling the embodiment in the built environment. This eliciting of the embodied perception is called the *arousal* of enactive.

Arousal, defined as "a general pattern of sympathetic nervous system excitation" [64, p. 379], explains that people are motivated to take actions in order to maintain an optimal level of physiological arousal, and thus must be labelled through an interpretive process of the environment [65]. According to Mandler, arousal is a critical factor in eliciting emotional behaviour [66], and it is intimately related to stimulating curiosity, attention, and motivation [54]. Berlyne asserted that the attraction arouses curiosity because of a "conceptual conflict" in perception, which can be triggered by doubt, perplexity, contradiction, incongruity, or irrelevance [67]. Additionally, research indicates that the sensory-motor system is perceptive of contrast, grouping, and symmetry [68]. These features have also been demonstrated in recent neuroaesthetics research to be critical for the emergence of aesthetic experience. Additionally, both low and high arousal levels result in suboptimal performance, whereas a moderate level of arousal results in optimal performance. If the organism's arousal levels fall below optimal levels, it will seek stimulation through exploratory behaviour. This indicates that either too little or too much stimulation is frequently ignored by individuals, leaving them with little opportunity to gain aesthetic experience [67, 69]. These findings already provide a possible answer to the structural engineers' question of what constitutes a moderate structure from an artistic perspective.

Thus, architectural aesthetic experience can be understood from an embodied perspective as the process of labelling a bodily resonance with the built environment, which also holds true for structural aesthetics. Architects and structural engineers' primary function, in the most primitive sense, is to house the body and celebrate the force of gravity because gravity is what keeps us there. Without gravity, the body-structure metaphor would be meaningless. These neuroaesthetics findings bear an uncanny resemblance to Wölfflin's empathic perspective on force flow in the Gothic church structure based on the body. Neuroaesthetics' findings help us better understand the principles that underpin our perception of structure and how we can use these principles to think about and create structural art.

Redefining structural art

Embodied structural art

The Eiffel Tower, as mentioned previously, is a representative example of *Structural Rationalism*, a movement whose focus on performance and objective realism significantly

Fig. 3 H mullions on the façade of 860–880 Lake Shore Drive Apartments, Chicago, 1949. Photo: Marc Rochkind

influenced how structural art is interpreted, placing it directly against decoration. This claim about structure's inherent authenticity is also mapped in theories of empathy in art. Neuroscience has the potential to resolve this longstanding debate about the relationship between authenticity and expressiveness (ornamentation), a debate that stems from the perceptual dichotomy between technique and art, structure and architecture [2]. Neuroscience suggests that architecture is not always an authentic expression of structural logic and that the proper conveyance of structural expression to the embodiment of bodily gestures and muscle experiences, as well as the stimulation of bodily movement and interaction, are the true objectives of structural design—to influence and enhance design intentions positively. Thus, structural technology is not the end but the beginning; with structural technology as the foundation, architects must consider how to express the structure's humanity and artistic dimension or design an "embodied structure." As Antoine Picon argues in his study of the concept of ornament, there is never a clear distinction between structure and ornament, but rather a dynamic operation of distinction between support and supported, as with the column, which serves as both support and ornament for the building [70, pp. 37–42]. Choisy also uses Gothic architecture as an example, arguing that it is only when ingenuity and camouflage are used wholly and effectively within the structure that a true architectural organism results [24].

For instance, in the 860–880 Lake Shore Drive Apartments (Fig. 3), Rudolph explained that Mies was well aware that his thin columns would not provide the necessary sense of security in a tall structure, and thus introduced his famous H mullions as a symbol for the column, allowing the curtain wall to be so continuous that it could be seen from the outside. While such considerations may bring up the structural issue of "honesty" [12, p. 180]. However, this structural expression can be interpreted as a realistic representation of force flow at the body's level of perception: it reinforces the structure's "artistic truth" in terms of perceptual continuity.

Fig. 4 Leutschenbach School, Zurich, 2009. Photo: Micha L. Rieser

Fig. 5 Plantahof Auditorium, Landquart, 2010. Photo: Ruizhe Liang

Thus, no inherent and essential structural expression exists when the viewer's perception of structural form is associated with prior bodily experience.

It cannot be denied that, as Billington et al. point out, the structural art of maximising compliance with construction logic and authenticity remains critical in terms of economics and energy. The purpose of this paper is not to erase the previous research on structural art, but to broaden our understanding of the dynamic relationships between construction, structure, and tectonics through the lens of spatial experience. As previously stated, the concept of "moderate structure" exists because structural art is not about optimising structural performance but about following and expressing the logic of force transmission within structures on a perceptual level. At the experiential level, the primary indicator of a structure's authenticity is how closely its artistic expression resonates with the body's internal forces. However, using structure solely for artistic expression is equivalent to decoration, and inventing form without regard for its primary load-bearing function is an even more egregious example of putting the cart before the horse.

Additionally, in some cases, the pursuit of maximum structural performance and technical aspects is motivated primarily by the desire to achieve a specific type of structural art, such as the expression of the structure's immovable movement (tendency to move). In these instances, the direct representation of the structural form via mirror perception may elicit an internal resonance in the body. Of course, in many cases, we can also see a difference—the structure does not directly resonate with the body, but its absence or anomalies can stimulate the imagination of the structure, which in turn triggers an interaction with the structure to induce another level of structural embodiment. For instance, Kerez's Leutschenbach School (Fig. 4) deliberately conveys a discontinuity in the force flow by offsetting the structure, evoking a sense of lightness and floating [71]. This approach is consistent with the neuroaesthetic of arousal, in which the appropriate stimulus arouses our curiosity in order to perfectly reorganise or rationalise the missing parts of the structural expression from bodily experience, thereby completing a conceptually similar reorganisation of a "dismembered body." As Olgiati interprets the structural reflection of the Plantahof Auditorium (Fig. 5): "the Plantahof Auditorium has an outer shape that does not allow one to understand the entire building organism…Only when we see the entire building, do we begin to recreate it in our mind and understand why it has supports, why they have the dimensions they do, and why they are positioned as they are… I am convinced that if people are confronted with something that resembles nothing and something that they cannot yet handle, they begin to fathom this and ultimately experience it positively… [72, p. 64]" Olgiati asserts that it has the potential to "stimulate thought," allowing for both physical and mental involvement. Additionally, as the degree of arousal emphasises, the representation of specific overcomplicated structures can make it challenging to develop an empathic relationship with the body and thus evoke an embodied aesthetic experience, a situation frequently criticised as a form of "structural expressionism." In summary, we value these structures because they are connected to our bodies and movements and elicit emotion. Whether deliberately or unintentionally, these structures are designed with our perception in mind and convey our own bodily experience through them, inspiring our artistic interpretation of them.

Towards a new structural art

By combining the aforementioned embodied perspective with the various parameters and principles of aesthetic experience, we can attribute the origins of structural art to three distinct embodied perception directions:

1. The sense of force. This dimension is concerned with the bodily implications of structural forces, allowing us to mirror the correspondence between the structure's

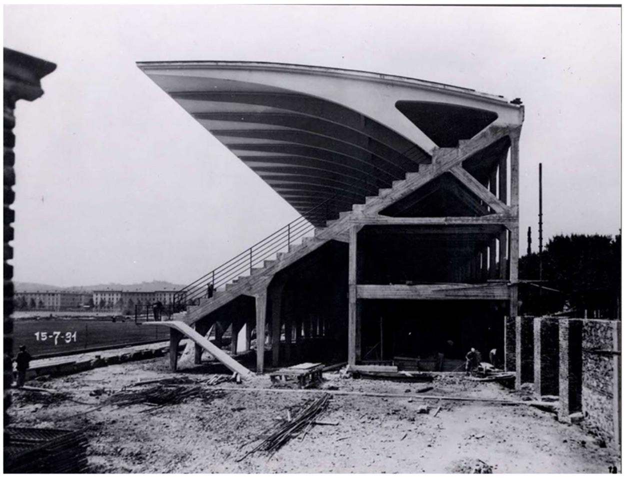

Fig. 6 Stadio Artemio Franchi, Florence, 1931. Source: 2020 PLN_Project, online at: https://salviamoilfranchi.com/artemio-franchi-stadium

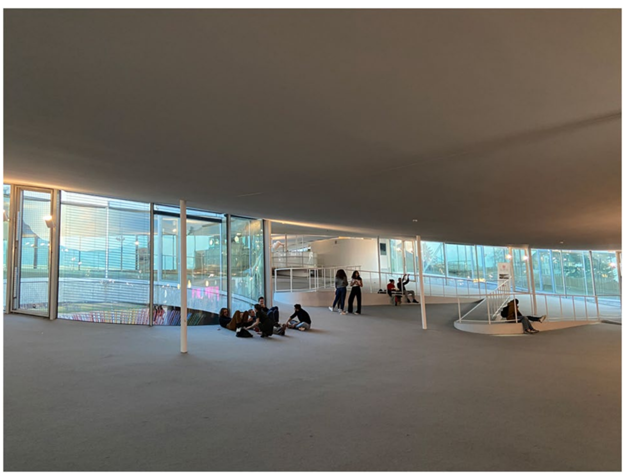

Fig. 7 Rolex Learning Centre, Lausanne, 2010. Source: from the authors

force flow and bodily experience. For instance, in Nervi's design for the Municipal Stadio Artemio Franchi (Fig. 6). Exaggerated cantilevering on the roof directly evokes a bodily sensation similar to straightening our arms, mirroring perceived bodily memory and emotion from the structures. This reinforces the roof structure's lightness.

2. The sense of affordance. This dimension is concerned with the possibilities for bodily interaction with us provided by structural elements or their relationships (affordance). An example is the Rolex Learning Centre (Fig. 7), designed by SANAA. The structure's undulating surfaces and column placement affect the movement possibilities. Or the Final Wooden House design by Sou

Fig. 8 Final Wooden House, Kumamoto, 2006. Photo: Iwan Baan. Source: https://www.archdaily.com/7638/final-wooden-house-sou-fujimoto

Fig. 9 Armadillo Vault, Venice, 2016. Photo: Jean-Pierre Dalbéra

Fujimoto (Fig. 8), in which the varying sizes of the wood logs hold the structure together and provide different opportunities for interaction with the structure, stimulating a rich bodily memory and emotion.

3. The sense of process. This can be accomplished by implying the process of assembling the structure or the transformation about to occur in the structure's relationship, or by conveying through texture the bodily movements of carving and moving during the structure's production, thus allowing the static structure to correspond to our dynamic bodily experience. For instance, Philippe Block's Armadillo Vault (Fig. 9) is composed of 399 individually cut limestone pieces. To emphasise the removal of excess material, he chose to hammer it away, leaving a very rough cutting surface. The piece's observation not only reveals the relationship between the individual blocks, but also elicits the act and process of striking, reinforcing and expanding the static structure's interaction with the body in the time dimension.

Fig. 10 Villa Stein-de-Monzie, Garches, 1926. Photo: Cemal Emden. Source: https://divisare.com/projects/199431-Le-Corbusier-Villa-Stein

Fig. 11 University of São Paulo's (FAU) School of Architecture and Urbanism, São Paulo, 1969. Photo: Nelson Kon. Source: http://www.nelsonkon.com.br/faculdade-de-arquitetura-e-urbanismo-usp/

The structure's embodied expression may also vary in response to various architectural intentions. For instance, a hospital's structure may minimise perceptual stimuli while considering and providing more appropriate affordance, whereas a church's sacred space may be quite the opposite. Understanding these principles of influence, on the other hand, can help us define the direction and purpose of structural design innovation. Additionally, it is worth emphasising that the three directions mentioned above do not exist in isolation but rather occur and influence perceptions simultaneously, in an interconnected state. Therefore, one should not focus exclusively on one of them at the expense of considering the structure as a whole.

Similarly, how architects and structural designers realise this embodied structural art varies significantly. However, when viewed through the lens of the body, certain structural expressions reveal their design intentions. As previously stated, the enactive and arousal processes that stimulate embodied interaction should be kept at an appropriate level. Thus, the relationship between structural authenticity and expressiveness should not be one of mutual invisibility between flesh and bone, but rather one of interdependent, resulting in the creation of a perceptual expression of artistry founded on structural rationality. This contextualises the previously mentioned "moderate" relationship between the "technical truth" and the "artistic truth" of structure. In a similar vein, Colin Rowe has referred to the long horizontal windows that run the length of the façade in Corbusier's Villa Stein de-Monzie (Fig. 10) as "Transparency," indicating the location of the floor behind and the necessity for structure [73]. Due to our experience with the body's continuity, we know that the structure between the two long windows cannot "float" in the air and must be supported by something else. The building's interior reveals a structure and spatial layout diametrically opposed to the open space implied by the façade, reinforcing the spatial tension and desire for infinite interpretation [73]. This ambiguous state between exposure and concealment also appears to be consistent with neuroscientific research on enactive: appropriate implication for the embodied nature of the structure. Another example is the columns designed by Artigas on either side of the University of São Paulo's (FAU) School of Architecture and Urbanism (Fig. 11), which exemplify the ambiguous structural expression. When observed from the front or side, this particular structural expression reveals that only a triangular structure supports a sizeable structural body via a point of the contact area. One can easily convey a sense of instability through physical experience, which generates tension. It is only through moving through the building's various perspectives that we can comprehend the logic of its load-bearing and thus dissipate this tension. Therefore, this structural expression embodies the oppression of the Brazilian people and his fantasy of a utopia: a state that is both real and unreal [74]. Due to the holistic nature of its systems' interpenetration, this structure's ambiguous expression elicits a range of perceptions and interpretations of space and concepts, i.e. multiple affordances, reinforcing the perceptual richness of space in terms of meaning. It has the potential to inspire individuals to reveal their hidden superimposed spatial considerations and architectural intentions gradually through a variety of distances, scales, perspectives, movements, and even listening and touching. And it is precisely this openness of these structures and their stimulation of interaction that contributes significantly to the neuroaesthetic experience of beauty.

Notably, this contrasts the perspective in which the structure is concealed behind the architectural form and is only used to support it. These examples and approaches to structural art demonstrate how design has shifted from passive to proactive. Similar to how embodied perception describes how people's perception of the external world is fundamentally an enactive act, structures that interact with people must actively shape the qualities associated with the perceptions through stimulation or guidance of their interaction with space and structure. For instance, Picon used to define Eduardo Torroja's structure concept as an active stimulation of structural forms for the perception of static equilibrium in the human body [75, pp. 5–19]. Recent advances in digital technology enable even more active and precise control over structural design and construction efficiency, allowing structures to engage in a pre-reflective dialogue with gravity, which is crucial for the future of structural art. Nowadays, virtual reality and agent-based modelling (ABM) can already simulate certain aspects of human perception and interaction, laying a solid technical foundation for structural art at the perception level.

However, this paper has discussed only one aspect of aesthetic experience, namely those that are likely to occur before formulating any explicit aesthetic judgement.[7] This is not meant to make all beauty judgments based on the body. Instead, it is meant to use the body to communicate in structural design on a more general basis. Other more complex and peculiar aspects of aesthetic experience are strongly influenced by personal preferences, background, memories, education, and expertise. They are a more conscious mode of perception that is far from universal and is thus excluded from this paper.

Conclusion

The focus on structural art will significantly impact architecture and structural design. By embracing and applying the history and concepts of structural art within the structural profession, the potential and quality of future structural design will significantly increase. Additionally, the concept of structural art would provide architects with a more concrete understanding of the material and engineering concerns. Our understanding of art is also becoming more precise, particularly in light of recent advances in cognitive neuroscience. The importance of incorporating neuroaesthetics and related perceptual theories into the structural design is that it results in a "bio-cultural" paradigm shift [76]. They can shed light on the nature and rules of the art of structure perception and provide a new lens through which to re-examine the question of structural expression, guiding our construction of structures and spaces more rigorously and scientifically. By focusing on the human being as a more fundamental perspective, the neuroaesthetic perspective can liberate structural design from the complexities of artwork, allowing the body to serve as a more precise anchor point between the tangible and abstract aspects of structure, thereby providing a theoretical and even quantitative foundation for the integration of the human perceptual dimension into structural design.

This neuroaesthetic perspective is not an entirely new concept but rather a clarification and expansion of previously held beliefs on structural art. It is not a refutation of the vintage structure's quest for efficiency, economy, and elegance, but rather an expansion of these concerns beyond a purely engineering definition to a broader human dimension—a rethinking of what it means to be efficient, economical, and elegant from the perspective of the user. Such a body-based quest for a balance of technology and art can provide a new perspective and platform for collaboration between architects and structural designers, allowing for more scientific and precise decision-making with design intent while retaining the ambiguity of structural expression.

As Billington and many other pioneers in the pursuit of structural art have argued, the advancement of structural art requires architects and structural engineers' combined efforts and collaboration. Today's increasingly complex architectural demands and technical challenges are difficult to meet through the heroic efforts of a single individual. The intersection of neuroscience and architecture also provides an example that interdisciplinary is not limited to engineering. Collaboration with experts in neuroscience or other fields frequently results in the generation of novel and ground-breaking ideas.

However, without new education and talent development models, expanding the focus on structural art proposed in this paper will be difficult to implement in practice. As Alan Holgate argues in his book *Aesthetics of built form*, advancing the technical and artistic integration of structures may necessitate the emergence of new professions equipped with aesthetic sensibility, technical understanding, and construction management abilities [20, p. 252]. The current digital environment provides a new platform for interacting with these intricate architectural challenges. The subsequent adoption of CNC construction machines in architecture and the emergence of the concept of Digital Tectonics are attempting to reclaim architecture's materiality and structural considerations, thus retracing the relationship between body and space. However, the experiential relationship between these complex forms, which are literally constructed and adhere to a structural logic, still remains an open question in relation to the viewer.

While the structural design is a complex consequence of multiple determinants and consequences, this embodied

[7] For some studies of art perception at other perspectives of neuroaesthetics see: Chatterjee, A., Coburn, A. & Weinberger, A. The neuroaesthetics of architectural spaces. *Cogn Process* 22, 115–120 (2021).

perception-based perspective on structural art is not intended to concentrate solely on perception. Instead, it is intended to emphasise that, in addition to the technical aspects of structural thinking, structural design from an artistic and perceptual perspective can have a beneficial effect on the spatial definition and expression of structures. Rather than serving as a constraining design criterion, the intention is to foster a new way of thinking—to abandon the complicated and abstract meanings associated with regional and sectarian architectural theories and return to the essence of architecture: the structure; and the subject of experience: the body, through the direct design of its form, composition, and materials. The objective is to reach the architectural and structural thinking sought by Herzog and de Meuron, one that transcends consciousness, culture, and context and arrives directly at perception [77].

Acknowledgements This study was funded by the China Scholarship Council Grant No. 202008170012.

Funding Open access funding provided by Swiss Federal Institute of Technology Zurich

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Semper G, Mallgrave HF, Robinson M (2004) Style in the Technical and Tectonic Arts, or, Practical Aesthetics. (Mallgrave HF & Robinson M, Trans.) Getty Research Institute, Los Angeles
2. Frampton K (1995) Studies in Tectonic Culture: The Poetics of Construction in Nineteenth and Twentieth Century Architecture. MIT Press, Cambridge, Massachusetts
3. Schwartz J, Kotnik T (2010) Transparenz, Stringenz, Leichtigkeit: Eleganz im Brückenbau. werk, bauen + wohnen 97(5): 20–25.
4. Billington DP (1983) The Tower and the Bridge: The New Art of Structural Engineering. Basic Books, New York.
5. Hu N, Feng P, Dai G-L (2014) Structural art: Past, present and future. Eng Struct 79:407–416
6. Mark R, Billington DP (1989) Structural Imperative and the Origin of New Form. Technol Cult 30(2):300–329
7. Vitruvius (1999) *Ten Books on Architecture.* (I. Rowland, Ed.) Cambridge University Press, Cambridge
8. Brown JL (2014) Iron Lady: The Eiffel Tower. Civ Eng Mag 84(11):44–47
9. Billington DP, Garlock M (2010) Structural Art and the Example of Félix Candela. J Struct Eng 136(4):339–342
10. Pogacnik M (2012) Technology as a Means of Expression in the Nineteenth Century – Architects and Engineers in Dialogue. In: Flury A (ed) Cooperation: The Engineer and the Architect. Birkhäuser, Berlin, Boston, pp 17–32
11. Nervi PL (1965) Architecture, Aesthetics and technology in building. Harvard University Press, Cambridge, Mass
12. Holgate A (1986) The art in structural design : an introduction and sourcebook. Clarendon Press, Oxford [Oxfordshire]
13. Kolarevic B, Malkawi A (2005) Performative architecture: beyond instrumentality. Spon Press, New York
14. Zaera-Polo A (2016) Well into the 21st century. The architectures of post- capitalism? In El Croquis 187: Sergison Bates 2004 2016. El Croquis, pp. 252–287
15 Woodruff S, Billington DP (2007) Aesthetics and Economy in Pedestrian Bridge Design. Int J Space Struct 22(1):81–89
16. Howard H (1966) Structure : an architect's approach. McGraw-Hill, New York
17. Schlaich, J. (2006). Engineering — Structural Art — Art. In James Carpenter. Birkhäuser, Basel, pp. 8–9
18. Marg V (2009) *Architektur ist – natürlich nicht unpolitisch.* Prestel Verlag, Munich, Berlin, London, New York
19. Schumacher F (1838) Der Geist der Baukunst. Deutsche Verlags-Anstalt, Stuttgart/ Berlin
20. Holgate A (1992) Aesthetics of built form. Oxford University Press, Oxford
21 Billington DP (1977) Structural Art and Robert Maillart. Archit Sci Rev 20(2):44–51
22. Lux JA (1910) lngenieur-Aesthetik. Verlag van Gustav Lammers, Munich
23. Moravánszky Á (2019) Anatomical constructs. The architecture of bones. In The bones of architecture. Structure and design practices. Triest Verlag, Zürich, pp. 26–41
24. Etlin R (2010) Auguste Choisy's Anatomy of Architecture. In J. Giron, & S. Huerta (Eds.), Auguste Choisy (1841–1909). L'architecture et l'art de bâtir. Editorial Reverte, Madrid, pp. 151–182.
25. Mayer H (2004) Die Tektonik der Hellenen: Kontext und Wirkung der Architekturtheorie von Karl Bötticher. Edition Axel Menges, Suttugart/London
26. Semper G, Mallgrave HF, Herrmann W (1989) The Four Elements of Architecture and Other Writings. (Herrmann W, & Mallgrave HF, Trans.) Cambridge University Press, Cambridge
27. Sekler EF (1965) Structure, Construction, Tectonics. In G. Kepes (Ed.), Structure in Art and Science. Braziller, New York, pp. 89-95
28 Mark R, Billington DP (2010) Structural art and the example of Félix Candela. J Struct Eng 136(4):339–342
29. Mallgrave HF (2004) Introduction. In Semper. G (ed) Style in the technical and tectonic arts, or, practical aesthetics. Getty Research Institute, Los Angeles
30. Wölfflin H (1994) Prolegomena to a Psychology of Architecture. In Empathy, Form, and Space: Problems in German Aesthetics, 1873–1893 (H. F. Mallgrave, & E. Ikonomou, Trans.).Getty Center Publication Programs, Santa Monica, p. 150
31. Forty A (2000) Words and Buildings : a Vocabulary of Modern Architecture. Thames and Hudson, London
32. Alberti LB (1988) De rea edificatoria (On the Art of Building in Ten Books).The MIT Press, Cambridge

33. Johnson ML (2015) The embodied meaning of architecture. In S. Robinson, & J. Pallasmaa (Eds.), Mind in Architecture: Neuroscience, Embodiment, and the Future of Design.MIT Press, Cambridge, Massachusetts; London, England, pp. 40- 45.
34. Pallasmaa J (2011) The Embodied Image: Imagination and Imagery in Architecture. John Wiley & Sons, Chichester
35. Rasmussen SE (1962) Experiencing architecture. The MIT Press, Cambridge
36. Merleau-Ponty M (1962) Phenomenology of Perception. Routledge & Kegan Paul, London
37. Mallgrave HF (2013) Architecture and Embodiment: The Implications of the New Sciences and Humanities for Design. Routledge, London
38. Zeki S (1999) Art and brain. J Conscious Stud 6(6–7):76–96
39. Gallese V (2017) The Empathic Body in Experimental Aesthetics – Embodied Simulation and Art. Empathy. Palgrave Studies in the Theory and History of Psychology. Palgrave Macmillan, London, pp 181–199
40. Freedberg D, Gallese V (2007) Motion, emotion and empathy in esthetic experience. Trends Cogn Sci 11(5):197–203
41. Rizzolatti G, Fogassi L, Gallese V (2006) Mirrors in the Mind. Sci Am 295:54–61
42. Gallese V, Keysers C, Rizzolatti G (2004) A unifying view of the basis of social cognition. Trends Cogn Sci 8(9):396–403
43. Pérez-Gómez A (2015) Mood and Meaning in Architecture. In S. Robinson, & J. Pallasmaa (Eds.), Mind in Architecture: Neuroscience, Embodiment, and the Future of Design. MIT Press, Cambridge, Massachusetts; London, England, pp. 219–235
44. Gallese V (2007) Embodied simulation: from mirror neuron systems to interpersonal relations. Novartis Found Symp 278:3–221
45. Damasio AR (1994) Descartes' error: emotion, reason, and the human brain. G.P. Putnam, New York
46. Mallgrave HF (2015). Embodiment and enculturation: the future of architectural design. Front Psychol. https://doi.org/10.3389/fpsyg.2015.01398
47. Varela FJ, Thompson E, Rosch E (1991) The Embodied Mind: Cognitive Science and Human Experience. The MIT Press, Cambridge
48. Jelic A, Tieri G, Matteis FD, Babiloni F, Vecchiato G (2016) The Enactive Approach to Architectural Experience: A Neurophysiological Perspective on Embodiment, Motivation, and Affordances. Frontiers in Psychology 7(481). https://doi.org/10.3389/fpsyg.2016.00481
49. Thompson E (2007) Mind in Life: Biology, Phenomenology, and the Sciences of Mind. Harvard University Press, Cambridge
50. Lipps T (1903) Einfühlung, innere Nachahmung und Organenempfindungen. Archiv für die gesammte Psychologie 1(36):185–203
51. Gallese V, Sinigaglia C (2011) What is so special about embodied simulation? Trends Cogn Sci 15(11):512–519
52. Gibson JJ (1986) The Ecological Approach to Visual Perception. PsychologyPress, NewYork
53. Moran D (1999) Introduction to Phenomenology. Routledge, London
54. Coburn A, Vartanian O, Chatterjee A (2017) Buildings, Beauty, and the Brain: A Neuroscience of Architectural Experience. J Cogn Neurosci 29(9):1–11
55. Vartanian O, Navarrete G, Chatterjee A, Fich L, Gonzalez-Mora J, Leder H, . . . Skov M (2015) Architectural design and the brain: Effects of ceiling height and perceived enclosure on beauty judgments and approach-avoidance decisions. J Environ Psychol 41: 10-18.
56. Johnson M (2007) The Meaning of the Body: Aesthetics of Human Understanding. University of Chicago Press, Chicago
57. Skov M, Vartanian O, Martindale C, Berleant A (2017) Neuroaesthetics. Routledge, New York
58. Ionescu V (2016) Architectural Symbolism: Body and Space in Heinrich Wölfflin and Wilhelm Worringer. Archit Hist 4(1):10. https://doi.org/10.5334/ah.213
59. Jelić A (2015) Designing "pre-reflective" architecture: : Implications of neurophenomenology for architectural design and thinking. Ambiances: International Journal of Sensory Environment, Architecture, and Urban Spaces, Special issue Experiential simulation 1.
60. Gallese V, Gattara A (2015) Embodied simulation, aesthetics, and architecture: and experimental aesthetic approach. In S. Robinson, & J. Pallasmaa (Eds.), Mind in Architecture: Neuroscience, Embodiment, and the Future of Design. MIT Press, Cambridge, Massachusetts; London, England, pp. 161–179.
61. Di Dio C, Macaluso E, Rizzolatti G (2007) The Golden Beauty: Brain Response to Classical and Renaissance Sculptures. PloS One 2(11):e1201
62. Boccia M, Barbetti S, Piccardi L, Guariglia C, Ferlazzo F, Giannini Am, Zaidel WD (2016) Where does brain neural activation in aesthetic responses to visual art occur? Meta-analytic evidence from neuroimaging studies. Neurosci Biobehav Rev. 60: 65-71
63. Nöe A (2004) Action in Perception. MIT Press, Cambridge
64. Schachter S, Singer J (1962) Cognitive, social, and physiological determinants of emotional state. Psychol Rev 69:379–399. https://doi.org/10.1037/h0046234
65. Colombetti G (2007) Enactive appraisal. Phenomenol Cogn Sci 6:527–546. https://doi.org/10.1007/s11097-007-9077-8
66. Mandler G (1984) Mind and Body: Psychology of Emotion and Stress. W.W. Norton, New York
67. Berlyne D (1960) Conflict, Arousal, and Curiosity. McGraw-Hill, New York
68. Ramachandran V, Hirstein W (1999) The science of art: A neurological theory of aesthetic experience. J Conscious Stud 6:15–51
69. Yerkes RM, Dodson JD (1908) The relation of strength of stimulus to rapidity of habit-formation. J Comp Neurol Psychol 18(5):459–482
70. Picon A (2013) Ornament: The Politics of Architecture and Subjectivity. John Wiley & Sons, Hoboken
71. Wang S, Kotnik T (2021) Embodied structural ambivalence: a neurophysiological perspective on structural expression. Proceedings of the International fib Symposium on Conceptual Design of Structures. Attisholz, Switzerland, pp. 23–30
72. Hasegawa G (2015) Conversation with Valerio Olgiati. Go Hasegawa Conversations With European Architects. LIXIL Publishing, Tokyo, pp 61–99
73. Colin R, Slutzky R, Hoesli B (1997) Transparency. Birkhäuser Verlag, Basel
74. Artigas J (1989) A Função Social do Arquiteto. Nobel, São Paulo.
75. Picon A (2005) Construction history: Between technological and cultural history. Construction History 21:5–19
76. Cometa M (2017) Perché le storie ci aiutano a vivere. La letteratura necessaria. Raffaello Cortina Editore, Milano.
77. Herzog J, Meuron Pd, Cecilia FM, Levene RC (2005) Herzog & de Meuron 1981-2000. El Croquis, Madrid