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THÉORIES ET MÉTHODOLOGIES

SENSORIMOTRICITY IN TOOL-BASED ARCHITECTURAL DESIGN: RECONNECTING WITH CORPORALITY

SENSORIMOTRICITÉ EN CONCEPTION ARCHITECTURALE INSTRUMENTÉE : RENOUER AVEC LA CORPORALITÉ

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SUMMARY

Beginning with the observation that architectural design models deny the existence and importance of sensorimotor intelligence in the decision-making processes of designers during project development, this speculative paper discusses the instrumented body in architectural design and is structured into three parts: (1) Drawing on biology and neuroscience, the permeability of the human epidermal interface and the coupling of the human body and the environment are highlighted, and a processual model of a sensorimotor organism is defined; (2) A reinterpretation of various activity theories, including constructivism, socio-constructivism, cultural-historical activity theory and systemic-structural activity theory brings to light the essential polarities inherent in any work-related action situation; (3) A sensorimotor design model, which can be generalized for other types of activities, is proposed by hybridizing internalist and externalist perspectives. Finally, a conclusive opening defines the designer in a new way, as a sensorimotorized designer.

Keywords: *architectural design, activity theory, sensorimotricity, embodied cognition, situated cognition, instrument*

RÉSUMÉ

Partant du constat que les modèles de la conception architecturale négligent l'existence et l'importance d'une forme d'intelligence sensorimotrice dans les prises de décision opérées par les concepteurs en cours de projettation, ce texte

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spéculatif est structuré en trois parties autour de la question du corps instrumenté en conception architecturale : (1) à partir de la biologie et des neurosciences, la porosité de l'interface épidermique de l'humain et son couplage corps/environnement sont remis en avant, alors qu'un modèle processuel d'un organisme sensorimoteur est défini ; (2) une relecture des différentes théories de l'activité, en passant par le constructivisme, le socioconstructivisme, la théorie de l'activité historico-culturelle et la théorie de l'activité systémique-structurale met en évidence les différentes polarités incontournables de toute situation d'action au travail ; (3) généralisable à d'autres types d'activités, un modèle sensorimoteur de la conception est proposé en hybridant les postures internalistes et externalistes. Enfin, une ouverture conclusive est proposée, en définissant une nouvelle facette du concepteur : le concepteur sensorimotorisé.

Mots-clés : *conception architecturale, théorie de l'activité, sensorimotricité, cognition incarnée, cognition située, instrument*

I. INTRODUCTION: A QUESTION OF EMBODIMENT

This speculative text addresses the central question of why the embodiment of the architect is not integrated into models describing architectural design processes. In other words, why is the existence and importance of a form of sensorimotor intelligence denied in designers' decision-making processes during the act of designing? And how can we apprehend these embodied cognitive capacities, especially when the body in action is mediated by design tools, both in a work environment and in collaboration with other designers?

The essay is structured into three parts around the question of the instrumented body in architectural design: (1) Starting from biology and neuroscience, we consider the porosity of the human epidermal interface and the body/environment coupling, while also defining a processual model of a sensorimotor organism; (2) A rereading of various activity theories – from constructivism to socio-constructivism, cultural-historical activity theory (CHAT) and systemic-structural activity theory (TASS) – highlights the essential polarities present in any action situation in a work environment; (3) By attempting to bridge internalist and externalist perspectives, and analysing several mythical cases of instrumentalization, a sensorimotor model of design is proposed.

In conclusion, a new facet is attributed to the designer: that of the sensorimotorized designer.

II. INSTRUMENTED BODY IN ACTION

II.1 Body/environment coupling and the epidermal interface

At the human scale, our consciousness perceives the bodily envelope as a boundary between the body and the environment, which primarily allows for mechanical interactions. The hypothesis of the existence of a material barrier between the inside and the outside explains a natural tendency towards a form of dualism based on a division between body and mind (subject/object), the most famous of which is Cartesian (Descartes, 1664).

Beyond the study of mental phenomena, psychology also examines behaviour, that is "actions performed by an individual in a given situation and environment". The action of the body should be central to psychological paradigms, yet the "cognitive revolution" sidelined this dimension, and it was not until the development of the concept of "enactivism" that action regained a central role in the study of cognition (Brouillet, 2019, p. 7). Despite significant advances in modelling consciousness, the various schools of psychology – *mentalist* (introspection-based observation of human cognition), *ideomotor* (action represented by its perceptual consequences in the environment), *behaviourist* (external observation of behaviour between inputs and outputs), *cognitive* (cybernetic analogy of symbolic reasoning), and *connectionist* (non-symbolic, distributed neural activation) – all tacitly preserve the Cartesian mind-body separation, while adopting a more or less internalist or externalist perspective. Furthermore, in the dominant paradigms of cognitivism and connectionism, "the body, through its effectors, is considered merely as a tool for executing commands sent as action potentials to our muscles" (Versace *et al.*, 2018, p. 17).

However, biologists have long shown that the human body constantly interacts with both its surrounding environment and the microbiota inhabiting it. The bodily envelope and the walls of internal organs thus serve as *interfaces*, sites of continuous exchange of matter, energy and information. On one hand, as a living organism in relation with its environment, the human body – seen as a "biont" (Margulis & Fester, 1991, p. 2) – modifies its environment through waste and actions, while also being altered from the *outside*. It possesses "organizational closure" (Maturana & Varela, 1994), which maintains the functioning of the living being while allowing for structural adaptation in response to environmental effects. This gives rise to "enacted thought" (Varela *et al.*, 1991), in which the mind transcends bodily boundaries, introducing a form of collective intelligence. On the other hand, as a macro-organism, the body is also altered from *within*. In its biophysical dimension, the organism is not merely viewed as an autonomous *self* in its environment, but rather as a "holobiont" composed of identifiable bionts (Margulis, 1990; Margulis & Fester, 1991) – a macro-organism encompassing both a host and the microorganisms that inhabit it, the result of a symbiosis between the global body and thousands of microbes.

The *enactivist* paradigm thus challenges the mind-body divide: "cognition is not the representation of a pregiven world by a pregiven mind but is rather the enactment of a world and a mind on the basis of a history of the variety of actions that a being in the world performs" (Varela *et al.*, 1991, p. 9). Indeed, by acknowledging that the subject and the environment co-determine one another, Varela *et al.* (1991, p. 173) remind us first that: "cognition depends upon the kinds of experience that come from having a body with various sensorimotor capacities, and second, that these individual sensorimotor capacities are themselves embedded in a more encompassing biological, psychological, and cultural context". In summary, enactivism supports the principles of self-organization (cognitive system autonomy), the sensorimotor nature of knowledge (bodily origin of meaning), and the emergence of knowledge through the repeated interaction of the body with the environment (Versace *et al.*, 2018, p. 19).

The "embodied cognition" (Lakoff & Johnson, 1999; Lakoff & Nuñez, 2001) has revitalized cognitive psychology, which previously paid little attention to the body. As a result, the body-mind system is now viewed as a self-organizing entity; the sensorimotor apparatus is a feedback loop, and the body is no longer reduced to a mere tool used by the mind to grasp the world. Rather, it regains its role as a medium through which meaning emerges for the mind, where significance arises from the encounter between the possibilities offered by the environment and the body's possibilities for action.

By combining these advances, researchers now advocate for an "embodied and situated approach to cognition" (Versace *et al.*, 2018, p. 20), considering it as a phenomenon rooted in sensorimotor interactions with the physical and social environment, and enabling the emergence of knowledge from past and present experiences.

II.2 Processual model of a sensorimotor organism

Once the permeability of the bodily envelope has been acknowledged, humans can be modelled by neuroscience *as* an information-processing system for neural signals, enabling sensory perception, integrative cognition and motor action.

The heuristic model below describes a generic and deliberately simplified human nervous system (see Figure 1). Indeed, the objective is not to detail the inner workings of nervous system elements, but to highlight the main loops that connect the internal and external environments through the bodily envelope.

The *nervous system* (NS) is a complex machine made up of approximately 100 billion neurons, each with thousands of connections (Pocock *et al.*, 2018, chap. 9). The NS "serves conscious perception, voluntary movement, and information processing (integration)" (Kahle & Frotscher, 2007, p. 2). It "receives sensory information from the environment, evaluates the significance of the information, and generates appropriate behavioural responses" (Kandel *et al.*, 2013, p. 352-354).

To understand the human nervous system, two "coding modes" are involved: "the topology of the connections determines the geometry of the network, and the impulses regulate over time the sequence of the behaviour associated with it" (Changeux, 2012, p. 127). On one hand, it is structured by the anatomical organization; on the other, the electrical processes define its functional operation.

In structural neuroanatomy (static), the NS can be broken down into two distinct "anatomical components": (1) the *central nervous system*

(CNS), consisting of the encephalon (mainly brain nerves) and the spinal cord (mainly spinal nerves). The encephalon receives and processes sensory and perceptual information, develops memory, generates thoughts and emotions, and initiates motor responses, while the spinal cord transmits information to/from the encephalon and controls reflex actions; (2) the *peripheral nervous system* (PNS), made up of specialized groups of neurons and peripheral nerves. The PNS is further divided into two subsystems: (1) the *somatic nervous system* (SNS) (voluntary motor control), which includes sensory neurons receiving input from the skin, muscles and joints. Their receptors provide information about muscle and limb position as well as touch and pressure on the body's surface (these receptors specialize in transducing specific types of physical energy – such as deep pressure or heat – into electrical signals used by the nervous system); (2) the *autonomic nervous system* (ANS) (involuntary control), which mediates the visceral sensations and motor control of internal organs, the vascular system and exocrine glands. The ANS, which also plays a role in emotions and motivation, includes three subsystems: (1) the *sympathetic nervous system* (SNS) (fight or flight response), which enables the body to respond to stress and prepares it for intense activity (whether physical or intellectual), by exciting or accelerating visceral function (its neurotransmitters are norepinephrine and adrenaline); (2) the *parasympathetic nervous system* (PSNS) (rest and digest/rumination response), which maintains the body's homeostasis (respiration, rest states and maintenance actions), by calming or slowing visceral activity (its neurotransmitter is acetylcholine); (3) the *enteric nervous system* (ENS), which controls the function of the smooth muscles of the intestine. The PNS includes an *afferent* sensory part, which detects changes in the internal and external environments, and an *efferent* motor part, which produces changes in those environments.

In functional neuroanatomy (dynamic), several neural processes are understood as flows of information, drawing on cybernetic (Wiener, 1948) and communication (Shannon, 1948; Shannon & Weaver, 1949) analogies. All human behaviour, even the simplest, "involves the integrated activity of several sensory, motor, and functional pathways" (Kandel *et al.*, 2013, p. 353).

Two *informational movements* are distinguished: (1) from the *affectors*, the PNS informs the CNS about the internal (body) and external (environment) states of the organism; (2) the PNS executes motor commands generated by the CNS, activating *effectors*. In other words: "Environmental stimuli (exteroceptive) are conveyed to the CNS from sensory cells via sensory nerves (afferent). Any CNS response follows a motor nerve (efferent) to the muscles. Sensory cells that send feedback to the CNS via sensory nerves control and regulate muscular response. These afferents do not transmit environmental stimuli but rather signals from within the body (proprioceptive). A distinction is made between exteroceptive and proprioceptive sensitivity." (Kahle & Frotscher, 2007, p. 2)

Two *sensorimotor loops* are defined: (1) an *autonomic loop*, linking the organism to its internal environment, with neural integration and proprioceptive sensitivity (CNS ↔ ANS); (2) a *somatic loop*, linking the organism to its external environment, with neural integration and exteroceptive sensitivity (CNS ↔ SNS).

Each loop contains a sensory/perceptual component, from perception to consciousness, and a motor component, from consciousness to action.

On the perceptual side, in the autonomic loop, changes in internal organ states send information via visceral sensory nerves to the affectors (receptors), which in turn transmit information to the CNS via somatic sensory nerves. In the somatic loop, changes in the external environment (a stimulus is a change in the environment carrying physicochemical energy), captured by sense organs (containing sensory receptors that translate this physicochemical energy into electrical energy), send information to the CNS via somatic sensory nerves. The CNS integrates the following sensory message: (1) if unconscious sensitivity is involved, a reflex is triggered; (2) if conscious sensitivity is involved, a sensation is constructed and becomes a perception (based on experience and personal memory). Thus, sensory and somatosensory nerves form the *afferent pathways* (the body is affected by an action).

On the active side, after information is integrated, the CNS sends information via somatic motor nerves both to effectors controlling visceral muscles (*idiotropic* motricity, driven by *smooth visceral muscle*) and those controlling skeletal muscles to trigger an action (*ecotropic* motricity, supported by *voluntary striated muscles*). These motor nerves constitute the *efferent pathways* (the body performs an action). In some cases, involuntary processes are active, such as reflex arcs when a rapid reaction is needed in the event of danger.

Broadly speaking, the *external* environment refers to what is connected with the organism via the somatic loop. But this external space includes *subjects* (other humans, for task collaboration) and *technical objects* (*artefacts* that can become *instruments* for *activities*). Neuroscience-inspired, the heuristic and generic model of the human nervous system (see Figure 1)

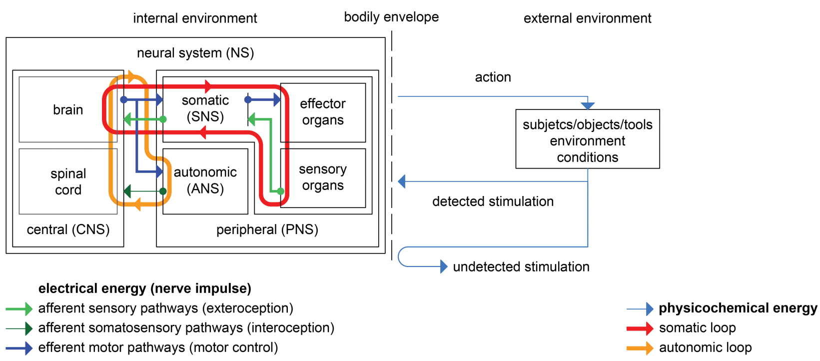

Figure 1. Heuristic and generic model describing the human nervous system and its interactions with an environment consisting of other humans, objects and tools.

Figure 1. Modèle heuristique et générique décrivant un système nerveux humain, ainsi que ses interactions avec un environnement contenant d'autres humains, objets, outils.

must therefore be complemented by further research in cognitive psychology. The relationship between sensory/motor organs and objects/subjects is studied through ergonomic interactions, using activity theory and Human-Computer Interaction (HCI). The aim is to overcome the fictitious boundary of the bodily envelope separating the body from the environment and to extend modelling to the subject ↔ instrument ↔ object/subject relationship.

III. INSTRUMENTED ACTIVITY THEORIES

III.1 Constructivism and action schemes

The *constructivist* stance is based on mediation activated by the subject/object dialectic (Piaget, 2012 [1947], 1967), describing the processes of knowledge construction by integrating "the valued knowledge of the thinking subject's experience" (Le Moigne, 1995). Subjects are at the centre of their learning process because they are capable of appropriating knowledge and putting it into perspective using their own lived experience and representations. In a certain way, *actions* shape the subject's cognition. "From the standpoint of knowledge, this means that the subject's activity is relative to the constitution of the object, just as the object's constitution implies that activity: it is the affirmation of an irreducible interdependence between experience and reason." (Piaget, 1977, p. 21)

Four key "genetic epistemology" concepts (Battro, 1966) are useful here to understand the dynamic construction of knowledge linked to bodily action: (1) the "scheme" is a revisable mental model, representing not only an event, an object or "the actions likely to be exerted on objects" (Piaget, 1977, p. 187), but also a cognitive structure associated with a class of action, allowing the subject to categorize the environment before building concepts: "The scheme of an action is, by definition, the structured set of generalizable features of that action – that is, those that allow the action to be repeated or applied to new content. Now, the scheme of an action is neither perceptible (we perceive a particular action, but not its scheme) nor directly introspectable, and one becomes aware of its implications only by repeating the action and comparing its successive results." (Beth & Piaget, 1961, p. 251); (2) the "assimilation" of things into the scheme refers to the reinforcement of a scheme, when the subject applies it to a situation and the new elements from the environment fit into the structure of the pre-existing scheme; (3) the "accommodation" of the scheme to things comprises the adaptation or replacement of a scheme, when the subject applies it to a situation and the new elements from the environment cannot be assimilated; (4) in correlation with experience, "equilibration" is the repeated process of "progressively balancing an assimilative mechanism and a complementary accommodation" (Piaget, 1977, p. 13), making it possible to *adapt* the scheme to better calibrate an action transforming the environment, and to better categorize that environment for the development of knowledge.

Within the subject/object dialectic of knowledge construction, structure and equilibration are two *inseparable* aspects of thought organization. A complementarity emerges between cognitive *structure* (organization of thought) and the *function* of "equilibration" (evolution of thought): "it is by adapting to things that thought organizes itself, and it is by organizing itself that it structures things." (Piaget, 1977, p. 14). "Accommodation to experience" and "deductive assimilation" alternate in a cyclical manner: "under the pressure of need (therefore of the main assimilation scheme) and the schemes initially tried out as means, tentative accommodation begins seeking new means and results in the formation of new schemes that can be coordinated with the old ones." (Piaget, 1977, p. 283). Thus, the development of intelligence can be described as the dynamic and progressive construction of schemes in interaction with the environment.

III.2 Socioconstructivism and activity theory

Rooted in *constructivism*, the *socioconstructivist* perspective shows that the relationship between humans and the world is shaped by the situations one experiences, and mediated by the culture one shares. As a result, every action must be understood within this sociocultural environment. Based on Soviet psychological research initiated in the 1920s, a dialectical approach to thought/practice developed in four stages (Cong-Lem, 2022; Dafermos, 2015).

(1) Lev Vygotsky (2019) proposed a sociocultural theory of activity, infused with Marxist ideas, asserting that the psychological evolution of humans is not only influenced by biological and hereditary roots, but also by their integration into a society and a culture, whose tools allow for the transmission of acquired knowledge. Relationships between humans and activities are described through objects and actors in their environment. *Mediation* plays a crucial role in the *activity*, and two types of mediation instruments are identified (see Figure 2.1): "technical instruments" and "psychological instruments". Knowledge development is facilitated through sociocultural mediation, especially via the use of "language" and "tools" (Vygotsky, 1978). Human activity is mediated by the use of tools (both material and symbolic) that transform psychological functions. Cognitive development is stimulated by the environment and relies on the *appropriation* of these socially constructed "mediating tools." Vygotsky highlights the existence of psychological instruments, aimed at transforming the subject, and other instruments, similar to technical instruments, aimed at transforming objects. These tools grant access to "crystallized" potentialities embedded in the instruments themselves.

(2) Alexis N. Leontiev (1965, 1978, 1981) developed a "cultural-historical activity theory" (CHAT). Mediated activity is represented as always being *collective* (even when performed alone), while actions are *individual*, implying *socio-institutional mediation* and three levels of activity (Leontiev, 1965) (see Figure 2.2): (a) an "Activity" is oriented towards

an object and is carried out by a community. Leontiev proposes the "instrumental act", a process oriented towards solving a given problem (Vygotsky, 2014); (b) an "Action" is oriented towards a goal and carried out by an individual or a group; (c) an "Operation" is oriented towards the conditions of execution and is performed by an individual or a machine. These tools are socially constructed and embedded in the history of a culture, which is renewed over time with the contribution of the actors within it.

(3) Activity theory remained largely unknown outside the Soviet Union until the mid-1980s, when it was adopted by Scandinavian researchers. Replacing the Marxist framework with a focus on organizational change, Yrjö Engeström (1987, 1999, 2001) reinterpreted the CHAT concepts through Western intellectual developments (cognitive science, constructivism, actor-network theory, etc.). He expanded the initial two-component model (individual and object) into a model comprising seven interacting entities as follows (see Figure 2.3): (1) the "subject" refers to the individual(s) carrying out the activity; (2) the "object" is the shared motive of the activity; (3) the "tools" are the physical or psychological mediating artefacts; (4) the "rules" refer to norms and regulations that constrain or enable the activity; (5) the "community" includes other groups of people involved in the activity; (6) the "division of labour" refers to how tasks and responsibilities are distributed among the community; (7) the "outcomes" are the effects or results of the activity.

(4) From the 1990s onward, in parallel with the digitalization of practices, activity theory was applied to information systems by English-speaking researchers. Initially, it was brought to the fore to study human-computer interaction (HCI) (Kuutti, 1996; Nardi, 1996). The focus shifted from describing a human, an interface and a single computer systematically to also including the study of human performance itself, and the ongoing cooperation and coordination tasks involved in real work situations – leading to the development of Computer-Supported Cooperative Work (CSCW). Later, in the early 2000s, the Systemic-Structural Activity Theory (SSAT) emerged as a synthesis of insights from various activity theories, integrating CHAT, AT, HCI, cognitive psychology and ergonomics (Bedny & Meister, 1997; Bedny & Karwowski, 2007; Bedny *et al.*, 2014; Bedny, 2015; Bedny & Bedny, 2019). SSAT aligns with the development of systems thinking (Bertalanffy, 1968) and the canonical definition of a "system" as "a set of dynamically interacting elements organized around a goal" (Rosnay, 1975, p. 101). In this view, "an activity can be defined as a goal-oriented system in which cognition, behaviour and motivation are integrated and organized by a self-regulation mechanism aimed at achieving a conscious objective" (Bedny & Karwowski, 2007, p. 1) (see Figure 2.4). Whereas Soviet theories were primarily descriptive, SSAT aims to develop predictive models. SSAT researchers have developed qualitative and quantitative techniques for describing work activity.

The initial socioconstructivist approach is enhanced by the question of action carried out with an instrument towards a goal. When a human sets their body in motion within the environment to perform *work*, they engage in a *practice* comprising a set of activities. Each *activity* involves the *action* of a *subject* upon an *object* to achieve a *goal*. The subject's action on the object is *direct* when the body exerts a physical force or a chemical influence on part of the environment, but can be *indirect* when the subject acts on the object via another object.

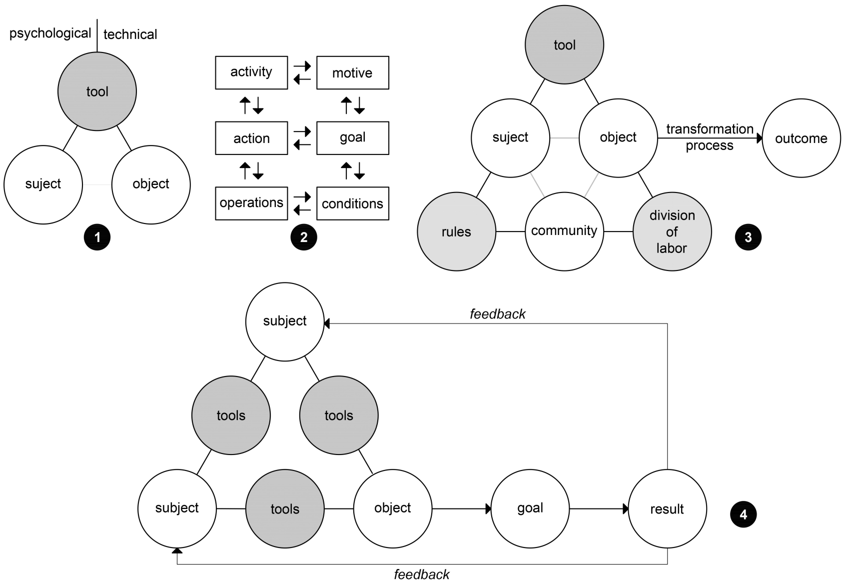

Figure 2. (1) Simple mediation through the tool (by Vygotsky, 2014); (2) Leontiev's hierarchy (1981); (3) Basic structure of an activity (by Engeström, 1987); (4) Structural and systemic triadic model of activity (based on Bedny & Karwowski, 2007, p. 40, fig. 1.5).
Figure 2. (1) Médiation simple par l'outil (d'après Vygotsky, 2014) ; (2) Hiérarchie de Leontiev (1981) ; (3) Structure de base d'une activité (d'après Engeström, 1987) ; (4) Schéma triadique structurel et systémique de l'activité (adapté d'après Bedny & Karwowski, 2007, p. 40, fig.1.5).

III.3 Instrumental theory of activity

Inspired by the contributions of Vygotsky, Leontiev, Engeström, Kuutti and by Francophone researchers including Piaget, Pierre Rabardel (1995, 2003, 2005; Rabardel & Bourmaud, 2005) has proposed an Activity Theory (AT) rooted in several scientific fields (psychology, didactics, ergonomics) and social domains (work, education, everyday life). In this framework, technical objects are not merely compensations for human sensorimotor limitations, like prostheses, but serve as aids to the activity of the acting subject.

Through his "instrumental approach", Rabardel (1995, p. 28) advocates for an "anthropocentric" stance, which emphasizes users' capacity to act (knowledge construction through experience), as opposed to a pessimistic and, in his view, more conventional "technocentric" stance, which aims to minimize users' actions. Artefacts exist through activity and are constantly modified by it; they should therefore not be analysed as isolated entities but rather as "mediators of use", as "bearers of shared and divided labour", and as having "meaning embedded in social practice" (p. 34). He uses the term "artefact" to refer to a "technical object" or "technical system", whether "material" or "symbolic". Artefacts have an "anthropotechnical origin" because they are "designed and conceived for a human environment" and are used by humans (p. 9). He goes on to distinguish between the "artefact" and the "instrument", which serves as an "intermediate entity" between "the subject, actor, or user of the instrument" and "the object upon which the action is directed" (p. 89). If the artefact is "unfinished" due to its lack of embedded use, then the instrument is a "dual-faced" object composed of two components: the "artefact" and the associated "use scheme(s)" (p. 93).

The use scheme is "constructed" by the "subject" or acquired through an "internalization" of the "procedures developed by others" (p. 7). The scheme is "an active organization of lived experience that integrates the past" (p. 100). It adapts to situational variations and environmental diversity. The evolution of schemes results from two complementary processes: "the incorporation of things by the subject – assimilation – and the accommodation to the things themselves" (p. 100). Several secondary schemes can be combined into a principal scheme intended for a particular action (p. 100). An instrument thus consists of two components: "a material or symbolic artefact, produced by the subject or others" (p. 117), and "one or more associated use schemes, resulting from the subject's own construction, or the appropriation of socially developed use schemes" (p. 118). However, artefacts and schemes are also linked by a "relationship of relative independence" (p. 12), since one scheme may apply to several artefacts, and an artefact may fit into multiple schemes that assign it different meanings and functions. Combining the parallel evolution of artefacts and use schemes – through accumulated knowledge in design and varied usage situations – the instrument becomes "a means of capitalizing on accumulated experience" and, in this sense, "every instrument is knowledge" (p. 91). The "instrumental relationship" requires that "the subject manages both the functional condition of the artefact (logic of functioning) and the transformation process of objects (process logic), so that the artefact becomes an effective means of action (use logic, instrumental relationship)" (p. 60).

Every activity is situated around three poles: "subject", "instrument" and "object" (p. 7), with three interactions occurring between them: (1) between the subject and the instrument; (2) "between the instrument and the object upon which it acts"; and (3) between the subject and the object "mediated by the instrument" (p. 11). Three distinct poles are involved in using instrument: the subject (user, operator, worker, agent, designer, etc.), the instrument (tool, machine, system, utensil, product, etc.) and the object towards which the action is directed (material, reality, object of the activity or task, another subject, etc.) (p. 65). The artefact holds "an intermediate and mediating position between subject and object" (p. 65).

Going beyond traditional subject-object models, Rabardel and Vérillon (1985) proposed the SAI model (see Figure 3.1), illustrating the characteristic triad of Instrumented Activity Situations. It reveals interactions between three poles: subject-object (S-Od), subject-instrument (S-I), instrument-object (I-O) and mediated subject-object (S-Om). The entire system is "immersed" in an environment that includes all the conditions the subject must account for in a purposeful activity. Thus, each pole and their mutual interactions are also influenced by the environment (pp. 65-66).

However, "instruments are not immediately given to the user"; the subjects develop their instruments through "instrumental genesis" activities (p. 12). The concept of "instrumental genesis" (Beguin & Rabardel, 2000) refers to the transition from "artefact" to "instrument", the process by which the "subjects" mentally appropriate the "artefact", integrating it into their activity through "schemes" (structures of subject action).

Instrumental genesis results from two processes undertaken by the subjects – towards themselves and towards the artefact – which "jointly contribute to the emergence and evolution of instruments" (Rabardel, 1995, p. 138):

(1) "instrumentalization": the enhancement of the artefact's properties; the assignment of an additional function (so-called "constituted functions", p. 143, as opposed to "constituent functions" intended by the artefact's designers), based on the current activity and situation. "Instrumentalization processes are focused on the artefact, including the selection, grouping, production and institution of functions, repurposing, attribution of properties, transformation of the artefact, its structure, its functioning, up to the complete production of the artefact by the subject" (p. 12). Instrumentalization concerns "the emergence and evolution of the artefact component of the instrument", which extends the creation and realization of artefacts whose boundaries are, as a result, difficult to define (p. 137);

(2) "instrumentation": the development of new schemes: "instrumentation processes relate to the subject: to the emergence and evolution of use and action schemes – how they are constituted, evolve through accommodation, coordination, and reciprocal assimilation, or integrate new artifacts into existing schemes" (p. 12); instrumentation concerns "the emergence and evolution of use and instrumented action schemes" (p. 137).

The action of instruments is analysed through two main features: (1) the *structuring effects* of artefacts on activity, and (2) the *transparency* of artefacts.

(1) Structuring effects: artefacts impose constraints and open up possibilities (p. 13). Different types of constraints are identified: "constraints of mode of existence", "constraints of finalization" and "constraints of action pre-structuring" (p. 13). Different "modes of action structuring" are also distinguished: "simple passive structuring", "organized passive structuring" and "active structuring". Two parallel cycles are noted: (1) the first in which designers plan operational modes to allow users to create use schemes, which in turn prompt designers to revise or expand

operational modes (p. 12); (2) and the second in which designers define "constituent functions" and users assign "constituted functions", which designers may then incorporate into a new generation of artefacts (p. 13). Moreover, users constantly negotiate between designer-predetermined uses (standardized in professional environments) and personalized adaptations for their own activities. Finally, instruments also influence the restructuring, emergence or disappearance of tasks (p. 53).

(2) Transparency: Two notions are distinguished: (a) instruments conceptualized as "glass boxes" to reveal part of their functioning, allowing the subject to consider it during an activity; and (b) instruments conceptualized as "black boxes" to conceal their functioning and thus avoid obstructing the subject's activity (p. 14). This leads to the relational concept of "operative transparency", which reflects "the variability of the subject's informational needs depending on the variability of the action situation, their states, and goals" (p. 14). Operative transparency connects the artefact's characteristics relevant for user action with the way in which these characteristics are made accessible (p. 14).

Drawing on Engeström's integration of the social dimension, Rabardel revises the SAI model – which links a *single* subject to an object via a technical object – by proposing a four-pole model: the SACI model of Collective Instrumented Activity Situations (1995) (see Figure 3.2), to which he adds a fourth pole – "other subjects" – to the original three. In this quadripolar model, mediations through instruments take multiple forms: (1) epistemic mediations from subject to object (oriented towards knowledge of the activity object); (2) pragmatic mediations from subject to object (oriented towards action on the activity object); (3) interpersonal mediations between subjects (whether the activity is individual or collective); (4) reflexive mediations from the subject to themselves (self-oriented).

Instrumented activity by the subject is both *constructive* (thinking subjects transform their action schemes, build knowledge, develop skills) and *productive* (acting subjects transform reality to complete a task, carry out a project or achieve a goal).

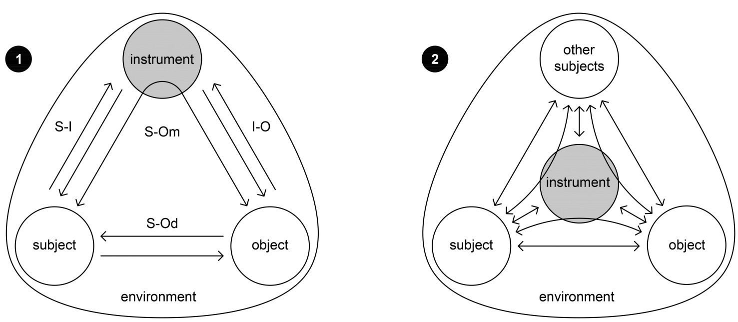

Figure 3. (1) "SAI Model: The characteristic triad of Instrumented Activity Situations" (Rabardel, 1995, fig. 4, p. 66, after Rabardel and Vérillon, 1985); (2) "SACI Model of Instrumented Collective Activity Situations" (Rabardel, 1995, fig. 11, p. 77).

Figure 3. (1) « Modèle SAI : la triade caractéristique des Situations d'Activités Instrumentées » (Rabardel, 1995, fig. 4, p. 66, d'après Rabardel et Vérillon, 1985) ; (2) « Modèle SACI des situations d'activités collectives instrumentées » (Rabardel, 1995, fig. 11, p. 77).

IV. THE INSTRUMENTED BODY IN DESIGN

Models of architectural design shed light on the architect at work – integrated (or not) into a design ecosystem – when they associate *action schemes* with *tools* to make them *instruments* of design. The various concepts of activity theory are present here (subject, instrument, object, other subjects, environment). In other words, a designer constructs an *instrument* from an *artefact*, within an *environment*, in collaboration with other designers, to complete a *task*.

IV.1 Internalist/externalist

Design models incorporate epistemological discussions from the cognitive sciences. Historically, the existence (or not) of the bodily envelope and the exchanges it allows (or not), as well as the location and scope of cognition, have raised numerous questions, leading to two opposing perspectives:

(1) *internalism*, as a classical dualism (e.g., Cartesian or cognitivist), claims that thought is subjective, relying solely on the subject's mental resources, independently of the body or environment, and can be characterized without reference to the individual's relations with the surrounding world (thoughts have a form of authority regardless of the environment);

(2) *externalism*, as a processual monism (e.g., enactivist), argues that the content of thought (through the exploratory activity of the body) cannot be characterized without reference to the environment (meaning depends on the existence of an external referent).

The debate between internalism and externalism concerns the status of the body: internalists see it as having little influence on cognition, favouring representational or even computational processes, while externalists see the body as an active agent oriented towards the environment, strongly influencing cognition as a source of experience and knowledge.

Parallel to this cognitive science dichotomy, the modelling of human activities in architectural design has been approached from two stances – both antagonistic and complementary – generating "productive debates" (Raynaud, 2001, p. 452):

(1) *internalists* seek an autonomous theory, initiated notably by the Design Methods Movement (Alexander, 1964; Broadbent & Ward, 1969), design sciences (Simon, 1969) and architecturology (Boudon, 1971). They "explore design acts from a cognitive perspective" (Raynaud, 2001, p. 452), modelling the cognitive activity of designers at work, that is, their mental operations and symbolic reasoning;

(2) *externalists* aim to induce a theory from contextual relationships, encouraged by, among others, the relation to the workplace (studio), tools (instruments) (Beguin & Rabardel, 2000), "social learning" (Bandura, 1997), collaborative design practices (Ben Rajeb, 2012), the formation of a "disciplinary culture" (Becher, 1994), "learning-by-doing" (action) and

a "reflective conversation with the situation" (situation) through the use of design and representation tools (Schön, 1983), as well as by the sociology of work (Callon, 1996) and Actor–Network Theory (ANT) (Callon, 1996; Latour, 2005; Yaneva, 2022). They "consider design as a site of social interactions among project actors" (Raynaud, 2001, p. 452), modelling the external factors influencing the designer's work (available references, design and representation tools, designer networks, workspaces).

The modelling of human–digital prosthesis relations (HCI) raises two distinct perspectives: (1) "Internalism is focused on the world internal to the user interface: *computer* interaction and e.g. logic, engineering, computation, etc."; (2) "Externalism is focused on the world external to the user interface: *human*-interaction and e.g. observation, evaluation, cognition, etc." (Thimbleby & Thimbleby, 2007, p. 1). For these authors, the exclusive debate is outdated and there is a balance between the two perspectives. The interface becomes significant, depending on whether and how it filters interactions. Therefore, modelling design processes should adopt a hybrid stance, combining the insights of both internalist and externalist research.

IV.2 Instrumental mythology

When the action of the body is extended by a tool, the designer establishes it as an instrument by associating it with action schemes. Certain characteristics of the bodily envelope are *displaced*, and the fixation of a precise bodily boundary seems to be *transcended*. This takes place to such an extent that the distinction between internalism and externalism becomes inadequate for understanding instrumented processes, where tools mediate between the subject and the object, between the designer and the representation medium. This aporia is particularly evident in the context of design instruments, whether analogue or digital, which are used to act upon and perceive representations of a project that is in the process of being designed. The debate over whether to use analogue or digital tools in design reflects the variety of bodily boundary shifts through two myths of representation (Claeys, 2018, 2021, 2023).

On the *analogue side*, Finnish architect Juhani Pallasmaa (2009) asserts that "human consciousness is an embodied consciousness", as we are "connected with the world through our senses", and thus: "Our hands and our whole body possess embodied know-how and wisdom." According to him, architecture is "the product of the thinking hand". Though his position is nuanced, he writes: "I am especially afraid of is the false precision and the apparent perfection of a digital image, which contrasts with the natural imprecision and hesitation which is characteristic of drawing." (p. 91) For him, "every meaningful artistic experience" erases "the boundary between the self and the world." (p. 15) In this first case, the distance between reality and representation seems to vanish through the creative act.

On the *digital side*, American architect Greg Lynn (1999) laments that with traditional methods, “the abstract space of design is conceived as an ideal neutral space of Cartesian coordinates” or “a dimensional space of idealized stasis”, (p. 11) although he states: “The availability and rapid colonization of architectural design by computer-aided techniques present the discipline with yet another opportunity to both retool and rethink itself as it did with the advent of stereometric projection and perspective.” (p. 41) He therefore promotes dynamic 3D modelling using tools originally developed for the creation of special effects in the film industry or streamlined prototypes in the nautical and aerospace industries. In this second case, the distance between reality and representation seems to vanish through the fluidity of 3D modelling.

However, this sterile dispute is (un)consciously grounded in two opposing myths about representation (Claeys, 2023, p. 2-3):

1. the myth of *analogue drawing*, according to which “the natural movement of the hand ensures an intuitive representation process, as an immediate transfer takes place from the mind to the mediating body, and from the body to the representation tool, resulting in a perfect dialogue between the designer and the real world”;
2. the myth of *digital drawing*, according to which “the immediacy of the commands guarantees the continuity of the representations (working in real time) and the transfer by total immersion guarantees a dialogue with a perfect double of the real world (working at real scale)”.

Typically, no designers truly believe that they can produce a perfect copy of a mental image on an external medium. But if a myth is understood as an imaginary story shared by members of a group to justify a social practice, then the existence of such myths allows groups of designers to justify the preferential use of one representation tool over another, based on shared values – such as the haptic quality of a pencil or the sensorimotor aspect of immersive virtual reality.

Without denying the sociocultural and professional significance of these myths, the study of design processes can be expanded to include the cognitive capacities of the designer’s consciousness and their interactions with the instruments used (both analogue and digital), through bodily mediation. The goal is to study the cycle that includes processes of perception, integration and action. On one hand, through perception, representation tools *instrument* the discontinuous flow of internal project representations formed by integrative consciousness. On the other hand, this succession of acts of thought *instrumentalizes* these same tools through action.

Since the digital revolution, new tools have emerged in architectural design processes. Proponents of hand drawing argue that digital tools have distanced designers from the representations they create, and thus from the objects they design. Hand drawing is said to provide a kind of immediacy – a tight body/environment coupling – that is lost when using digital tools. Indeed, using a computer to create a 2D or perspective drawing, similar to what could be done by hand, seems to distance the designer's body from the representation medium. The sensorimotor relationship with the mouse is limited to a few restricted hand movements, and the body's motions are not directly tied to the creation of the lines of the drawing on the screen. However, new immersive tools (VR headsets, gloves, haptic suits) appear to reestablish a connection with the body, in the sense that sensorimotor relations between the body and the representation seem more direct. The study of these new tools also supports design models that bridge internalism and externalism, surpassing the body/environment divide. Given that designers' decision-making ability is linked to their perceptual and active capacities, could the emergence of immersive design tools allow them to reconnect with a form of sensorimotor intelligence? Moreover, could the integration of this sensorimotor dimension promote knowledge acquisition and the development of creativity?

IV.3 Sensorimotor architectural design model

By moving beyond the sterile polarization between internalist and externalist approaches, architectural design can be modelled as both a mental (sensory) and practical (motor) activity. Here, we propose an initial general sensorimotor model specific to architectural design (see Figure 4), integrating the various concepts from activity theory (subject, instrument, object, other subjects, environment), while adopting an "embodied and situated approach to cognition" (Versace *et al.*, 2018, p. 20). This includes body/environment coupling (integrating the epidermal interface) and body/body coupling (co-design). This model represents a first step in ongoing research. Although it is developed within the field of architecture, it can also be adapted to other design domains (ergonomic, industrial, graphic, etc.).

Being non-linear, any architectural design process is "circular", "iterative" and "reflective", alternating between phases of "latency", "convergence" and "divergence", before arriving at a "suboptimal solution" (Claeys, 2013). The term *process* refers to *step-by-step progression towards a result*, while *design* denotes the cognitive effort of *mentally grasping elements together*. As such, every *designer* engaged in a design process accounts for the interwoven complexity inherent in the architectural project by operating on the successive states of the mental model associated with it. The *projettation* is thus the mental development of a model within a dynamic process of data processing, information cross-referencing and knowledge mobilization. The process is *goal-oriented*, in the sense of an *operational* – not metaphysical or theological – finality. It begins with an initial state (*ill-defined* knowledge), is punctuated by intermediate states (variations of the project's mental model) and concludes with a final state (in the form of a project that generates *knowledge*).

Architectural design includes mental acts that enable a succession of cognitive operations performed on mental representations of the ongoing project. As a form of *work*, these integrative acts are influenced by perceptual input and involve motor activities directed towards and from the environment. The sensory and motor effects of the body are repeatedly filtered through interfaces associated with the technical objects – whether analogue or digital – used for perception, design and action. To adopt a purely internalist or purely externalist stance is illusory. Although rarely addressed in research, the interfacing between perception, cognition and action is crucial for achieving a comprehensive understanding of design.

The designer uses technical objects – artefacts – to which they assign action schemes, thereby establishing them as design *instruments*. The designer engages in dialogue and negotiation with the instruments used. Through *instrumentalization* of the artefacts, they add constituted functions to the constituting functions of the instruments, broadening their usage. In response to the environment and its affordances, through *instrumentation*, the designer adapts or replaces the action schemes associated with these instruments. Finally, design instruments possess a degree of transparency, and are characterized by their structuring effects on the orientation of the process.

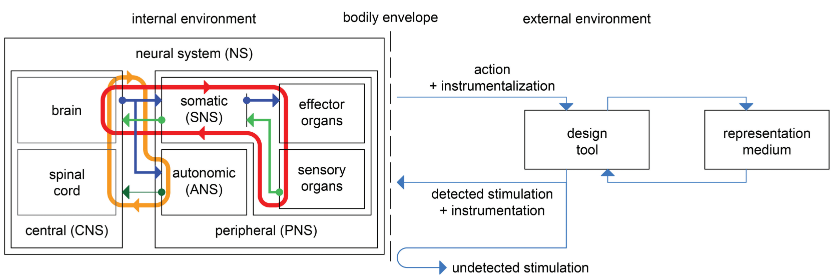

Figure 4. Sensorimotor model of instrumented architectural design.
Figure 4. Modèle sensorimoteur de la conception architecturale instrumentée.

V. OPENING: THE HOMUNCULUS DESIGNER

Based on curative surgical procedures aimed at identifying neural sites linked to the onset of epileptic seizures, neurosurgeon Wilder Penfield proposed the concept of *somatotopy* – a relative correspondence between each area of the body (*soma*) and a specific location (*topos*) in the nervous system (Penfield & Boldrey, 1937; Penfield & Rasmussen, 1950; Penfield & Jasper, 1954). Called a "grotesque creature" by Penfield, the homunculus represents a distorted human figure in which different parts of the body are visually enlarged or reduced in size (see Figure 5.1). The homunculus "illustrates both sensory and motor representation. The size of the parts of the body in the drawing correspond with the comparative extent of cortex occupied by each part. The order of the parts is that found in the cortical sequence but there are unavoidable inaccuracies in the figurine" (Penfield & Jasper, 1954, p. 69). Penfield illustrated somatotopy with two emblematic representations of *homunculi*: (1) on the side of *action*, involving the primary motor cortex located in the precentral gyrus, the "motor homunculus" is a map of the brain areas associated with motor processes, engaging various parts of the body; (2) on the side of *perception*, involving the somatosensory cortex located in the postcentral gyrus, the "sensory homunculus" is a map of the brain areas assigned to sensory processes for different body parts. With the advent of Magnetic Resonance Imaging (MRI) use, Penfield's model has been revised, corrected and adapted numerous times, while also being generalized to all senses (Catani, 2017). Across these many iterations, it becomes apparent that "somatosensation plays a major role in human cognition", and that future neuroscience research should aim to establish a "joint framework" for "somatosensory cognition" (Saadon-Grosman *et al.*, 2020, p. 9).

Given that architectural designers are multifaceted, J. Christopher Jones (1969), in the historical *Design Methods in Architecture* Portsmouth symposium proceedings, published three iconic caricatures: the "designer as a magician" (the black box), the "designer as a computer" (the glass box) and the "designer as a self-organizing system" (the box within the box). Fifty years later, three additional portraits were proposed: the "immersed designer" (the body in a box), the "externalized designer" (the box outside the body) and the "networked designer" (the body is a box within a network of boxes) (Claeys, 2019). Today, we would like to propose a new portrait (see Figure 5.2): the *sensorimotorized designer* – to embody the necessity for architectural design researchers to hybridize internalist and externalist stances, and to reintroduce the question of the body and its effects on perception, action and the creation of knowledge within the design process.

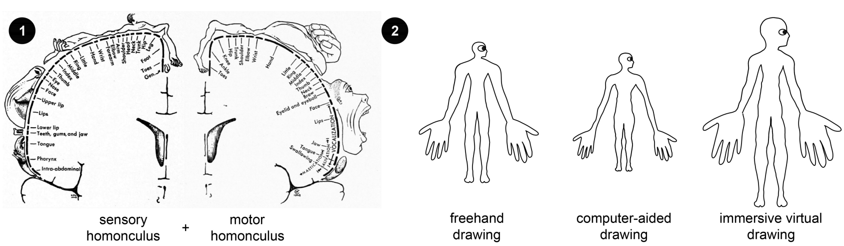

Figure 5. (1) Sensory homunculus and Motor homunculus (Penfield & Rasmussen, 1950, fig. 114–115, pp. 214–215); (2) Conceptual illustration showing variations of the sensorimotorized designer depending on the instruments used.

Figure 5. (1) Homoncule sensoriel et homoncule moteur (Penfield & Rasmussen, 1950 fig. 114-115, pp. 214-215) ; (2) Illustration de principe, présentant des variations du concepteur sensorimotorisé en fonction des instruments utilisés.

Ethics
The research presented in the article does not involve any experiments.
Role of the co-authors
D. Claeys – Conceptualisation, methodology, validation, writing, illustrating
S. Cleven – Conceptualisation, methodology, validation, illustrating
L. Roobaert – Conceptualisation, methodology, validation
Conflict of interest
There is no conflict of interest.

RÉFÉRENCES

Alexander, C. (1964). *Notes on the synthesis of form*. Harvard University Press.
Bandura, A. (1997). *Self-efficacy. The exercise of control*. W. H. Freeman & Co.
Battro, A. M. (1966). *Dictionnaire d'épistémologie génétique [Dictionary of genetic epistemology]*. D. Reidel.
Becher, T. (1994). The significance of disciplinary differences. *Studies in Higher Education*, *19*(2), 151-161. https://doi.org/10.1080/03075079412331382007
Bedny, G. Z. (2015). *Application of systemic-structural activity theory to design and training*. CRC Press. https://doi.org/10.1201/b17976
Bedny, G. Z., & Bedny, I. S. (Eds.). (2019). *Applied and systemic-structural activity theory. Advances in studies of human performance*. CRC Press.
Bedny, G. Z., & Karwowski, W. (2007). *A systemic-structural theory of activity. Applications to human performance and work design*. CRC Press.
Bedny, G. Z., Karwowski, W., & Bedny, I. S. (2014). *Applying systemic-structural activity theory to design of human-computer interaction systems*. CRC Press. https://doi.org/10.1201/b17975
Bedny, G. Z., & Meister, D. (1997). *The russian theory of activity. Current applications to design and learning*. Lawrence Erlbaum Associates.
Beguin, P., & Rabardel, P. (2000). Concevoir pour les activités instrumentées [Designing for instrumented activities]. *Revue d'Intelligence Artificielle*, *14*(1-2), 35-54.
Ben Rajeb, S. (2012). *Modélisation de la collaboration distante dans les pratiques de conception architecturale. Caractérisation des opérations cognitives en conception collaborative instrumentée [Modeling remote collaboration in architectural design practices. Characterization of cognitive operations in instrumented collaborative design]*. École Nationale Supérieure d'Architecture Paris La Villette.
Bertalanffy, L. von. (1968). *General system theory*. Georges Braziller.
Beth, E. W., & Piaget, J. (1961). *Épistemologie mathematique et psychologie [Mathematical epistemology and psychology]*. Presses Universitaires de France.
Boudon, P. (1971). *Sur l'espace architectural. Essai d'épistémologie de l'architecture [On architectural space. An essay in the epistemology of architecture]*. Parenthèses.
Broadbent, G. H., & Ward, A. (Eds.). (1969). *Design methods in architecture*. AA papers.
Brouillet, D. (2019). *Agir pour connaître [Acting to know]*. Presses Universitaires de Grenoble.
Callon, M. (1996). Le travail de la conception en architecture [The work of design in architecture]. *Cahiers de la Recherche Architecturale*, *37*, 25-35.

Catani, M. (2017). A little man of some importance. *Brain*, *140*(11), 3055. https://doi.org/10.1093/brain/awx270
Changeux, J.-P. (2012). *L'homme neuronal [The neural man]*. Pluriel.
Claeys, D. (2013). *Architecture et complexité. Un modèle systémique du processus de (co)conception qui vise l'architecture [Architecture and complexity. A systemic model of the (co-)design process aimed at architecture]*. Presses universitaires de Louvain.
Claeys, D. (2018). Discontinuités des processus de conception architecturale. Crises de la representation [Discontinuities in architectural design processes. Crises of representation]. *Acta Europeana Systemica*, *8*, 19-36. https://doi.org/10.14428/aes.v8i1.56203
Claeys, D. (2019). Trois figures architecturales post 1969. Les concepteurs immergé, externalisé et en reseau [Three post-1969 architectural figures: the immersed, the externalized, and the networked designers]. *Lieuxdits*, *17*, 25-35. https://doi.org/10.14428/ld.vi17.52423
Claeys, D. (2021). Construction historique de la figure de l'architecte. Mythe analogique et fiction numérique [Historical construction of the figure of the architect. Analogical myth and digital fiction]. In D. Claeys (Ed.), *Anticrise architecturale. Analyse d'une discipline immergée dans un monde numérique* (pp. 249-272). Presses universitaires de Louvain.
Claeys, D. (2023). Physiological and cognitive discontinuities. From mythical mediation to implicit discretization of architectural design tools. *Frontiers of Architectural Research*, *12*(1), 1-12. https://doi.org/10.1016/j.foar.2022.06.008
Cong-Lem, N. (2022). Vygotsky's, Leontiev's and Engeström's cultural-historical (activity) theories. Overview, clarifications and implications. *Integrative Psychological and Behavioral Science*, *56*(4), 1091-1112. https://doi.org/10.1007/s12124-022-09703-6
Dafermos, M. (2015). Activity theory. Theory and practice. In I. Parker (Ed.), *Handbook of Critical Psychology* (pp. 261-270). Routledge.
Descartes, R. (1664). *De homine*. Charles Angot.
Engeström, Y. (1987). *Learning by expanding. An activity-theoretical approach to developmental research*. Orienta-Konsultit.
Engeström, Y. (1999). Activity theory and individual and social transformation. In R.-L. Punamäki, R. Miettinen, & Y. Engeström (Eds.), *Perspectives on Activity Theory* (pp. 19-38), Cambridge University Press. https://doi.org/10.1017/CBO9780511812774.003
Engeström, Y. (2001). Expansive learning at work. Toward an activity theoretical reconceptualization. *Journal of Education and Work*, *14*(1), 133-156. https://doi.org/10.1080/13639080020028747
Jones, J. C. (1969). The state-of-the-art in design methods. In G. H. Broadbent & A. Ward (Eds.), *Design Methods in Architecture* (pp. 193-197). AA papers.
Kahle, W., & Frotscher, M. (2007). *Atlas de poche d'anatomie. 3. Système nerveux et organes de sens [Atlas of human anatomy. 3. Nervous system and sensory organs]* (P. Bourjat, Trad.; 4e éd.). Flammarion.
Kandel, E. R., Schwartz, J. H., Jessell, T. M., Siegelbaum, S. A., & Hudspeth, A. J. (Eds.). (2013). *Principles of neural science* (5th ed.). McGraw-Hill.
Kuutti, K. (1996). Activity theory as a potential framework for human-computer interaction research. In B. A. Nardi (Ed.), *Context and Consciousness. Activity Theory and Human-Computer Interaction* (pp. 17-44). The MIT Press.
Lakoff, G., & Johnson, M. (1999). *Philosophy in the flesh. The embodied mind & its challenge to western thought*. Basic Books.
Lakoff, G., & Nuñez, R. (2001). *Where mathematics come from*. Basic Books.
Latour, B. (2005). *Reassembling the social. An introduction to actor-network-theory*. Oxford University Press.

Le Moigne, J.-L. (1995). *Les épistémologies constructivistes [Constructivist epistemologies]*. Presses universitaires de France.
Leontiev, A. N. (1965). *L'homme et la culture [Man and culture]. Recherches internationales à la lumière du marxisme, 46*. Éditions sociales internationales.
Leontiev, A. N. (1978). *Activities, consciousness, and personality (1975)* (M. J. Hall, Trad.). Prentice-Hall.
Leontiev, A. N. (1981). *Problems of the development of the mind (1959)*. Progress Publishers.
Lynn, G. (Ed.). (1999). *Animate form*. Princeton Architectural Press.
Margulis, L. (1990). Words as battle cries. Symbiogenesis and the new field of endocytobiology. *BioScience*, *40*(9), 673-677. https://doi.org/10.2307/1311435
Margulis, L., & Fester, R. (Eds.). (1991). *Symbiosis as a source of evolutionary innovation. speciation and morphogenesis*. The MIT Press.
Maturana, H. R., & Varela, F. J. (1994). *L'arbre de la connaissance. Racines biologiques de la compréhension humaine [Tree of knowledge. Biological roots of human understanding]* (F.-C. Jullien, Trad.). Addison-Wesley France.
Nardi, B. A. (Ed.). (1996). *Context and consciousness. Activity theory and human-computer interaction*. The MIT Press.
Pallasmaa, J. (2009). *The thinking hand. Existential and embodied wisdom in architecture*. John Wiley & Sons.
Penfield, W., & Boldrey, E. (1937). Somatic motor and sensory representation in the cerebral cortex of man as studied by electrical stimulation. *Brain*, *60*(4), 389-443. https://doi.org/10.1093/brain/60.4.389
Penfield, W., & Jasper, H. (1954). *Epilepsy and the functional anatomy of the human brain*. Little Brown and Company.
Penfield, W., & Rasmussen, T. (1950). *The cerebral cortex of man. A clinical study of localization of function*. Macmillan & Co.
Piaget, J. (Éd.). (1967). *Logique et connaissance scientifique [Logic and scientific knowledge]*. Gallimard.
Piaget, J. (1977). *La naissance de l'intelligence chez l'enfant (1936) [The origins of intelligence in children]* (9e éd.). Delachaux & Niestlé.
Piaget, J. (2012). *La psychologie de l'intelligence (1947) [The psychology of intelligence]* (7e éd.). Armand Colin.
Pocock, G., Richards, C. D., & Richards, D. A. B. (2018). *Human physiology* (5th ed.). Oxford University Press.
Rabardel, P. (1995). *Les hommes et les technologies. Approche cognitive des instruments contemporains [Men and technologies. A cognitive approach to contemporary instruments]*. Armand Colin.
Rabardel, P. (2003). From artefact to instrument. *Interacting with Computers*, *15*(5), 641-645. https://doi.org/10.1016/S0953-5438(03)00056-0
Rabardel, P. (2005). Instrument subjectif et développement du pouvoir d'agir [Subjective instrument and the development of the power to act]. In P. Rabardel & P. Pastré (Eds.), *Modèles du sujet pour la conception. Dialectiques, activités, développement* (pp. 35-49). Octarès.
Rabardel, P., & Bourmaud, G. (2005). Instruments et systèmes d'instruments [Instruments and systems of instruments]. In P. Rabardel & P. Pastré (Eds.), *Modèles du sujet pour la conception. Dialectiques, activités, développement* (pp. 211-229). Octarès.
Rabardel, P., & Vérillon, P. (1985). Relations aux objets et développement cognitive [Relations to objects and cognitive development]. In A. Giordan & J.-L. Martinand (Eds.), *Communication, éducation et culture scientifiques et industrielles*. Actes des septièmes Journées internationales sur l'éducation scientifique (pp. 395-399). Université Paris 7.

Raynaud, D. (2001). Compétences et expertise professionnelle de l'architecte dans le travail de conception [Competence and professional expertise of the architect in the design process]. *Sociologie du travail*, *43*(4), 451-469. https://doi.org/10.4000/sdt.35398
Rosnay, J. de. (1975). *Le macroscope. Vers une vision globale [The macroscope: A new world scientific system]*. Seuil.
Saadon-Grosman, N., Loewenstein, Y., & Arzy, S. (2020). The "creatures" of the human cortical somatosensory system. *Brain Communications*, *2*(1), fcaa003. https://doi.org/10.1093/braincomms/fcaa003
Schön, D. A. (1983). *The reflective practitioner. How professionals think in action*. Basic Books.
Shannon, C. E. (1948). A mathematical theory of communication. *Bell System Technical Journal*, *27*(3-4), 379-423, 623-656.
Shannon, C. E., & Weaver, W. (1949). *The mathematical theory of communication* (Vol. 34). The University of Illinois Press.
Simon, H. A. (1969). *The sciences of the artificial*. The MIT Press.
Thimbleby, H., & Thimbleby, W. (2007). *Internalist and externalist HCI*. Proceedings of the 21st British HCI Group Annual Conference University of Lancaster. https://doi.org/10.14236/ewic/HCI2007.74
Varela, F. J., Thompson, E., & Rosch, E. (1991). *The embodied mind. Cognitive science and human experience*. The MIT Press.
Versace, R., Brouillet, D., & Vallet, G. (2018). *Cognition incarnée. Une cognition située et projetée [Embodied cognition. A situated and projected cognition]*. Mardaga.
Vygotsky, L. S. (1978). *Mind in society. Development of higher psychological processes (1930)* (M. Cole, V. John-Steiner, S. Scribner, & E. Souberman, Eds.). Harvard University Press.
Vygotsky, L. S. (2014). La méthode instrumentale en psychologie (1928?) [The instrumental method in psychology] (F. Sève, Trad.). In M. Brossard & L. Sève (Eds.), *Histoire du développement des fonctions psychiques supérieures* (pp. 565-574). La Dispute.
Vygotsky, L. S. (2019). *Pensée et langage (1934) [Thought and language]* (F. Sève, Trad.). La Dispute.
Wiener, N. (1948). *Cybernetics, or control and communication in the animal and the machine*. The MIT Press.
Yaneva, A. (2022). *Latour for architects*. Routledge.

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