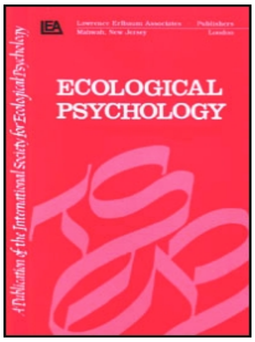

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From Kepler to Gibson

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ABSTRACT
We argue that the idea of embodiment and the strategies for carrying out embodied approaches are some of the most prevalent and interdisciplinary legacies of early modern science. The idea of embodiment is simple: to explain the behavior of bodies, we must understand them as unified wholes in their environments. Embodied approaches eschew explanations in terms of qualitative descriptions of the intrinsic properties of bodies and promote explanation in terms of the interaction between bodies. This idea can be found in Kepler's optics, Descartes' physics, and Newton's physico-mathematics. *The Senses Considered as Perceptual Systems* (Gibson, 1966) is the culmination of this centuries-long embodiment movement which can be traced back to the 17th century.

At first glance, it seems that radically different approaches to scientific explanation are in vogue at different times.[1] For example, before Gibson's *The Senses Considered as Perceptual System* (1966), embodied approaches to cognitive scientific explanation were scarce. Since, however, they have grown in popularity and are currently a mainstay of the cognitive sciences. We argue that these approaches are not as novel or distinctly contemporary as they might first appear. In fact, the origins of embodiment trace to the scientific revolution. We claim that the process of embodiment drove the creation of modern physics and modern science more generally. In other words, we show that embodiment is not a feature of cognitive science alone but a philosophical *maneuver*—a strategy for constructing scientific explanations—that is central to the history of science. Embodiment lies at the heart of what we understand by *science*.

From this perspective, *The Senses Considered as Perceptual Systems* (1966) was both the impetus for contemporary embodied cognitive science and the culmination of a centuries-long embodiment movement. To illustrate this point, we first analyze different types of embodiment in the scientific revolution, paying special attention to the main motivation for early modern embodiment approaches, namely, anti-Aristotelianism. Second, we explain why embodiment approaches did not become central to the sciences of the mind until the latter half of the 20th century. And finally, we show how embodiment finds its role in psychology through Gibson's work and how previous considerations on the nature of the embodiment can be found in that work.

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[1]This is also a familiar scholarly opinion; see Kuhn (1970).

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Embodiment

Embodied cognition (see Clark, 1997; Shapiro, 2014) is one of the central components of contemporary cognitive science. Put simply, it is the idea that in order to understand cognitive processes we must understand them as features of the whole body (including the brain) and its relations with the environment (i.e., the body embedded in a given environment, the body using different tools in a given environment, etc.). Although the details of the conception may differ across practitioners, the specification of the whole body, or the whole-body-in-an-environment, as the correct unit of analysis is common. This basic idea is not an achievement of cognitive science alone. Embodiment played a central role in the very foundation of modern science (particularly physics) in the 16th and 17th centuries.

Although different overlapping types of embodiment can be found in the rise and development of early modern science, two are particularly important to us: embodiment in physico-mathematics, particularly optics, and embodiment as an anti-Aristotelian explanatory strategy. Between them, they capture some of the most salient features of contemporary approaches to embodiment. Although anti-Aristotelianism is the focus of this article, it is worth briefly considering physico-mathematical embodiment for two reasons. First, these types of embodiment are interrelated. Second, anti-Aristotelian approaches were multifaceted and general. Physico-mathematical embodiment provides a specific example through which we can discover the salient features of more general anti-Aristotelian approaches.

Physico-mathematical embodiment

Johannes Kepler was an influential proponent of physico-mathematical embodiment. In his *Astronomiae pars Optica [The Optical Part of Astronomy]* (1604/2000), he made clear that the physical organ of vision—the eye—could not be considered independent of the remainder of the human body, and that human body could not be considered independent of its environment. He wrote,

> The eyes are attached to the head, so, through the head, they are attached to the body; through the body, to the ship or the house, or to the entire region and its perceptible horizon. (p. 336)

The resemblance between this idea and some proposals concerning visual perception in the work of Gibson (1966, 1979/1986) is surprising. In Kepler's case, however, the assertion is also significant because it promoted the idea that the human body is an instrument that can be studied for its reliability, bounds of accuracy, and so on. Studying the human body thus became intertwined with a general justification of the scientific reliability of optical (and other) instruments and observations (Gal & Chen-Morris, 2013). It was a step toward the naturalization of mind.

Kepler also championed the mathematical study of light and vision. He revolutionized the field of optics by turning it "into a mathematical-physical study of the production of images by light" (Gal & Chen-Morris, 2013, p. 35). Before him, optics was closely related to vision, but the study of perception, the study of the physical properties of light, and the study of geometrical optics were mostly separate. Perceived images, although carried by light, were thought to be objects in their own right. These so-called species or ideas were likenesses of the perceived object that were transported (more or less) by the medium of light but which carried information that was not exhausted by the light that transported them. The mismatch meant that one could not understand perceived images simply by studying the light that generated them. Kepler, however, championed the idea that studying light is a way to study the perceived images. Because the study of the former was a mathematical activity since antiquity (at least partly; see Lindberg, 1978), Kepler's position implied that even perceived images could be studied by mathematics, and, furthermore, relatively independently from the biological underpinning of the process of vision. In a sense, the eye became one more surface that light could influence.

Kepler was followed (and eventually overshadowed) by Rene Descartes, who exemplified most clearly the idea of physico-*mathematical* embodiment. According to Descartes, mathematics could be used to explain all natural phenomena. Before him, mathematics was thought to be the science of abstract or otherwise perfect entities (e.g., celestial bodies, which were thought to be constituted by the incorruptible fifth element, the quintessence). But Descartes believed that mathematics held the key to explaining *all* physical phenomena, including the changing, natural bodies of the sublunary realm. In other words, in his hand mathematics became the main tool of natural philosophy.

Why this approach to mathematics counts as *embodiment* depends on Descartes' metaphysical justification for the usefulness of mathematics. For him, bodies were simply "the objects of geometry made real" (Garber, 1992, p. 63). They were essentially and wholly "extension," and "extension" was the mathematical concept used to describe the nature of space and continuous magnitude. Descartes' new metaphysics was a striking departure from scholastic-Aristotelian metaphysics. For Aristotelians, bodies (and "substances" more generally) were compounds of matter and form. Matter was the *stuff* from which substances were made. Form was the essence of substances; it gave substances their unity and identity and made them the kind of substances they were. Although some believed that matter could be studied mathematically, form—the metaphysically primary component of any being—was not susceptible to mathematical analysis. Extension, in contrast, was (and is) a mathematical concept. Descartes' reduction of all physical substances to extension meant that mathematics was not only useful for understanding the physical world but also it was the *only* tool by which we could understand the physical world. This mathematization further entailed a plenist view of the universe: because extension and matter were identical, the concept of empty space was a contradiction in terms. Without empty space, however, the movement of any one bit of matter necessitated a compensatory movement in some other bit. In other words, there could be no motion that would not elicit changes in its environment and no bit of matter that could be completely isolated from changes in its environment.

Descartes also believed that all physical processes arose from the collision of bits of matter. The collision model had an important consequence: it suggested that in order to understand physical change, one had to study *two or more* bodies. In this way, the model, like the plenist view of the universe, suggested that in physics the appropriate unit of analysis was the object-in-its-environment. And because this analysis had to be rendered in the language of mathematics, the models further suggested that physical analysis concerned the *mathematics of the object-in-its-environment.* This is what we mean by "physico-mathematical" embodiment. It is the early modern push to turns physics into a system of mathematical relations that governed the interactions between bodies. Since the mid-20th century, this push has often been characterized as a "mathematization" or a "mechanization" of natural philosophy (e.g., Dijksterhuis, 1961). These are important labels. However, we are pointing out that mathematization and mechanization brought with them a contextualism/situationalism that has been underappreciated, one that it central to *embodied* approaches.

Embodiment as anti-Aristotelianism (and its limits)

Physico-mathematical embodiment is a species of a more general type of embodiment prevalent in early modernity: embodiment as a rejection of the scholastic-Aristotelian approach to scientific explanation. In scholastic-Aristotelianism, natural change was primarily explained by means of its end states, what the Aristotelians called "final" or "telic" causes. At first glance, some processes might appear to have *external* end states for Aristotelians: for example, a falling stone seeks its proper place at the center of the universe, a location that is independent of features of the stone. But this incorrectly locates the *engine* of Aristotelian change. In falling, the stone does not seek to attain an *external* state but acts according to its form in a way that seeks to actualize the potential(s) inherent in it. Take also the case of a human being: a human being cannot act toward the good without a host of *external* circumstances that allow him or her to do so. Those circumstances determine what actions are possible as well as their moral valence. However, acting toward the good is the actualization of a potential for virtue inherent in the human, a potential whose possession is independent of the situations in which it can be actualized. For both the stone and the human, what drives change is the expression of *internal* form, a constitutive component of both substances.[2]

Embodiment as anti-Aristotelianism consists in ceasing to appeal to *internal teleological states* as explanations. As we saw in the case of physico-mathematical embodiment, it consists in trying to explain natural behavior in terms of bodies as wholes and their interactions with other bodies. Following Gal & Chen Morris (2013, p. 39), we can see this rejection of teleology—with the rejection of intentionality being a species thereof—in Kepler's reformulation of optics, where images are causal effects produced by light bouncing off an object and falling on a surface but where no forms or visual rays are invoked. The key idea is that by changing the subject matter of optics, Kepler (1604/2000) was able to avoid explanations of optical phenomena in terms of forms ("species" or "ideas") that travel from the object of vision to the organ of vision. This opens optical phenomena to explanation in mathematical/physical terms—that is, without needing to appeal to a *telos* that guides the phenomena in some specific way. Similarly, once Descartes (1644/1983) rejected forms in his metaphysics, he did away with teleological or intentional features of natural bodies. To see the connection between teleology, intentionality, and forms, we must consider the relation of forms to the scholastic-Aristotelian account of scientific explanation.

As we noted earlier, in Aristotelian metaphysics bodies (and "substances" more generally) are compounds of matter and form, but form is of primary importance. Form constitutes the "essence" of being, and this essence determines what any particular thing *is*, what it *does*, and what it *is for* (see Matthen, 2009).[3] Form thus determines *telos* (i.e., goal, intention, function, etc.), and an appeal to form is necessarily an appeal to teleology. See, for example, how it works for development:

> The formal cause of generation is the definition of the animal's substantial being, while the final cause is the adult form, which is the goal of the process of development. … Aristotle tells us that these two causes refer to the same thing. This is plain enough, since the form specified in

[2]We thank an anonymous referee for urging us to clarify this.

[3]We are giving a canonical interpretation of Aristotle. There are, of course, some divergent opinions concerning Aristotelian essences. The view we outline here is the consensus on this point. See S. M. Cohen (2009) and Lewis (2009) for further analysis on the topic.

> the account of an animal's substantial being is also the *telos* of its natural development. (Henry, 2009, p. 379)

In this case, the form of the animal determines both what the animal is and what the final state of the animal is. Consequently, for scientific explanations to capture the world as it really is, they must appeal to forms—internal, intrinsic features of substances. Because forms determine teleology, scientific explanations must also be teleological.[4] Such explanations were almost always *qualitative.*

According to Garber (1992), this internal, qualitative kind of explanation was Descartes' target in natural philosophy. He thought of forms as "little minds attached to bodies, causing the behavior characteristic of different sorts of substances" (p. 287). This was problematic because in his metaphysics there was an unbridgeable gap between material things (*res extensa)* and thinking things (*res cogitans).* Little minds *could not* be attached to bodies because minds and bodies were essentially different. Thus, Descartes rejected internal, qualitative explanation and with it (almost) the entirety of Aristotelian natural philosophy. We say "almost" because Descartes allowed for one exception: human beings.

To see the significance of Descartes' treatment of human beings, we must step back a bit. We have contended that embodiment—the rejection of internal teleological states and promotion of mathematical, relational explanation—lies at the root of early modern physics. Given the historical significance of early modern physics, embodiment is thus one of the main concepts that constitute modern science as we understand it today.[5] However, if this is so, why is embodiment a *recent* phenomenon in cognitive science? What is special about cognitive science and its subject that made it seem disembodied until the last few decades? The story has to do, again, with Descartes. He is implicated in both the embodiment of modern physics and the disembodiment of the sciences of the mind.

Our story, as before, starts with Kepler in his *Astronomiae pars Optica* (1604/2000). Although Kepler changed the subject matter of optics, he left vision itself out of the equation, that is, he left the mental field, the psychological processes, out of the range of mathematical or physical analyses of the images produced by light:

> How this image or picture is joined together with the visual spirits that reside in the retina and in the nerve, and whether it is arraigned within by the spirits into the caverns of the cerebrum to the tribunal of the soul or of the visual faculty; whether the visual faculty, like a magistrate, given by the soul, descending from the headquarters of the cerebrum outside to the visual nerve itself and the retina, as to lower courts, might go forth to meet this image—this, I say, I leave to the natural philosophers to argue about. (p. 180)

Thus, whatever vision is—which remains a mystery according to Kepler—it is not to be explained by optics. Descartes' case is similar. In a sense, he generalizes Kepler's separation of perception from the physical processes leading to it. This generalization is made possible by his underlying metaphysics. Because Descartes separates *what is* into two mutually exclusive categories (*res extensa* and *res cogitans)*, he "invents the eye of the mind, modeled on

[4]Again, some objections could be raised to this claim by noting that Aristotle himself proposed four causes (material, effective, formal, and final) to be explained to give a full account of any phenomena. However, final causes are privileged within his schema. See Matthen (2009) and Lennox (2009).

[5]What happened in physics happened later in other sciences: appeal to whole bodies and not inner-body entities became increasingly common. Perhaps, molecular biology and genetics still hold a different status in this sense—that is, they still appeal to genes (and not whole organisms) as cause and agent of evolution and development. Nevertheless, there are dissenting voices (e.g., see Lewontin, 2000; Oyama, Griffiths, & Gray, 2001).

but completely independent from the eye of the flesh" (Gal & Chen-Morris, 2013, p. 65). Although he promotes embodiment in the material realm, he holds that embodiment is impossible in the mental realm. The same Cartesian metaphysics that made possible the shift toward embodiment in the physical sciences also blocks its application to the sciences of the mind.

Until the last 2 decades the framework within cognitive science did not differ too much from the Cartesian one—famously, Jerry Fodor (1987) claimed that the only difference between his proposal and that of Descartes was the computer metaphor. It is not until ecological psychology and enactivism came around that embodiment gained importance in the field. Cognitive science before the embodied turn, of course, did use the vocabulary of "forms" or "ideas," but representations played similar roles. Representations are entities within bodies, which are not bodies themselves, and to which cognitive scientists appealed in order to explain the behaviors of bodies. After the embodied turn—at least in the radical embodied approaches (see Chemero, 2009; Hutto & Myin, 2013; O'Regan & Nöe, 2001)—the explanation of behavior ceases to appeal to representations and begins to appeal to lawful or law-like relations between bodies and their environments. This turn started, we contend, with Gibson's *The Senses Considered as Perceptual Systems* (1966).

Gibson

The main tenets of ecological psychology, arguably the first proposal of embodiment in psychology and cognitive science, were developed by J. J. Gibson during the late 1950s and early 1960s. During these years, as he noted in the preface of *The Senses Considered as Perceptual Systems* (1966), he had to write his seminal book twice. The difficulty was that in order to offer a coherent theory of perception, he had to integrate new empirical evidence on the anatomy and physiology of the senses with his studies on 17th and 18th centuries' perceptual theories. The resulting theory questioned the assumptions of the computational approach that was coming into focus at the time and that is still held by the majority of cognitive scientists. This questioning was a direct consequence, we claim, of Gibson's embodied approach: whereas the computational approach to cognitive science is an example of disembodiment or, in the terminology used in the previous section, a facet of explanation in Aristotelianism, the Gibsonian approach represents the anti-Aristotelianism that was applied to physics in the 17th century. Gibson applied this anti-Aristotelianism to the sciences of the mind, more specifically, to perception.

In what follows, we analyze the philosophical maneuvers that Gibson employed. These consist of a redescription of the environment, the organism, and their interactions in terminology suitable for a nonteleological, nonintentional, full-fledged mathematical theory of perception. These maneuvers are parallel to those of Descartes described earlier, that is, his description of the categories *res extensa* and *res cogitans*. However, before describing the content of *The Senses Considered as Perceptual Systems* (1966), we need to say a few words about the book's form. In a book on perception, one expects to find chapters on anatomy, physiology, brain issues, and so on. Gibson's book starts with a chapter on the environment. Moreover, when at the beginning of its second half it focuses on visual perception, there is another chapter on the environment (Chapter 10). So, Gibson spent an important part of the book talking about the environment (this is even more clear in Gibson, 1979/1986). Far from being a mere curiosity, these chapters reflect the aim of making the environment an integral part of perceptual theory. In other words, the environment is as important a part of the perceptual phenomenon as the organism. Thus, from the very structure of Gibson's book we can see that the focus is moving from intraorganismic considerations toward incorporating an embodied-embedded twist. This movement is more clear in the details of Gibson's philosophical maneuvers. We now turn to those.

The environment: Ecological optics

In what we have characterized as a movement toward embodiment in optics, Kepler developed a fully physical-mathematical model in which optics are understood in terms of the interaction of light and surfaces and in which the phenomenon of vision has no place. In 1966, Gibson developed a new understanding of optics that makes possible the study of vision in the same physical-mathematical fashion. Gibson's *ecological optics* is the first philosophical maneuver toward embodiment in vision.

Ecological optics is concerned with ambient light instead of being concerned with radiant light, that is, with the structure of the light in the environment and not in the sources of light:

> The only terrestrial surfaces on which light falls exclusively from the sun are planes that face the sun's rays at a given time of the day. Other surfaces may be partly or wholly illuminated by light but not exposed to the sun. They receive diffused light from the sky and reflected light from other surfaces. A "ceiling," for example, is illuminated wholly by reflected light. Terrestrial airspaces are thus "filled" with light; they contain a flux of interlocking reflected rays in all directions at all points. This dense reverberating network of rays is an important but neglected fact of optics, to which we will refer in elaborating that may be called ecological optics. (Gibson, 1966, p. 12)

The main idea is, then, that the ambient illumination does not solely depend on the influence of the radiant body (e.g., the sun or a lightbulb) in a given surface (e.g., the top surface of a table or the lateral surface of a building), but it depends on the light source plus the set of reflections and refractions the light undergoes as it interacts with all the surfaces of the environment. Each point of the ambient light array is differently illuminated depending on all these factors. Such a phenomenon generates a light structure that is different for any position the organism is situated within the environment and that is *specificational* regarding the layout of the surfaces in that environment—that is, the structures of light at each point specify the layout of the environment. In the case of vision, the environmental information needed for perception comes from these structures: "The environment consists of *opportunities* for perception, of *available* information, of *potential* stimuli" (Gibson, 1966, p. 23), and information is available thanks to the structures in the ambient light. The stimulus for perception depends on this ambient light and not on radiant light, that is, we need ecological optics and not physical optics to give an account of vision. According to Gibson (1966), this is a neglected fact in psychological sciences and the main reason of their lack of progress:

> The ecology of stimulation, as a basis for the behavioral sciences and psychology, is an undeveloped discipline. These sciences have had to depend on the physics of stimulation in a narrow sense. I believe that this situation has led to serious misunderstandings. (p. 21)

Any theory of perception based solely on Kepler's optics (physical optics) will fail to account for the nature of perception. So, a redescription of the behavior of light in the environment, that is, a new kind of optics, is needed for psychology and behavioral sciences. Gibson's redescription of the role of environmental light and environmental information in visual perception unlocks the possibility of the embodiment of vision (see Gibson, 1966, 1979/1986). In both Kepler's and Descartes' systems, vision was not part of the study of optics because physical optics were not able to describe the process of vision under the assumptions of the model. This is one of the reasons vision remained disembodied. Now, however, the ecological redescription of the ambient light allows for an embodiment of vision in which the interaction of organisms with the structured ambient light is the key to explaining the phenomenon and is also suitable for a mathematical model. So, the philosophical maneuver carried out by ecological optics enables the development of an embodied-embedded theory of vision.

The organism: Perceptual systems

Ecological information—of which ecological optics are an example—represent just one step toward embodiment in psychology and the cognitive sciences. One might accept the relevance of ecological information for perception but still think that the way in which organisms deal with it has to do with processing, computation, or another kind of teleological inner states. For example, one might claim that ecological information is represented in discrete inner entities (representations) within the mind/brain of the perceiving organism and that perception is explained by appealing to these inner entities. In this case, the explanation would be completely disembodied (i.e., Aristotelian; appealing to "little minds within the bodies"—as Aristotle appealed to forms—to explain bodies' behavior) even if ecological information were part of the equation. Thus, Gibson's philosophical maneuvers toward an embodied psychology needed a further step that defined organisms as embodied, that is, as complete bodies interacting with other bodies and their environment, and blocking the possibility of the appealing to inner/mental states as the cause or the explanation of that interaction. He accomplished this by considering the senses as *perceptual systems*:

> We shall have to conceive the external senses in a new way, as active rather than passive, as systems rather than channels, and as interrelated rather than mutually exclusive. If they function to pick up information, not simply to arouse sensations, this function should be denoted by a different term. They will be here called perceptual systems. (Gibson, 1966, p. 47)

We can find two redescriptions of the senses in this quote. First, senses are systems and not individual organs. The visual system, for example, is constituted by moving eyes situated in a moving head, situated on a moving body, and also by the brain, by the optic nerve, by the extraocular muscles, and so on. Put simply, the whole body constitutes the visual system—the exploratory skills of the organism, for instance, depend on the whole body. And second, perceptual systems are active and not passive. They are not only receiving stimuli but also are actively exploring the environment and picking up information. They are open and directed toward the environment. This fact allows for a different understanding of the organs implicated in the system.

> Instead of looking to the brain alone for an explanation of constant perception, it should be sought in the neural loops of an active perceptual system that includes the adjustments of the perceptual organ. Instead of supposing that the brain constructs or computes the objective information from a kaleidoscopic inflow of sensations, we may suppose that the orienting of the

> organs of perception is governed by the brain so that *the whole system of input and output resonates to the external information.* (Gibson, 1966, p. 5; emphasis added)

That is, taking senses as perceptual systems allows us to take the whole body and its interactions with the environmental information as the correct level of analysis of perception. No more inner states in charge of perception. No more Aristotelianism. Under this paradigm, to understand perception is to understand the organism-environment relation, to understand how the whole body resonates to the environment. In other words, the embodied scale is the ecological scale. By this ecological reformulation, Gibson achieved an embodied approach to psychology that followed the process initiated by Kepler and Descartes in optics and physics during the 17th century. As the with his predecessors, Gibson needed to redescribe the components of the phenomena—in philosophical terminology, he needed to develop new metaphysical foundations to perception—in order to be able to offer an explanation in terms of bodies and their interactions. Just as within the Cartesian paradigm (in physics), we do not find form and matter anymore, within the Gibsonian paradigm, we do not find an outer environment modeled by organisms in a series of teleological inner entities that are internally manipulated. In both cases we just find bodies interacting with other bodies and their environments and rules and laws to describe these interactions. In the case of Gibson's proposal, this is possible thanks to a new conception of environmental information and the perceptually skilled organism (see Gibson, 1966, 1979/1986). An organism, a body, taken as a whole, resonates with specifying environmental information. This is what makes the ecological approach an embodied approach. A questions still remains, though: What mathematical tools do we have to quantify the interaction between bodies and environments?

Perception–action loops and dynamic systems

The embodiment movement in the cognitive science, initiated by Gibson's ecological psychology, is a dramatic conceptual shift, just as was the embodiment movement in physics initiated by Descartes and Kepler. However, the shift would be sterile if it remained merely conceptual and was not accompanied by a substantial difference in the methodologies and tools used by these sciences. The methodological difference in early modern physics was deep: the one from qualitative to quantitative explanations. It was clear when Isaac Newton famously stated in the General Scholium of his *Philosophiæ Naturalis Principia Mathematica [The Mathematical Principles of Natural Philosophy]* (1687/1962)[6] that he did not frame hypotheses and that "to us it is enough, that gravity does exist, and acts according to the laws which we have explained" (p. 392). This is what sometimes has been called "saving the phenomena." Nevertheless, Newton tried to express that there is no need for postulating anything beyond the existence of a phenomenon or for pursuing further qualitative explanations once we have the power to explain and predict the motion and interactions of bodies. In other words, once you know the dynamics[7] of the system (i.e., how the system changes over time) you have

[6]This quote comes from Motte's translation (1962)—this translation was first published in 1729.

[7]Notice that we are using "dynamics" in the sense of change. Classically, Leibniz attributed the term *dynamics* to Newton's theory because it was a theory based on forces (δύναμις). These two senses are different although closely related (for the definition of motion—changes in the system—in terms of forces see Gal & Chen-Morris, 2013, pp. 187–188). Anyway, we are always going to use "dynamics" in the first sense.

an explanation of the phenomenon.[8] So, we contend that dynamics (motion, change over time) becomes the central concept for physical explanation after the embodied twist and that explanations are implemented by dynamic laws.[9]

The centrality of motion is clear both in Kepler (Gal & Chen-Morris, 2013, pp. 135–137) and in Descartes. For the latter, motion has both metaphysical and explanatory roles. Motion is the principle of individuation for bodies because without it, the universe would be an undifferentiated lump of extension. Similarly, motion determines the shape and size of bodies and, therefore, is the central explanatory principle in Cartesian physics. The French philosopher claimed that "all variation in matter, that is, all the diversity of its forms depends on motion" (Principles Part II, Art. 23; as quoted in Garber 1992, p. 307; see also Garber, 1992, pp. 303ff., Stein, 2004, p. 257). However, it is in Newton's works that the study of dynamics and motion, although with some significant differences from the Cartesian concept (DiSalle, 2004, p. 37), achieves a completely distinctive role in physics: a new mathematical tool, *calculus*, is developed for the study of change (for a deeper study, see Brackenridge & Nauenberg, 2004; Guicciardini, 2004). Calculus represents the mathematization of the underlying intuitions of embodiment, namely, a specific tool was required to give a correct account of the interactions between bodies over time. For example, for explaining the time one body needs to change its place, velocity, we use calculus (velocity is the first derivative with respect to time of the space an object travels). It is the change of the position of body with respect to another body (e.g., the Earth or a field) over some temporal interval. The mathematical description of the behavior of the bodies in these terms, that is, in terms of change over time, takes its modern form with the new tool of calculus. Thus, embodiment is not only a theoretical change but it also entails a methodological change.

Embodied cognitive science, initially via ecological psychology, introduces some new mathematical tools as well. *Dynamic systems theory* (DST) is one of them (Kugler, Kelso, & Turvey, 1980).[10] The central idea is that the perception–action loops constitute the correct unit of analysis of the perceptual phenomenon, and these perception–action loops are best explained using calculus. *Perception–action loops* are interactions between organisms and their environments. For example, a human is in a perception–action loop when she is searching for her eyeglasses. As she moves through the environment, her perception changes, which changes her actions, which changes her perception, and so on. In other words, perception constrains action while action constrains perception; they are two parts of the same loop. So, there is an ongoing perception–action loop when a given organism exhibits eyeglass-finding behavior. The primary explanatory aim of ecological psychology, in particular, and of an embodied cognitive science, in general, is to make the underlying mathematical laws that regulate this kind of perception–action loops explicit. Dynamic

[8]Some may object that Newton did not offer "explanations," a position endorsed by some contemporary scholars. A full discussion of this topic is beyond our scope, but we note that, for the historical Newton, the laws of motion and the law of gravity clearly offered "explanations." In the *Rules for the Study of Natural Philosophy*, which preceded the third book of the *Principia* (the book in which Newton deduced universal gravitation), Newton explicitly noted that he only employed causes that are "true and sufficient to *explain* their phenomena" (Newton, 1999, p. 794; emphasis added). This is not to say that Newton thought he could explain gravity in itself, but that is a whole other issue.

[9]This topic is worthy of a whole paper. However, for a matter of space, we do not address it in depth. If the brief discussion we offer here is not persuasive, the reader can take it as one of our assumptions until we develop a further elaboration elsewhere.

[10]We picked DST as an example, but other tools, close or not to DST, might be chosen as well—for example, matrix calculus to measure momentum of inertia tensor (see Shockley, Carello, & Turvey, 2004; Turvey, Burton, Pagano, Solomon, & Runeson, 1992).

systems theory is one of the mathematical tools used to reach this aim, and these laws typically take the form of differential equations. In this sense, the use of DST as a methodology is just the use of calculus in cognitive science.

Beyond the terminological resemblance to Newtonian dynamics, DST plays the same role that calculus played in early modern physics: it gives cognitive science the possibility of deploying a mathematical study of the interactions between bodies. As Newton's universal gravitation law explains an interaction (force) between two bodies without appealing to any inner entity of the body, the HKB Model (see Kelso, 1995) explains the interaction between two bodies engaging in rhythmic behavior—like walking, clapping, rocking in rocking chairs, and so on. In both cases, the introduction of a new mathematical tool allows for the explanation of the dynamics of the whole system with no reference to substantial forms, in the case of early modern physics, or representations, in the case of cognitive science. In both cases, calculus is the methodological face of embodiment, and the intent is to replace the explanatory structures that came with the prior conceptualization of the phenomenon.

Embodiment in cognitive science, as we said at the beginning of this section, boils down to taking bodies and their relation with other bodies and their environments (i.e., perception–action loops) as the correct unit of analysis in order to explain cognitive behaviors. This is exactly the same movement Descartes led in early modern physics but that he blocked in the sciences of the mind. Cognitive science, 5 centuries later, is going against both Aristotle and Descartes at the same time and is using new mathematical tools—derived from Newton's calculus—to do so. The embodied movement in cognitive science, started by Gibson and his philosophical maneuvers, is the same one that happened during the 17th century in physics. Thus, embodiment is not a feature of the cognitive sciences alone but a philosophical maneuver at the very base of the sciences such as we understand them nowadays.

Gibson, mechanism, and Aristotelianism

Before concluding, we must acknowledge that we are disagreeing with the analyses of several Gibsonian psychologists, such as Lombardo (1987), Costall (1995), and Reed (1996). First, for these scholars, our lumping of Gibson with, say, Newton and Kepler is inappropriate because Newton and Kepler, unlike Gibson, are mechanists. Second, their positions suggest that it is inappropriate to attribute anti-Aristotelian moves to Gibson because Gibson is an Aristotelian. We agree that Newton and Kepler are, in many ways, mechanists and that Gibson is, in many ways, an Aristotelian. However, the way in which Newton and Kepler are mechanists is not in conflict with the ways in which Gibson is an Aristotelian (i.e., in his views on the life sciences [Lombardo, 1987]). Let us extend these points a bit.

Some well-known ecological psychologists (e.g., Costall, 1995; Reed, 1996) claim that the Gibsonian approach to psychology is openly anti-mechanistic and, thus, anti-modern. The foundation for this claim is that a mechanistic ontology is incompatible with some crucial features of mental phenomena. In other words, although mechanistic principles can account for strictly physical phenomena, they are unhelpful in accounting for the mental. This inability of mechanist ontology to provide an explanation for mental phenomena prompted scholars like Lombardo (1987) to try to ground ecological psychology in premodern, Aristotelian concepts (e.g., functions, teleology).

However, we tried to show (albeit briefly) that there is nevertheless a deep similarity between the philosophical *maneuvers* carried out by Gibson and those carried out by early modern scientists. The similarity has gone unnoticed because the *mechanization of the world picture*—a historiographical thesis that is more than a half century old—has been largely misunderstood and certainly exaggerated.[11] For example, some scholars cite the idea that early moderns saw the universe as a great big clock and so conceived of animals (not to mention inanimate objects) merely as assemblages of parts, not unified wholes. But the clock metaphor is more complex. It certainly suggested that both animals and inanimate objects were composed of *ontic* parts, but it also suggested that those parts could not be *understood* independent of the wholes of which they were a part. Robert Boyle, for example, who coined the term *mechanical philosophy* and repeatedly invoked the clock metaphor, wrote, "I consider … that the faculties and qualities of things [are] (for the most part) but certain relations, either to another, as between a lock and a key; or to men, as the qualities of external things referred to our bodies, and especially to the organs of sense …" (Boyle, 1772, Vol. 3, p. 479). The lock-and-key metaphor makes explicit what is only implicit in the clock metaphor: a key does not function as a key (it *is not* a key) without a lock; a lock is not a lock without an appropriate key. The mechanistic ontology does entail that the lock-key combination is decomposable into two objects, but it does not entail that the functions of those parts can be understood independent of one another. Only the whole gives meaning to its parts. The same goes for the clock metaphor: a gear is not a ratio-wheel outside a clock; really, it is not even a gear unless it can interact appropriately with some other appropriately shaped object. *This* approach to explanation, we claim, is common to both Gibson and the early moderns.[12] Embodiment is an *explanatory shift*, an appeal to relations between bodies and environments as the bases of explanation. It is shared by Gibson and early modern mechanists and, in early modernity, was a distinctly anti-Aristotelian explanatory strategy.

There are other features of the clock metaphor that are not apt to Gibson, for example, the stress on blind necessity and the underdetermination of the clock mechanism by the timekeeping function. However, we do not claim that Gibson is similar to early modern in all ways, only in the stress on embodiment as we defined it. In our view, the tensions between Gibson and early modern mechanists highlighted by Reed and Costall can be traced to various features in the two belief systems (e.g., appeal to teleology or ontology of exclusively geometrical properties) but *not* to their shared emphasis on understanding objects in their environments. Although Gibson holds some Aristotelian ideas regarding the life sciences (Lombardo, 1987), this says relatively little about the concept of embodiment defined here. Embodiment is the rejection of explanations in terms of *inner teleological states*, such as substantial forms. This rejection is what Kepler, Descartes, and Newton instantiated in physics and cosmology. In the sciences of the mind, such a rejection entails the repudiation of mental representations as explanatory entities. Gibson championed this in his 1966 book. Thus, he championed

[11] See H. F. Cohen (1994), Chapters 1 and 2.

[12] Boyle's sentiment also belies now dated historiographical statements like "[Modern science substituted] for our world of quality and sense perception, the world in which we live, and love, and die, another world—the world of quantity, of reified geometry, a world in which, though there is a place for everything, there is no place for man" (Koyré, 1965, p. 23). Boyle clearly thought the world of quality and sense perception is part of the natural world and explicable in similar ways. This point, and the ways in which early moderns dealt with the sciences of the life and mind, is explored by the current vanguard of early modern scholarship (see, e.g., Distelzweig, 2013; Manning, 2015).

an anti-Aristotelian strategy. This strategy is compatible, however, with other plainly Aristotelian commitments at different levels or regarding some different issue (e.g., regarding functional states or a nonreductively-geometrical ontology).

Further consequences

As a last remark, it is worth noting one of the main consequences of embodiment in cognitive sciences: the horizontality of explanation. Once embodiment and the new mathematical tools are applied, any phenomenon is explained in the same terms independent of its nature. The movement of the planets is explained by appealing to a law of interaction, as is the approach of a climbing bean to a climbing pole,[13] the steering to a target when navigating in a little crowed environment (Fajen & Warren, 2003), hummingbird feeding (Delafield-Butt, Galler, Schögler & Lee, 2010), interpersonal coordination (Schmidt & Richardson, 2008), sentence processing (Olmstead, Viswanathan, Aicher, & Fowler, 2009), and so on. Thus, any behavior (in the broadest sense) of any entity is explained by a law of interaction that appeals to the dynamics of a system of bodies as wholes. The scientific explanation is, thus, horizontal.

This horizontality was depicted by Turvey (1992) as *strategic reductionism*. There is no ontological reduction but a reductionism of the means of explanation used in sciences to give an account of different phenomena. The embodied movement in cognitive science, and especially its use of calculus, enables the explanation of cognitive phenomena in physical terms. Insofar as cognitive science was the last citadel of qualitative explanations, the embodied twist allows for the same kind of explanation in every science, that is, allows for horizontality of explanation. The horizontality of explanation we propose here is different from, but compatible with, van Dijk and Withagen's (2014, 2016) *horizontal worldview*. Their horizontal worldview is an ontological commitment contrary to the dominant vertical worldview in most sciences. Put simply, according to the vertical worldview, the world has a layered supervening ontology in which building blocks at lower layers constitute entities at higher layers (e.g., atoms constitute molecules, which constitute cells, which constitute organs, etc.). Under this kind of worldview, scientists tend to abstract from the target phenomenon to lower or higher levels to provide an explanation. On the contrary, according to van Dijk and Withagen, adopting a horizontal worldview would allow for explanations focused on the phenomenon at its own scale, where the attention is directed to the interactions at the given scale and not to higher or lower ontological levels. The horizontality based on strategic reductionism (Turvey, 1992) we propose here has no specific ontological commitments. We claim that embodiment provides a way to explain phenomena at different scales by using the same tools, methodologies, and strategies. In this sense, explanation is horizontal, namely, all phenomena, whatever scale they belong to, may be explained by the appeal to laws of interaction between the entities that constitute such a phenomenon at that given scale.

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[13]An unpublished technical report of this phenomenon can be found at http://www.um.es/documents/2103613/2107123/Technical+report.pdf/ed976b1e-e2f0-47b6-be33-a04ddf283baf

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