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COVARIANCE/INVARIANCE: A COGNITIVE HEURISTIC IN EINSTEIN'S RELATIVITY THEORY FORMATION

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Relativity Theory by Albert Einstein has been so far little considered by cognitive scientists, notwithstanding its undisputed scientific and philosophical moment. Unfortunately, we don't have a diary or notebook[i] as cognitively useful as Faraday's. But physics historians and philosophers have done a great job that is relevant both for the study of the scientist's reasoning and the philosophy of science. I will try here to highlight the fertility of a 'triangulation' using cognitive psychology, history of science and philosophy of science in starting answering a clearly very complex question: *why* did Einstein discover Relativity Theory?

Here we are not much concerned with the unending question of precisely *what* Einstein discovered, that still remains unanswered, for we have no consensus over the *exact* nature of the theory's foundations (Norton 1993). We are mainly interested in starting answering the '*how* question', and especially the following sub-question: what (presumably) were his *goals* and *strategies* in his search?

I will base my argument on fundamental Einstein's publications, aiming at pointing out a theory-specific heuristic, setting both a goal and a strategy: *covariance/invariance*. The result has significance in theory formation in science, especially in concept and model building. It also raises other questions that go beyond the aim of this paper: why was he so confident in such heuristic? Why didn't many other scientists use it? Where did he keep such a heuristic? Do we have any other examples of similar heuristic search in other scientific problem solving?

1 Orientative heuristics

In Einstein's publications, we find a lot of support for *abstraction heuristics* (Nersessian 1992): *analogical* and *imagistic reasoning, thought experiment, limiting case analysis*. We can also trace other, more theory-specific heuristics that I call *orientation heuristics*[ii]: *inner perfection*[iii], *explain-or-assume*[iv], *explanatory correspondence*[v] and *covariance/invariance*[vi]. I will now concentrate on the last ones, as they are at present less investigated, highlighting their common peculiarities before showing in some detail *covariance/invariance* in Einstein's work.

Following Herbert Simon (*e.g.* Simon 1977; Langley *et al.* 1987) these are *heuristics* properly speaking, *i.e.* not foolproof, systematic procedures, but just rules-of-thumb. The scientist (Albert Einstein, in this case) uses them to formulate theories because, unfortunately, he has not at his disposal any general purpose, fail-safe algorithm for this purpose. Not even the scientist, realistically, has enough cognitive and time resources to judge trial-and-error generated hypotheses using strict *adequacy requirements*. Anyway, he can rely on some *cognitive devices* governing his construction of hypotheses, no wonder therefore that the hypotheses constructed actually meet, but only to some degree, the requirements (Zahar 1989). So, not only do we have a theory, we also have a *research program* designed to improve such degree. And in it, such theory is but a step.

Unlike abstractive, the four orientation heuristics are strongly *reflexive*. In first approximation, they are cognitive tools stating the desiderata of a privileged route to knowledge.[vii] In other words, they are first of all knowledge of knowledge building, judged as a reliable receipt in scientific inquiry (*research principles*). So, in some sense, it is matter of *metacognition* about how to use available cognitive resources strategically and towards what goals.

But neither a successful result, nor *tout-court* a result can be a priori guaranteed for each of such heuristics, notwithstanding they are together so selective as a guidance, as to *direct* the scientist to one (or maybe very few) possible results, once cognitive *initial condition* are stated (*ceteris paribus*). Their outputs are far narrower than abstractive ones' (*output rigidity*). But they have also another major peculiarity: they are *context sensible*. While we can imagine a very general usability of abstractive heuristics, the orientation ones are strictly linked to theory building and refining. Moreover, their use is possible just in those cases where theory is already rich enough (*input rigidity*). Indeed, orientation heuristics, literally, mould parts of an already available theory (e.g. concepts or models), producing a sort of 'theory mutation', to be carefully tested afterwards in order to be accepted. But it is now worth to further investigate the relationship between heuristics, on the one side, and models and concepts, on the other.

As it is well known, we have a lot of different 'kinds' of *models*. Among them, we find iconic analog or *picturable models* (as thought the 'Duhemian' in Hesse 1966), abstract replicas or *physical systems* (Suppe 1972), *set-theoretic* or *state-space structures* (van Fraassen 1980), representation driven by the process of understanding or *mental models* (Johnson-Laird 1983). Anyway, following Giere (1994), we can try to *identify models in philosophers' model-theoretic accounts of theories with the concepts in cognitive scientists' accounts of categorization*. In so doing we fall into a historically very difficult subject about: the nature of concepts.[viii]

In fact, here we recently find a major transition from the *classical* (definition-based) to the *prototype view* (based on a graded structure, with some variants) (Smith and Medin 1981). Adopting a *prototype view* also for theory models, as proposed by Giere, some laws (particularly the second Newton's law) function as a *recipe for constructing a model family*. It supplies a radial structure, some similarity criteria among different models, the guide lines for the construction of new members of the same family, the idea itself of a family, and so on. Indeed, this is pretty similar to what cognitive scientists are doing about the role of theory with concepts (Carey 1985; Lakoff 1987; Murphy and Medin 1985; Neisser 1987).

But, in order to focus on theory change, as it is necessary to deal with a so relevant 'conceptual revolution' as Relativity Theory, we should better consider the so called *non-model* of categorization proposed by Barsalou (*e.g.* 1989; 1993), for it appears more suitable to treat closely conceptual dynamics. Taking into account the differences between *folk categories* and *scientific theories*, the fundamental idea could be stated in this way: to shift the focus of our attention from the mental product (concept or model, and maybe law itself), rather unstable across different theories (e.g. from Ptolemaic to Copernican, from Newtonian to Einsteinian), towards the underlying cognitive processes, suited with regularities still not well known, localized inside a context of activation.

In so doing, the problem of what *object* to have in mind at a certain moment is now converted into the problem of what *process* has been activated in modifying mental representations available in the given *context* of activation (personal experience, background knowledge, disciplinary background, etc.). And the logic relationship between two following conceptualizations is also converted in a cognitive dynamics. I cast as a hypothesis that we shall find, with more empirical research and theoretical comprehension, that cognitive processes at work in scientific theory change are well represented by *orientation heuristics*.

Fig.1 Orientative heuristics

Heuristics versus algorithms

Epistemological weakness: not foolproof, systematic procedures, just rule-of-thumb.
Cognitive nature: not logical adequacy requirements, just cognitive devices.
Trial-and-error: not guaranteed results, just a tentative way, possibly of no use at all.

Orientation versus abstraction heuristics

Reflexivity: knowledge about knowledge building.
Unwarrantness: a result is not guaranteed.
Directionality: result (almost) uniquely determined by cognitive initial conditions & ceteris paribus (*output rigidity*).
Content sensibility: their usability is limited to theory building or refining (*input rigidity*).

Heuristics versus theory concepts and models

Process nature: heuristics are underlying subroutines of the cognitive process transforming concepts and models available in the context (inputs) into partly new ones (outputs).

It is now time to look in depth at the more powerful heuristic Einstein used to direct his search. It is a heuristic very characteristic of Relativity Theory: *covariance/invariance heuristic*.

2 Covariance/invariance heuristic and its reliability

Here I will only discuss *covariance/invariance*, a guideline Einstein is assumed to have actually followed all over the Relativity Theory formation period (1905-1916).
Covariance/invariance heuristic is a two-branch search governing guideline.[ix] According to it, the scientist is guided at the same time:
(a) to represent each relevant physical quantity (involved in fundamental equations) in a *co*-varying manner, *i.e.* allowing its measure to change[x] from one reference system to another, exactly in the same way as do coordinate (differential) measures (*covariance*) [xi];
(b) to draw a relation among such quantities, via an equation able to stay *in*-varied while changing system of reference (*invariance*).[xii]
Following such receipt, Einstein is driven toward a physics in which we have fewer absolute quantities (none, in his mind). And any observer in it is expected to be able to find out exactly the same equation: only if this requirement is met, in Einstein's view, can such equation be a fundamental law of physics representing a regularity in nature.[xiii]

Fig.2 Covariance/invariance heuristic

Two-branches

Branch a - covariance:
measures change (transform) from coordinate system to coordinate system exactly as coordinate do.

Branch b - invariance:
physics' fundamental relations (equations) have not to vary as coordinate system changes, in order to represent nature's regularities.

Relativity: we cannot attach a physical signification to concepts as absolute rest, absolute inertial frame *et sim.*, because the reference system we actually use *affects* our measures.
Equivalence: every system is equivalent to represent nature's regularities, because we attain invariance of relations among measures *while* looking for covariance among measures (and vice versa).

Indeed, we find much evidence of Einstein's use of *covariance/invariance* as a *cognitive rule of thumb*, and not as an *inflexible adequacy requirement* of his hypotheses. He schedules his search in following steps, each being characterized by a specific satisfying degree, and he also admitted future theories would better satisfy this requirement (*e.g. Foreword* to Jammer 1954). We now examine three main evidences, among many others, leaving apart every technical detail.[xiv]

1) Einstein (1905) starts with this formulation of his Principle of Relativity: *the phenomena of electrodynamics as well as of mechanics possess no properties corresponding to the idea of absolute rest. They suggest rather that* (…) *the same laws of electrodynamics and optics will be valid for all frames of reference for which the equations of mechanics hold good. We will raise this conjecture (the purport of which will hereafter be called the 'Principle of Relativity') to the status of a postulate*. As soon as we take light speed[xv] as a universal constant (stating a new fundamental law, indeed), we see that the only way we can actually measure time intervals with clocks (and space lengths with rods), is a relativistic one. So, he concludes, *we cannot attach any absolute signification to the concept of simultaneity*. In other words, if we assume laws to be invariant, measures of (almost) every physical quantity come out to be relative. Right in so doing, however, we get the right transformations that leave Maxwell's equations exactly unvaried, as far as *inertial systems* are concerned (*i.e.* for a non-accelerated system and all those systems moving at a constant speed with respect to it). This is the *core* of Special Relativity, and as soon as we understand how fundamental quantities actually *co*-vary, we can get fundamental relations that stay *in*-variant (for some class of systems, of course): the two branches are connected in just one heuristic.
The concepts of *rest* and *simultaneity*, among others, come out immediately with an irreversible mutation.

2) Einstein (1911) considers two systems: K chosen to be stationary in a homogeneous gravitational field, and K' moving with uniform acceleration (equal to the gravitational acceleration experienced by K) in a gravitation-free space region. Then, he observes, *relatively to K, as well as relatively to K', material points which are not subjected to the action of other material points, move in keeping exactly with the same equations*. In this case the two systems are *physically exactly equivalent*, and then *we cannot attach any absolute signification to the concept of acceleration*, either. But, as soon as he dismisses this absolute, he finds that: if we take K and K' to be equivalent with respect to *all* physical processes, *we arrive at a principle which, if it is really true, has great heuristic*

importance. For by theoretical consideration of processes that take place relatively to a system of reference with uniform acceleration, we obtain information as to the career of processes in a homogeneous gravitational field. In other words, symmetry among reference systems is strictly tight (or, better, *equivalent*) to gravitational force existence. As a consequence, Einstein is led to investigate gravitational field regularities in parallel with accelerated reference systems, and in a few years he will discover General Relativity.
Concepts such as acceleration and gravitational force are now irreversibly mutated, as it is for every model we can construct about a physical system embedded in a gravitational field.

3) Einstein (1916) notes that *all our space-time verifications invariably amount to a determination of space-time coincidences.* (…) *the results of our measurings are nothing but verifications of such meetings of the material points of our measuring instruments with other material points, coincidences between the hands of a clock and points on the clock dial, and observed point-events happening at the same place at the same time*. In other words, Einstein argues, we have to represent any fundamental physical quantity with a *tensor*, that is a mathematical object composed by functions of (generalized) system coordinates that change in value, system by system, exactly as system coordinates do. And then we have to draw an equation among such expressions in a *tensorial* form, *i.e.* in such a manner that it is either true in all systems, or false in all systems (e.g. van Fraassen 1989). Anyway, hard as a job it could be, it is enough for us to work in one whatever system, and then we have the equation valid for everyone.
With this step, the mental representations of any physical quantity and measure are forever radically mutated. We can also say that here starts the contemporary *theoretical physics*, a new way of work in physics and a new scientific theory (discipline), indeed.

We have to note, however, that there is a short period during which, in confronting a mathematical problem particularly hard to be solved, he thinks to have found good physical reasons for abandoning *covariance/invariance*.[xvi] But he soon returns on his way, deciding *not to attribute any reality to reference system* (letter to Ehrenfest, December 26, 1915, cit. in Pais 1982), and lastly recognizing his precedent *mistakes* (letter to Lorentz, January 1, 1916, cit. in Pais 1982). So, we can trace such heuristic as the more reliable guideline along his (at least) twelve-year search for relativity.

3 Methodological conclusions: localization and internalization

It is now worth adding some philosophical remarks, taking advantage of our heuristical formulation of Relativity Theory formation.
It is methodologically relevant to look at *covariance/invariance*'s route in getting through intrinsic measure's relative dependence, and gaining an invariant equation. It is possible to gain invariant equations only by making measuring procedure dependence *explicit*. Then, casting light upon this *relativity*, we acquire information relevant to the discovery of fundamental laws, from system *whatever*.
This is really a second face of Relativity Theory, *reflexive*, as it concerns *knowledge about knowledge relativity*. It is quite often disregarded by methodological studies, though having a general meaning as we can now easily recognize. *Invariance* is not the last defense against otherwise overflowing relativism or subjectivism, as it is usually understood (especially outside physics). It is better thought of as a direct consequence of transforming an *absolute relativism* into a scientific program on *knowledge relativity*.
We can now look further at Relativity Theory from the methodological point of view.
Of course, description *varies* with reference (how should it be otherwise?). But we have to observe:
(a) We can try to find exactly *how* this happens (Einstein *gets* it in a pretty general family of

physical phenomena, indeed); and

(b) We luckily have not to exhaust *all* systems, as it is enough to stay in the one we *freely* choose (we can choose the easiest to compute, as a matter of fact). Generally speaking, there is not any 'from-nowhere view' (Eddington 1920, Nagel 1986), but, so to speak, each 'from-somewhere view' can be sufficient to grasp nature's regularities, if only we get inside *sight processes*, *i.e.* inside our nature itself. Epistemology has to be *naturalized* in order to escape the dichotomy *absolute* vs. *relative*, and grasp some reliable knowledge. And philosophy of science meets defintely cognitive science.

So, (Kantian) *possible* experience (and its absolute categories and concepts) becomes an *actual way of being* of existing world: the naturalistic formation process of *human* knowledge. Along with this view, in effect, our knowledge appears intrinsically *embodied* (Lakoff 1988), *i.e. localized* in the ground of what we name 'mind' *in his actual biological functioning in a physical and social environment*. For so strong a reason, our most general laws should be better thought of as 'glocal' (general-local) rather than as *tout-court universal* statements. We actually have, and cannot have but, *human sized science*, *i.e.* science designed along with our *evolved nature and society*, and so intrinsically and inevitably rooted. And exactly for this reason, it is attainable, understandable and fruitful. Besides the *genetic mark* of local subject, we can only hope to keep in science also nature's *regularity marks*, through reliable methods settled by both biological evolution and shared cognitive efforts.

We can also recognize that the core methodological message of this heuristic is equivalent to the concept of *method internalization* (Shapere 1987). Along with this methodological heuristic principle, *every aspect of our beliefs ought, wherever possible, to be formulated, and to be brought into relation to well-founded beliefs, in such way that it will be possible to test that aspect*. So, claims Shapere, there has to be a sort of *coevolution* between, on the one hand, goals and methods and, on the other, our beliefs about nature. Moreover, if it is true, we can also suppose a similar coevolution between (reflexive) knowledge about our beliefs and knowledge about (external) nature. And we should also find some traces of such coevolution in the context of knowledge about beliefs, largely falling in what we commonly name *culture*.

Fig.3 Methodological conclusions

Localization of knowledge

Embodiment: our knowledge is in some way a causal consequence of the nature of human biological properties and the experience of functioning in a physical and social environment.

Glocality: we have to recognize our law pretended to be universal, are at most 'global-local'. Their rootedness is the cause of their usability.

Internalization of method

Reflexivity: every aspect of our beliefs ought, wherever possible, to be formulated, and to be brought into relation to well-founded beliefs, in such way that it will be possible to test that aspect.

Coevolution: goals and methods co-evolve with beliefs about nature. Maybe, there is also a coevolution between (reflexive) knowledge about beliefs and knowledge about (external) nature.

So, In conclusion, I don't see *covariance/invariance* only as the solution to a specific problem confronted by Albert Einstein, but also as a more general way of *problem solving* in constructing reliable knowledge: a typical scientific 'self-therapy' of such a philosophical 'disease' as knowledge relativity.

4 Outlook in heuristic study

Once more, as a matter of fact, a heuristics works as a useful cognitive tool *in the search for the general laws of nature* (Einstein 1917). Actually, it warrants a (rather) *reliable belief-forming process* in science, as requested by Papineau (1993), at least in a simonian, *satisficing* way.

It is also well known that Einstein has always preferred *theories of principles* rather than *constructive theories* (*e.g.* Einstein 1948), and a constructive theory was relativity theory in his mind. In other words, instead of empirically firm hypotheses from which *to construct* a full theory, he tried to state some very general (often philosophically based) physical principles from which *to deduce* empirically testable hypotheses. I think that such *principles* are the theory constituents closest to *heuristics* and in developing a theory compatible with the (epistemologically theoretic) *principle* of relativity, he is actually using the (cognitively empirical) covariance/invariance heuristic. So, while exploring this one and the other Relativity Theory *orientation heuristics*, no wonder we also reconstruct the very theory content, and the encapsulated gain of knowledge. In tracing Einstein's heuristic path, we even an insight in what the Einsteinian route Relativity Theory is a step of, possibly well above his actual attainments. In a sense, we can have a look beyond Einstein's conquest. But the questions I sketched at the beginning still remain: we should still explain why he was so confident with such heuristics, where he kept them and why so many others did not. In my opinion, the main reason why Einstein achieved Relativity Theory, while a lot of others were working just around him[xvii], is a matter of heuristics. Questions about model and concept generation should then be answered in terms of the underlying heuristic reasoning.

If this picture is fairly correct, we should figure Einstein had a far better definition and a more consistent use of relativity *orientation heuristics*. He succeeded in reassessing basic concepts from common sense, through a convenient scheduling of all such heuristics according to a *satisficing* rationality along a highly ambitious, long-term inquiry. But a very strong motivation it was indeed needed during all his life-long work, indeed. The cognitive sources of such tools and styles of reasoning as heuristics, and emotional source of such motivations, in my opinion, should be found in what Einstein himself named (referring to religions) *powerful traditions* (Einstein 1939). In other words, Einstein could draw heuristics from his culture: epistemological backtrack of relativity, disciplinary tradition and cultural milieu. In fact, relativity appears as a key *fil rouge* (a holtonian *theme*) in philosophy, physics and culture at his time, and in his religion, too (Cerroni forthcoming). Only in considering all such aspects of Einstein's work, we could try to answer the last goal question: *why* did he discover Relativity Theory?

Far more research is still needed in order to get a deep insight into human culture, the peculiar product of such an 'evolutionary expert system' as we are. However, while investigating the actual cognitive processes of scientists' reasoning, we will gain an insight into the psychology of reasoning, the philosophy of science, and culture as well.

NOTES

[i] We are still waiting for the publication of Collected Papers from material collected at Hebrew University in Jerusalem, Mudd Manuscript Library at Princeton University, and Mugar Memorial Library at Boston University.

[ii] This is done according to an intuition by Immanuel Kant (1786): (…) *in the empiric use of our intellect and reason, other heuristic thought methods are still hidden such that, if only should we cautiously extract them from experience, they should certainly enrich philosophy with some useful maxim even for abstract thinking*. For an overview on all these heuristics see (Cerroni forthcoming).
[iii] See (McAllister 1996; Mamchur 1987). Very often cited by scientists themselves is *simplicity*, *elegance* or *thought economics* (*e.g.* Mach 1883). However, these are but elements ('sub-heuristics') of such master heuristic. *Inner perfection* aims at gaining coherence between what is already stated in the available theory and what is thought to be a relevant reference in scientist's mind. So, in satisfying the following heuristics scientist tries to fulfill, in his personal view, some *inner perfection*, too.
[iv] See (Earman and Glymour 1978; Mamchur 1987; Petroni 1990; Zahar 1989). As Earman and Glymour state it, scientist is often driven to think both that *what he cannot do cannot be done* and that *what is possible is also necessary*. So, from a psychological point of view, we can conclude that he tries to *assume* as new theoretical assumption of a 'mutating theory' what he thinks is important *and* not-*explained* by the available theory.
[v] See (Fadner 1985; Koertge 1973; Krajewsky 1977; Nickles 1987; Popper 1934; Post 1971; Radder 1991, Zahar 1989). As Einstein himself stated it, the new theory has to be built in such a way as to become exactly the already available and well established one, in some particular case family: the already successfully tested one.
[vi] For *covariance* as a heuristic, see (Zahar 1989).
[vii] Just to give an idea, we can sketch them in this quick way, respectively: 'you have to remove inconsistencies, pushing symmetries and compactness in the limelight', 'you have to assume as new theory building blocks those strong evidences you are not able to explain inside the old one', 'you have to preserve previous, well confirmed knowledge as limit case of the new', 'each reference system has to be equivalent in order to gain physical knowledge'.
[viii] For a review see (Cerroni forthcoming, chapters 2-3).
[ix] I use *covariance* and *invariance* as methodological terms following the intuition of Reichenbach (1927), in a way I think it is very close to Einstein's mind. For the contemporary technical use of them in connection with *covariance group* and *symmetry group*, see the excellent book by Friedman (1983).
[x] We can equivalently think of such change either as an (*active*) transformation between coordinates system (*e.g.* as from Cartesian to polar ones), or as a displacement (*diffeomorfism*) from point to point in the same coordinate system (*e.g.* changing origin, speed, acceleration) (*passive transformation*). We can also equivalently figure *coordinate systems, frames of reference* or *relative spaces*. All this is compatible with Einstein's view, following authoritative Norton (*e.g.* 1989).
[xi] An apparent exception is gravitational energy, but it doesn't affect the otherwise generality of the heuristic, as it is due to the intrinsic non-linearity of gravitational field, being itself a source of gravitation.
[xii] We have also to add that *branch-b* is equivalent to the requirement that such equations have to be either true in all systems or false in all systems (van Fraassen 1989), thus maintaining exactly the same physical solutions (*invariance under symmetry*). For physical (*i.e.* not mathematical) meaning of *covariance/invariance* in Einstein's view, see (Norton 1992).
[xiii] Anyway, some observer can arrive at a fundamental law of physics in an overwhelming easier way.
[xiv] For a reference, see (Landau and Lifšits 1973; Misner *et al.* 1973; Torretti 1996; Weinberg 1972).
[xv] Remember that this constant is critically present in Maxwell's fundamental equations of electrodynamics: if it was not a constant over every coordinate system, Maxwell's equations themselves should heavily change from system to system, thus not being *fundamental laws*.
[xvi] To put precise dates on the period during which Einstein shows not having doubts on abandoning

general covariance requirement, we can follow Norton (1986): from 1913, mid-August to 1915, mid-July. See also (Earman and Glymour 1978) and (Pais 1982).

[xvii] First of all, we think of Ernst Mach, Henri Poincaré and Hendrik Lorentz. Many other highly rated scientists, too, were working on relativity sometimes together with Einstein himself: Joseph Larmor, Hermann Minkowski, Max Planck, Gregorio Ricci Curbastro, Tullio Levi-Civita, David Hilbert, Hermann Weyl, Richard Ch. Tolman, Arthur S. Eddington, Karl Schwarzschild, Max Abraham, Adriaan Fokker, Gunnar Nordström, Gustav Mie and others.

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