Springer
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London
Milan
Paris
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2002

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Symbol and Physical Knowledge

On the Conceptual Structure of Physics

Springer

which would have a difficult time defending itself against the reproach that it represents a variant of metaphysical substantialism.

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5. Heinrich Hertz and the Concept of a Symbol

Andreas Hüttemann

In a recently published article A. Nordmann highlighted the fact that Hertz considered it as the greatest pleasure of scientific research to be "alone with nature" and to learn "directly from nature" (see Nordmann, 1998, p. 156). Hertz contrasts this being on his own with nature with the "disputes about human opinions views and demands". (see Nordmann, 1998, p. 156). It is this contrast between nature on the one hand and human beliefs etc. on the other that is fundamental for his central epistemological pursuit: the attempt to sort out which features of our theories can be attributed to nature as opposed to those which depend on us. I will discuss the various writings in which Hertz touches this subject.

1 Hertz on Helmholtz's Theory of Signs

The context in which Hertz discusses his epistemological question for the first time is Helmholtz's theory of signs. Hertz was particularly impressed by the claim that the structure of the eye partly determines what is perceived.

In a newspaper article on Helmholtz's 70^{th} birthday in 1891, Hertz calls Helmholtz's research in physiology one of his main achievements. He characterizes this research in terms of questions that eventually lead to his own interests:

> "How is it possible for vibrations of the ether to be transformed by means of our eyes into purely mental processes which apparently can have nothing in common with the former; and whose relations nevertheless reflect with the greatest accuracy the relations of external things? In the formation of mental conceptions what part is played by the eye itself, by the form of the images which it produces, by the nature of its colour-sensations, accomodation, motion of the eyes, by the fact that we possess two eyes? Is the manifold of these relations sufficient to portray all conceivable manifolds of the external world, to justify all manifolds of the internal world?"[1]

These questions concerning visual perception can be asked with respect to all knowledge. Thus Hertz continues:

[1] See Hertz (1896) p. 336. It should be noted here that Hertz uses the concept of an *image* to characterize those items that are not only determined by nature but also by some features of the eye. This is noteworthy because Helmholtz himself prefers the notion of *sign* in this context. Helmholtz (1896), p. 586.

> "We see how closely these investigations are connected with the possibility and legitimacy of all natural knowledge. The heavens and the earth doubtless exist apart from ourselves, but for us they only exist in so far as we perceive them. Part of what we perceive therefore apertains to ourselves: part only has its origin in the properties of the heavens and the earth. How are we to separate the two?" (See Hertz 1896, p. 336/7.)

Nature is accessible to us through perception only. The question concerning the exact borderline between what among our representations, perceptions or ideas is grounded in nature in contrast to what is determined by ourselves is the epistemological question that Hertz deals with in his writings on both electrodynamics and mechanics – his central epistemological question. Even though this newspaper article was written in 1891, considering the fact that he connected his question with the theory of signs, which he presumably came across much earlier, combined with his remarks quoted at the very outset of the paper, we might very well conclude that this epistemological question was something that was on his mind for a long time before the 1890s.

In what follows I intend to show that Hertz's considerations concerning the comparison of theories and the introduction of the concepts of symbol and image ought to be seen as attempts to answer this central epistemological question. Hertz tried to determine the borderline between what we can legitimately attribute to nature and what has to be counted as our own construction.

Hertz's reflections on the comparison of electrodynamic theories are a first attempt to invent an appropriate terminology to solve this question. It does not yet rely on the concepts of symbol and image.

2 The Comparison of Electrodynamic Theories

In the introduction to *Electric Waves*, Hertz indicates what kind of understanding he has gained at the beginning of the 1890s of his own experimental and theoretical research. On the basis of the work done by Helmholtz, Hertz had tried to compare the theories of Weber, Helmholtz and Maxwell. His experimental research in this area was decisive for the ultimate acceptance of Maxwell's theory of electrodynamics.

The second part of Hertz's introduction summarizes what he takes to be his main achievements with regard to his theoretical investigations of electric waves. His starting point is the question "What is it, that we call the Faraday-Maxwell theory?" (see Hertz, 1962, p. 20). In order to answer his question he draws a distinction between the representation (Darstellung) and the content (the English text uses "inner significance" as a translation for "Inhalt") of a theory. Hertz distinguishes three representations of Maxwell's theory: Maxwell's [illegible]

Helmholtz's electrodynamics and his own. All of these are representations of the *same* content. What all of these representations have in common is the system of Maxwell's equations. For a representation to be a representation of Maxwell's theory, it is a both necessary and sufficient condition to yield these equations.[2] This is why he famously answered to the question "What is Maxwell's theory?" as follows: "I know of no shorter or more definite answer than the following: – Maxwell's theory is Maxwell's system of equations." (Hertz, 1962, p. 21). That, however, does not yet answer the question as to the nature of a representation of a theory. In the particular case at hand, Hertz contrasts the mathematical relations with the *physical significance* of Maxwell's claims (Hertz, 1962 p. 20). The representations thus add physical significance to the system of equations. They do this by invoking physical conceptions (Vorstellungen) such as "pictures of electrified atoms" or "concrete representations (Vorstellungen) of the various conceptions as to the nature of electric polarisation, the electric current etc." (Hertz, 1962, p. 28). Elsewhere we read:

> "Maxwell originally developed his theory with the aid of very definite and special conceptions as to the nature of electrical phenomena. He assumed that the pores of the ether and of all bodies were filled with an attenuated fluid, which, however, could not exert forces at a distance." (Hertz, 1962, p. 27).

A representation of a theory adds physical significance to abstract concepts such as polarization or electricity by correlating them, for instance, to more familiar concepts or pictures of other branches of physics.

It is important not to misconstrue Hertz's notion of a representation and its conceptions. Hertz was not a precursor of the so-called received view of theories, as is sometimes claimed.[3] According to the received view a physical theory comprises two essential features, an abstract uninterpreted mathematical calculus (e.g., Maxwell's equations) and a set of correspondence rules that

[2] "Every [representation of a] theory which leads to the same system of equations, [...] I would consider as being a form or special case of Maxwell's theory; every theory which leads to different equations, [...] is a different theory" (Hertz, 1962, p. 21). Instead of "theory" Hertz should have used "representation of a theory" at the beginning of this passage. Hertz does not always live up to the criteria that he requires theories to have (see Sect 6) while presenting his views on their nature. For instance, he uses not only "theory" in places where he clearly means "representation of a theory"; instead of this latter expression there are a lot of further expressions that he apparently regards as synonymous, such as "form", "special case" (in the above quotation), and "Fassungen" which has been translated as "modes of representation" (p. 21). There is also the notion of "standpoint", whose relation to the above is not entirely clear. (There are *four* standpoints but only *three* representations with respect to Maxwell's system of equations).

[3] This view is held by de Agostino (1998), p. 89–102, see especially p. 90/91. It [illegible]

serves to link the theoretical terms to experimental procedures.[4] The correspondence rules provide a (partial) interpretation of the theoretical terms; they confer empirical significance. Maxwell's equations are taken to lead to predictions of phenomena independent of any representation as the following passage indicates:

> "Every theory which leads to the same system of equations, *and therefore comprises the same possible phenomena*, I would consider as being a form or special case of Maxwell's theory; every theory which leads to different equations, *and therefore to different possible phenomena*, is a different theory." [my emphasis] (Hertz, 1962, p. 21).

The upshot is that we should not consider a representation of a theory as an interpretation in the sense of the received view of theories.

Having said that, we are still left with the question of why we need representations of theories and the images, models, etc., they come along with. Ultimately Hertz does not provied a clear-cut answer to this question. He is clearly suspicious of models, images, etc. In fact, Hertz defines his own objective in his theoretical papers, as he outlined in the introduction to *Electric Waves*, as the attempt to develop a representation of the system of Maxwell's equation that can do without pictorial conceptions (Vorstellungen) as far as possible:

> "I have [...] endeavoured in the exposition to limit as far as possible the number of those conceptions which are arbitrarily introduced by us, and only to admit such elements as cannot be removed or altered without at the same time altering possible experimental results." (Hertz, 1962, p. 28).

Hertz claims that he has removed all pictures etc. that he could possibly remove. Thus, it is apparently impossible to eliminate all of these "elements". Hertz does not give us a reason why it is impossible to do entirely without images, models, etc., nor does he provide a conjecture as to their positive use (Hertz, 1962, p. 28). In *Principles of Mechanics* he links this indispensability to the structure of the human mind.

Be that as it may, Hertz's attempt to do without pictorial conceptions relies on a distinction he draws. On the one side are those features which we introduce arbitrarily into a theory; on the other side are features whose modification yields a modification of possible experience. This distinction coincides with the distinction that characterizes his main epistemological question as becomes apparent in the following passage:

> "It is true that in consequence of these endeavours, the theory acquires a very abstract and colourless appearance. [...] But scientific accuracy requires of us that we should in no wise confuse the simple and homely figure, as it is presented to us by nature, with the gay garment which we use to clothe it. Of our own free will we can make no change whatever in the form of the one, but the cut and colour of the other we can choose as we please." (Hertz, 1962, p. 28).

[4] For a detailed discussion and a presentation of the development of the received view of theories see Suppe (1977), p. 1–241

Hertz distinguishes two factors that determine a theory, nature herself and us. What nature contributes turns out to be mutable only at the cost of a change in the description of possible phenomena, whereas what *we* contribute is *arbitrary* and by implication does not yield a change in the phenomena if modified.

Hertz conceives his own papers in theoretical electrodynamics as attempts to sort out these two features. Thus, he attempts to give an answer to his main epistemological question. It is not only his explicitly epistemological remarks that deal with this question but also his theoretical work in physics – at least according to his self-assessment.

3 The Objective of *Principles of Mechanics*

In a paper that Hertz delivered in 1889, he refers to the question concerning "the essence, the properties of the space-filling medium – the ether, his structure, his rest or movement, his infinity or limitedness" as the question of supreme importance in physics. "The question whether everything that is, has been created out of ether isn't any longer out of the reach of today's physics. These things are the ultimate aim of our science, physics." (Hertz, 1894, p. 354). To achieve the aim of physics, that is, to explain the essence of the ether, the equations of motions have to be reduced to the laws of mechanics. This reduction, however, cannot be successful, as Hertz remarks in the preface to *Principles of Mechanics* "until we have obtained a perfect agreement as to what is understood by this name [of laws of mechanics]". (Hertz, 1956). Thus the elucidation and explanation of the foundations of mechanics are a necessary prerequisite for the realization of the ultimate goal of physics, that is, the investigation of the ether. His research in mechanics concerns solely this prerequisite, not, however, the physics of the ether itself, as he points out to his former Strasbourg colleague E. Cohn in 1891:

> "What you have been hearing about my work by way of Halle is unfortunately without any basis and I don't know how this opinion originated. I haven't worked on the mechanics of the electrical field at all, and haven't anything about the motion of the ether. This past summer I reflected a lot about ordinary mechanics, but I don't remember speaking about this in Halle at all." (Nordmann, 1998, p. 160).

The question arises as to what kind of problems in "ordinary" mechanics Hertz intended to solve. As the letter to Cohn continues, it becomes obvious

> "Here I would like to put some things in order and to determine the order of concepts in such a manner that one can see more clearly what is definition and what is empirical fact, e.g., in the concept of force, of inertia, etc." (Nordmann 1998, p. 160).

Hertz's attempt to distinguish definition and empirical fact is again aimed at answering his central epistemological question – now with respect to mechanics. It is *Principles of Mechanics* as a whole and not just the introduction that has to be taken to be an elaborated attempt to draw the distinction between what can be attributed to nature herself and what not.

4 The Concept of a Symbol or Image in *Principles of Mechanics*

The concept of a symbol is used only once in *Principles of Mechanics* but Hertz makes it clear he considers it to be synonymous with the concept of an image that he uses throughout.[5] These concepts are introduced by Hertz to characterize what we rely on when we make predictions, *i.e.*, what he calls the "most direct, and in a sense most important, problem which our conscious knowledge of nature should enable us to solve" (see Hertz 1956, p. 1):

> "We form for ourselves images or symbols of external objects; and the form which we give them is such that the necessary consequents of the images in thought are always the images of the necessary consequents in nature of the things pictured." (Hertz, 1956, p. 1).

The images (Bilder) Hertz speaks of are also called "conceptions" (Vorstellungen) of things:

> "The images we here speak of are our conceptions of things. With the things themselves they are in conformity in one important respect, namely in satisfying the above-mentioned requirement. For our purposes it is not necessary that they should be in conformity with the things in any other respect." (Hertz. 1956, p. 1/2).

The first thing to be noted is that Hertz makes use of the concept of an image in a narrow and in a broad sense. Images in the narrow sense are parts of theories that refer to particular things in nature. This is the sense in which the concept of a symbol or image is used in the above quotation. When he compares the different images of ordinary mechanics, it is rather theories as a whole that he has in mind. The above-quoted requirement for symbols or images is valid both for the narrow sense as well as for the broad, as becomes clear directly after the introduction, where he exclusively deals with the broad sense of an image.

[5] There are more occurrences in the english edition. Thus on p. 139 the translator uses "symbol" for the german "Zeichen".

What an image ought to aim at is therefore clearly determined: the prediction of future (and presumably the explanation or retrodiction of past) events. What Hertz refers to as the "conformity" of the consequents of the images of things with the consequents of the things pictured would nowadays be referred to as the empirical adequacy of theories.

How do we compare the consequents of images with the consequents of things? Let us start with the constitutive elements of images. Hertz refers to *fundamental ideas* and *principles*, connecting them as the main elements that are characteristic for a particular image. Principles of mechanics are defined as

> "[a]ny selection from amongst such and similar propositions, which satisfies the requirement that the whole of mechanics can be developed from it by purely deductive reasoning without any further appeal to experience." (Hertz, 1956, p. 4).

Thus the whole experiential input of a theory has to be captured by its principles. Hertz's own principle is therefore not discussed in the first part of his book, which does not concern itself with experience at all, but in the second.

The examples of images Hertz discusses in *Principles of Mechanics* are the customary representation of mechanics which is characterized through the fundamental ideas of space, time, mass and force as well as Newton's laws of mechanics and D'Alembert's principle. The ideas of space, time, mass and energy together with Hamilton's principle constitute the "energetical" image. Hertz's own image presupposes just three fundamental ideas, space time and mass – plus a fundamental law that serves as his principle.

Thus far we have dealt with principles and fundamental ideas of images. We may also deduce propositions from the fundamental ideas and the principles, i.e., the consequents of our images. The question arises as to how we are able to check the conformity of the latter with the consequents of the things pictured. The first book of *Principles of Mechanics* does not deal with this problem; it treats the fundamental ideas and introduces definitions without making any reference to nature. "The subject matter of the first book is completely independent of experience." (Hertz, 1956, p. 45). It is only in the second book that such a connection is established. At the beginning of the second book Hertz introduces three *rules* (Festsetzungen) for his fundamental ideas. The first of these rules concerns time:

> "Rule 1. We determine the duration of time by means of a chronometer, from the number of beats of its pendulum. The unit of duration is settled by arbitrary convention." (Hertz, 1956 p. 140).

There are similar rules for space and mass. Even though these rules remind one of correspondence rules that give meaning to the concepts in question Hertz does not conceive them as such. Rather, he thinks of them as providing

definite and determinate values for a determinable. If Hertz had – anachronistically – conceived of the rules as correspondence rules, they would have served to determine the meaning of, say, time. That is something Hertz does not consider to be lacking. The conceptual structure, the fundamental ideas have been outlined in the first book – they do not need an interpretation. Hertz himself puts it like this:

> "The three foregoing rules are not new definitions of the quantities time, space and mass, which have been completely defined previously. They represent rather the laws of transformation by which we translate external experience, i.e., concrete sensations and perceptions into the symbolic language (Zeichensprache) of the images of them which we form [...] and by which conversely the necessary consequents of this image are again referred to the domain of possible sensible experiences." (Hertz, 1956 p. 141).

What is important is that it is not only the fundamental ideas and the principles but also these rules that are constitutive for the concept of an image (or symbol):

> "Thus only through these rules can the symbols (Zeichen) time, space and mass become parts of our images of external objects. Again, only by these three rules are they subjected to further demands than are necessiated by our thought." (Hertz, 1956 p. 141).

Thus, it is only with the help of these rules that the images become images of external things. It is not that Hertz thinks that his fundamental images lack all meaning in the absence of rules. They lack empirical significance. Not being an empiricist, he does not equate these two.

5 Images and Models

At one point in the introduction to *Electric Waves* Hertz explicates the concept of an image (or symbol) by referring to models. This is interesting because Hertz gives an explicit definition of a model in the second part of *Principles of Mechanics*. This definition of a model and its relation to the notion of an image highlights the fact that images are underdetermined by the aim or criterion of empirical adequacy.

A material system is a model, as defined by Hertz, if it stands in the following relation to another material system (Hertz, 1956, p. 175):

> "**Definition.** A material system is said to be a dynamical model of a second sytem when the connections of the first can be expressed by such coordinates as to satisfy the following conditions:
> (1) That the number of coordinates of the first system is equal to the number of the second.

> (2) That with a suitable arrangement of the coordinates for both systems the same equations of condition exist.
> (3) That by this arrangement of the coordinates "the expression for a magnitude of a displacement agrees in both systems"."

According to this definition the model relation is symmetric. Two systems are models of each other. Furthermore, material systems are not completely characterized through the modelrelation:

> "A system is not completely determined by the fact that it is a model of a given system. An infinite number of systems, quite different physically, can be models of one and the same system. Any given system is a model of an infinite number of totally different systems. For the coordinates of the masses of the two systems which are models of one another can be quite different in number and can be totally different functons of the corresponding coordinates." (Hertz, 1956 p. 176).

It is this concept of a model that Hertz uses to characterize images. At the outset of the introductio (Hertz, 1956, p. 1) he had already pointed to a connection that he explicates in more detail in the second part:

> "The relation of a dynamical model to the system of which it is regarded as a model, is precisely the same as the relation of the images which our mind forms of things to the things themselves. For if we regard the condition *(Zustand)* of the model as the representation of the condition of the system, then the consequents of this representation, which according to the laws of this representation must appear, are also the representation of the consequents which must proceed from the original object according to the laws of this original object. The agreement between mind and nature may therefore be likened to the agreement between two systems which are models of one another." (Hertz, 1956, p. 177).

Hertz does not identify image and model, it is rather the *relation* between two material systems that is the same as the *relation* between the system and the image. As Hertz uses these terms, for an image to be a model of a *material* system it has to be a material system not a mental system.

The identity of the relations entails that just as a material system is not completely determined if it stands in a model relation to another system, an image is similarly *underdetermined*. It is underdetermined by the conformity requirement, i.e., by the requirment of empirical adequacy.

6 Criteria for the Evaluation of Images

The requirement of empirical adequacy does not determine an image completely. Besides this criterion, which Hertz sometimes calls "correctness", he

introduces two further criteria for the evaluation of images. These are the criteria of *admissibility* and *appropriateness*. An image is admissible if it does not contradict the laws of our thought, i.e., if it is logically consistent. An image can be appropriate in two respects. It can be more appropriate than another image if it is more distinct. This is the case if it "pictures more of the essential relations of the object" than its competitor (Hertz, 1956, p. 2). Also, an image may be more appropriate than another if it is simpler, i.e., if it contains "in addition to the essential characteristics, the smaller number of superfluous or empty relations." (Hertz, 1956, p. 2).

The three criteria of correctness (empirical adequacy), admissibility (logical consistency) and appropriateness that Hertz invokes in order to compare the different images of mechanics are definitely linked to three factors that, according to Hertz, determine an image.

> "What is ascribed to the images for the sake of appropriateness is contained in the notations, definitions, abbreviations, and, in short all that we can arbitrarily add or take away. What enters into the image for the sake of correctness is contained in the results of experience, from which the images are built up. What enters into the images, in order that they may be permissible, is given by the nature of mind." (Hertz, 1956, p. 2/3).

Hertz requires that a presentation (Darlegung) of an image ought to analyze to what extent the image satisfies these criteria. This requirement is tantamount to asking for an answer to his central epistemological question. What are the features of an image that depend on nature (or experience) and what are the ones that depend on us? Hertz distinguishes in *Principles of Mechanics* two kinds of theoretical features that cannot be attributed to nature. First, there are those features for which we are responsible willingly (definitions, abbreviations, etc.) and, second, there are those features for which we are responsible unwillingly, *i.e.*, the conformity of the image to the laws of thinking. It is this additional distinction of arbitrary and non-arbitrary elements of a picture that had been introduced neither in Helmholtz's theory of signs nor in Hertz's earlier conception of scientific theories in the introduction of *Electric Waves*. Thus we have the following links between criteria on the one hand and determining factors of a theory on the other: nature (experience) – correctness; necessities of thought – admissibility; arbitrary choice – appropriateness.

Hertz is critical of the fact that the traditional (received) image of mechanics has never been analyzed with respect to these elements:

> "It still fails to distinguish thoroughly and sharply between the elements in the image which arise from the necessities of thought, from experience and from arbitrary choice." (Hertz, 1956, p. 8).

In *Principles of Mechanics* Hertz attempts to present an image of mechanics such that it becomes apparent what the determining factors of his image

are. Given this aim one would expect *Principles of Mechanics* to consist of three books – one for each of the determining features. It does, however, contain only two booksn which reflects the difficulty of sorting out the determining factors (see Sect. 7). The first book is devoted entirely to those elements that are dependent on us. He presents definitions of fundamental concepts or ideas that are arbitrary in the sense that he could have chosen other definitions. He then deduces with the help of our laws of thinking propositions that are not yet connected to anything in nature. It is only in the second book that predictions become possible – thanks to the rules (Festsetzungen) and his fundamental principle (which comprises the whole empirical content of the theory). The latter is the factor that represents to what extent the image depends on nature or experience.

7 Problems

There are some problems that Hertz has to face in carrying out his analysis in order to answer his central epistemological question. One problem is that it does not seem to be altogether easy to isolate certain features of a theory as being dependent on exactly one determining factor. This becomes apparent if one looks at his criticism of the competing images of mechanics. As he points out, these images are not appropriate in the sense of being simple, i.e., they postulate too many (empty) relations. This in turn yields logical inconsistencies:

> "But we have accumulated around the terms 'force' and 'electricity' more relations than can be completely reconciled amongst themselves. We have an obscure feeling of this and want to have things cleared up. Our confused wish finds expression in the confused question as to the nature of force and electricity. But the answer which we want is not really an answer to this question. It is not by finding out more and fresh relations and connections that it can be answered; but by removing the contradictions existing between those already known, and thus perhaps by reducing their number. When these painful contradictions are removed, the question as to the nature of force will not have been answered; but our minds, no longer vexed, will cease to ask illegitimate questions." (Hertz, 1956, p. 7/8).

If we were to remedy this situation by postulating less relations, we would at the same time enhance appropriateness and admissibility. However, if the criteria are connected in this way it seems difficult to attribute certain features of the theory to exactly one of the determining factors (which are definitely connected to exactly one of these criteria).

A second problem is that Hertz is not entirely clear about the relative merits of these criteria. In the introduction to *Principles of Mechanics* he maintained that correctness or empirical adequacy is the most important aim

that our knowledge of nature can achieve. What then is the status of the other criteria? Are admissibility and appropriateness merely pragmatic virtues? Maybe correctness presupposes admissibility. Is it the case that theories that are more appropriate are more likely to be correct? Why should a physicist be interested in appropriateness if that were not the case?

Also, Hertz is not quite clear about why his favourite image outdoes the competitors.[6] At one place it seems to be admissability (logical consistency) that is the most important criterion in virtue of which his image surpasses the competitors.

> "This merit of the representation I consider to be of greatest importance, indeed of unique importance." (See Hertz 1956, p. 33.)

However, later on he claims that the traditional images and his own are on a par with respect to admissability and it is rather the correctness that will have to decide between the two pictures:

> "We shall then have as our sole criterion the correctness of the images [...] and here it is important to observe that only one or the other of the two images can be correct: they cannot both at the same time be correct." (Hertz, 1956, p. 40).

This leaves us with the impression that we have two theories of mechanics that differ in their predictions.

8 Conclusion

Conceiving physical theories as images or symbols is a means to answer Hertz's central epistemological question. Theories as images or symbols owe *some* of their features to what they stand for – in this case nature or experience. However, they also owe some of their features to those who produce or construct them. These features are partly non-arbitrary and partly arbitrary. For the further development of the concept of the symbol, Hertz's insistence on the latter factor became important. Thus, Cassirer always referred to the constructive element in Hertz's account of images or symbols.[7]

[6] This is a point Alfred Nordmann has highlighted (Nordmann, 1998, p. 161).

[7] Cassirer called symbols in the sense of Hertz "konstruktiver Entwurf" (Cassirer, 1954, p. 25).

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