The mathematisation of the sciences and the observability of causal relations

Uwe Oestermeier

Applied Cognitive Science Department

German Institute for Research on Distance Education

at the University of Tuebingen

Konrad-Adenauer-Str. 40, D-72072 Tuebingen

uwe_oestermeier@diff.uni-tuebingen.de

Abstract

For a long time now divergent views have existed in the fields of philosophy of science and psychology as to whether or not causal relations are observable in particular cases. This disagreement can be resolved if one assumes that within this debate, divergent everyday and scientific concepts of observation are used. The main thesis of the present paper is that a normative theory, which strictly separates observations from causal interpretations and which evaluates observations in terms of inter-subjectivity, objectivity as well as precision, places cognitive demands on a subject which can only be fulfilled in practice within the framework of scientific mathematical methods. The mathematisation of the sciences will be described as an extension of cognitive abilities by means of external representations and cognitive artefacts.

Introduction

In philosophy of science and psychology, there is an ongoing disagreement about whether or not causal relations are observable. The position that the relation of cause and effect as such cannot be observed in particular cases but rather only be inferred is commonly attributed to David Hume.[1] According to Hume, only the temporal priority of a cause before its effect and the spatio-temporal proximity between cause and effect can be observed. Hume illustrates his thesis with the collision of two billiard balls. The necessity with which the effect (movement) seems to follow the cause (impact) is due to preceding experiences and a completely subjective addition. The subject interprets the observable spatio-temporal events in terms of unobservable causal relations. A majority

[1] Certainly, Hume was the most influential author in this respect. But most aspects of his analysis of causation have been anticipated by islamic and scholastic philosopher as well as French occasionalists (see. Weinberg 1973).

of modern theoreticians of science regard this as an important and correct discovery by Hume (Stegmüller 1983) and many psychologists share Hume's view:

"Because causal relations are neither observable nor deducible, they must be induced from observable events" (Cheng 1997, p. 367).

"It is logically impossible to observe causal processes per se" (Ross & Fletcher 1985, p. 112).

Psychologists working in the tradition of "phenomenal causality" are standing in direct opposition to this Humean analysis. They assume that straight forward elementary mechanical interactions, as Hume regards them in his billiard ball example, are directly observable if certain Gestalt laws are obeyed by the interacting objects (Michotte 1982).[2]

This disagreement can easily be explained, if one assumes that the opponents in this debate use divergent concepts of observation. In any case, in terms of everyday language is correct to link verbs of observation and perception to descriptions which imply a causal relationship:

"I saw, how the cat licked up the milk."

"He did observe that the little boy pushed over the bike."

Similar examples can be found in every newspaper archive. According to common sense, there are thus specific causal relations accessible to observation. From a Humean point of view, however, this shows only that everyday language is too vague for a precise philosophical analysis of causality.

Which of these positions is based on better arguments, will not be further examined here. I am simply working on the assumption that, following Hume, many philosophers of modern science and psychologists apply a normative concept of observation to everyday processes of perception and inference. My main thesis is that this normative

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[2] This psychological debate has a counterpart in the philosophy of science. Some philosophers question the regularity view of Hume and defend a singularist position instead (Ducassse 1993, Mackie 1974). According to this minority of singularists causal statements do not presuppose general causal laws but general causal laws presupose singular causal statements.

concept of observation is attached to cultural and scientific-historical conditions of external representation and measurability, which are necessary for a systematic differentiation between pure observation and the causal interpretation of observation. This concept of observation developed with the mathematisation of the natural sciences and is normative in as much as it demands that observations

- are to be strictly separated from the causal relations infered from it;
- are to be as independent as possible of the observing subject, i.e.are in the ideal case *intersubjective, objective* and *precise* .

These demands cannot be fulfilled by human beings who only have available their everyday language and sense organs. The normative concept of observation thus, tacitly presupposes a cultural environment with external representations (such as, e.g. calculi for notations of proofs and tables for coding observational data) and cognitive artefacts (such as e.g. measuring instruments), with which humans extend their perceptual and inferential abilities. These representational forms and artefacts are common features of our cultural background and thus mostly taken for granted, but they are based on discoveries and inventions each of which were by no means inevitable and obvious.

The development of a neutral observation language

One can point to numerous examples showing that in everyday language observations are described by means of causal expressions.[3] In recent statistics textbooks, however, a strict distinction is drawn between descriptive and inferential statistics. This distinction is a rather new one. In journals of psychology before 1935, this difference had hardly been considered. This situation only changed with the introduction of the t-test and the analysis of variance into the arsenal of the standard methods of psychology (Gigerenzer 1987). One could regard this as merely one of the many coincidences in the history of psychology yet, in my view, there is more behind it: a systematic transition from descriptions and interpretations in ordinary language to mathematical methods with quantitative data and formalised inferential procedures. This transition is also to be observed in other sciences, which orient themselves on the model of modern physics.

The cognitive conditions for a consistent separation of description and interpretation becomes obvious if one imagines that all scientific aids disappear: Publications and laboratories, tables and measuring instruments, graphs and mathematical computation methods etc. Oral cultures, which manage entirely without these aids, become extinct, but precisely such cultures are relevant contrast cases in this respect: A characteristic quality of oral cultures seems to be the fact that causal explanations are primarily handed down in narrative formats while, in literate cultures, besides narrative genres, argumentative-logical texts and forms of discourse have been developed (Donald 1991, Lindberg 1992). Writing and printing are necessary conditions for the scientific revolution which has also been described as the transition from mythical to scientific, from concrete to abstract, from superstitious to rational modes of thought. Naturally, such clichee words and dichotomies are always to be regarded with reservation, but nobody can doubt that divergent levels and qualities of knowledge, and thereby causal knowledge, exist. There are various text forms which support the separation of observation and interpretation in very different ways.

Narrative texts

As in spoken narratives the linear structure of written texts alone indicates a causal order. The sentences “Hans became ill and went to the doctor” and “Hans went to the doctor and became ill” are, in this regard, to be interpreted completely differently, without the

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[3] A strict division between perception and inferences is not self-evident within psychology, as can be seen by the numerous approaches that explain perception as a process of inference (e.g. Rock 1983).

presence of an explicit temporal and causal expressions. Listeners and readers tacitly and automatically draw the appropriate causal conclusions (Warren, Nicholas, & Trabasso, 1979). In everyday language, sequences of events are thus not firstly described in a neutral observational language in order then to proceed with inferential causal judgements, but rather everyday linguistic descriptions of processes already imply causal interpretations of the described processes. In this connection, Strawson (1985) refers to the fact that our everyday vocabulary of causal conditions is similarly differentiated as our vocabulary for material articles. Just as we have an abundance of object categories (furniture, mountains, tables, vehicles, food etc.) we have an abundance of transitive verbs (to push, lift, bend, tilt, press, draw etc.) and dispositional predicates (water-soluble, courageous etc.), which describe how something or someone interacts with its or his environment. These expressions belong to our observational vocabulary, i.e. we describe sequences of events spontaneously and immediately after single observations as causal, most of the time without using the expressions "cause" and "effect".

Argumentative texts in ordinary language

Causal everyday knowledge forms the background or framework for the scientific use of language with its explicit definitions and criteria. However, an explicit argumentative-logical scientific language could be formed only with the invention of writing. This does not mean that in scientific prose the basal narrative principles are made completely obsolete, but only that in scientific language logical structures are explicitly marked by keywords such as “because”, “thus”, “therefore”, “thesis”, “premise”, “argument”. The difference to narrative genres is, however, gradual. In principle, one can articulate all necessary epistemic distinctions by means of the common vocabulary of science but in practice, descriptions and observations are often not distinguished from theoretical considerations and arguments (Gigerenzer 1987).

Argumentative texts in formal language

A consciousness for logical stringency and thus of the difference between premises and conclusions only arose with the development of rigid proof forms in geometry, algebra and logic. In all these proof forms the linear order of narrative time in ordinary language no longer plays a role. One may regard geometric, algebraic and logical proof forms as an intellectual corset, which the scientist uses voluntarily, in order to force the explication of his assumptions and to control each step in his proof. In the historical development of the sciences one can recognise a tendency towards increasingly abstract and more compact representations. In modern calculi, each sign represents a concept and not a vowel or a syllable, as in normal written languages.[4] Only in literate cultures has this degree of abstraction in argumentative thinking been achieved (Olson 1996). The externalisation of thought on paper or other media seems to be a necessary condition for this: There are no oral counterparts to formal logical, algebraic, geometrical and statistical forms of inference (Goody 1987).

The cognitive effects of notation, as used in formal reasoning, ought not to be underestimated. If one uses insignificant symbols instead of ordinary verbal expressions, which nearly always have causal connotations, one does not fall prey to the danger of drawing unwarranted causal conclusions and generalisations. In contrast to everyday language, in which the asymmetry of cause and effect, agent and patiens is deeply rooted (Fiedler, Semin & Finkenauer, 1994), formal representations require additional steps of interpretation and explanation, in order to be able to express the asymmetry of cause and

[4] Aristotle was the first who used letters in his syllogistic logic as variables for terms, and thereby abstracted completely from the content of the terms. In algebra, this symbolic notation was introduced by Vieta. It was Descartes who first used the last letters of the alphabet x, y and z for unknown and the others for known values as it is common practice today

effect. The equation $F = m \cdot a$, for instance, abstracts completely from the fact that in the everyday life force is regarded as a cause of acceleration and not vice versa.

A characteristic of mathematical notations is their dual function as a medium of representation and operation. The symbols are not only representatives for statements and assumptions, they are also a medium with which one may perform specified operations according to the permitted inferential rules. Thus, a formal notation forces one to make hidden premises explicit and to check each step in the proof.[5]

Today, logical and statistical calculi are mastered only by a few experts and in Europe it is only with the invention printing that written calculation has become a general cognitive ability (Menninger 1969). With algebraic calculation and the invention of analytic geometry, quantitative arguments became the ideal of the natural sciences. Quantitative and formal modes of argumentation exceed normal language in precision, uniformity and degree of generality and are inconceivable in exclusively oral cultures. It is thus probably no coincidence that the concept of a quantitative law of nature - which, in contrast to ordinary language, abstracts to a large degree from contents and contexts, - only appears in societies with an elaborate mathematical knowledge (Kelsen 1941).

Scientific quality standards for observations

In everyday situations causal problems (whose fault was the accident? Who knocked the glass over? Where does this rash come from?) are mostly not solved by repeated experimentally controlled observations. One cannot systematically vary accident and

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[5] Rumelhardt (1989) points out that our brain is primarily a pattern-recognition apparatus and is relatively unsuited for formal reasoning. By means of external notation, abstract logical problems can be transferred to concrete problems of pattern recognition. The pioneers of modern logic were aware of the far-reaching cognitive effects of mathematical notations: „."...by the aid of symbolism, we can make transitions in reasoning almost mechanically by the eye, which otherwise would call into play the higher faculties of the brain." (Whitehead, 1911, quoted from Copi, 1968, p. 213) Copi (1968) commented on Whitehead as follows: "From this point of view, paradoxically enough, logic is not concerned with developing our powers of thought but with developing techniques that enable us to get along without thinking!" (p. 213).

disease processes. Moreover, in many cases, there are no or only few eye-witnesses, so that comparisons between various observation reports are impossible from the outset. In addition, many relevant processes cannot be observed directly: one cannot see whether an electronic brake assembly is defective. In natural science, however, there is the possibility for controlled, repeated observation and measurement which can be accomplished by various methods. For this purpose, normative standards were developed, which guaranteed the intersubjectivity, objectivity and the precision of observations.

Intersubjectivity

Intersubjectivity requires that observations and experimental findings should, in principle, be examinable for each competent member of the scientific community. For several persons to be able to compare their observations, these observations must be communicated with as little margin for error as possible. This may appear trivial but it is extremely difficult to achieve with media that are not exactly reproducible. As regards error free duplication, oral reports can be excluded from the beginning, but graphic representations could also not be duplicated error free prior to the invention of printing, woodcut and engraving techniques. In this regard, digital words and numbers fundamentally differ from analogous drawings and diagrams. Naturally, in copies of travel journals dating from the period of classical antiquity and the middle ages, numerous errors can be found, but in contrast to the errors which resulted from hand-made copies of maps, these errors are marginal. Before the problem of exact replication was solved, drawings were inpractical means for the communication of spatial data and technical inventions (Ivins 1969). Due to their economic relevance, maps and technical drawings very quickly found widespread application subsequent to the invention of print and engraving techniques, whereas purely scientific non-spatially data (air pressure, temperatures, etc.) continued to be fixed and disseminated primarily in numerical tables.[6]

Against this background, it becomes clear on what abstract and extremely condensed informational foundation the modern mathematicisation of the natural sciences is based. Geometrical figures also played an important role for a long time after the invention of analytic geometry, but these figures only served exclusively mathematical proof and not the concrete representation of observed events. The idea that, in contrast to the Aristotelian world view, all sub and supra-lunar features obey uniform and general quantitative laws of nature was thus introduced at a time when the available observational media were static, symbolic and abstract. The direct phenomenal experiences of colliding billiard balls were similarly reduced to numbers as only indirectly observable planetary motions. Accordingly, the intersubjective confirmation of new quantitative laws, primarily lay in the fact that numerical data were compared to theoretical calculations on paper. Experiments still allowed a direct access to natural phenomena, yet the experimental results were only intersubjectively examinable by the use of media. Not the phenomena themselves, but the mathematical representations on paper were the actual objects of scientific reflection. Thereby, to a large extent, subjective and directly experiences, in the sense of phenomenal causality, played no role in the justification of causal knowledge.

Objectivity

The objectivity of observation requires that even psychological factors, that are common to all humans such as e.g. symptoms of fatigue, are to be minimised. Therefore, ideally a machine should take the place of a human cognitive system. A measurement device is completely free of the distortions of human judgement and provides observations without

[6] Johann Heinrich Lambert was the first to use graphs for the visualisation of measurements. Although the analytic geometry of Descartes and Fermat had already existed for a long time, the graphic visualisation of data became common practice only in the 19th century (Tilling 1975).

an observing subject. Such mechanical observations are “pure” if the numeric output can be used in calculations without additional translation and interpretation.[7] To my knowledge, a measuring device which shows “degrees of causality” on its display, has so far not been invented. For this reason alone, causal relations are not measurable and thus also not objectively observable.

It should not be forgotten, however, that in contemporary physics numerous causal concepts have been differentiated, which can be considered as measurable. Hume criticised (probably quite rightly) that many causal terms are used interchangeably: “efficacy, agency, power, force, energy, necessity, connection, and productive quality, are all nearly synonymous; and therefore ' tis an absurdity to employ any of them in defining the rest.” (Hume 1978, p. 157). Nowadays, a number of these expressions have generally accepted definitions. One could describe this development as a differentiation of everyday causal terms into scientific quantitative definitions of force, work, power and energy. This development came about only after formulas increasingly supplemented the scientific texts in ordinary language.[8] What is remarkable about this is that some concepts mentioned by Hume (e.g. force and power) are nowadays explicitely regarded as measurable in modern physics. The objectively measurable then, is relative to the available equipment and the established operational rules. A consensus valid for all times with regard to the observability of qualities is, therefore, not to be expected.

[7] The first automatic measurement devices date back to the second half of the 17th century. In 1663 Wren invented a weather clock, which recorded the direction of the wind, the quantity of rain and the temperature.

[8] Historians of science often introduce definitions by formulas that have not been used by the relevant authors themselves. Descartes' concept of force, for instance, is defined as $m \cdot v$, Leibniz' as $m \cdot v^2$ and Newton's as $m \cdot a$. This practice is based on the assumption that only formulas provide clear definitions of central concepts of physics (as e.g., the definition of force in Newton's axioms).

Precision

Although the significance of measuring devices increases in everyday life, so far this has had a minimal effect on the common understanding of causality. This does not hold for modern physics. A matter of repeated debate at that time was whether or not an upper limit for the propagation of effect exists. Descartes, for instance, was of the opinion that there are no actions at a distant, but he believed that mechanical impact could have instantaneous effects over several mediating stations. Newtonian physics, with its law of gravitation permitted instantaneous effects, while Einstein's relativity theory excludes such effects and regards the speed of light as the upper limit of the propagation of energy. The empirical question, as to which of these views is correct, is clearly not to be decided by means of the naked eye although this question is of crucial importance for the philosophical problem as to whether the asymmetry of the causal relation can be reduced to the arrow of time. Hume postulated a temporal asymmetry between cause and effect, but the empirical verification of such an priority presupposes often very precise time measurements, which are not available in ordinary circumstances. If someone grasps a glass, holds it and suddenly shifts it, only a simultaneous movement of the hand and glass is perceptible, although, in terms of physics, the walls of the glass are minimally imprinted, before the glass is put into motion as a whole. In other words: The general asymmetry of cause and cannot rely on solely perceptible temporal differences. This assumption has its roots in prior knowledge that could only be acquired by means of the mathematicisation of physics and the development of precision instruments.

Summary and conclusions

With the mathematisation of the sciences, a combination of ordinary language and formal notations became a normative standard. During this long development, myths and other narrative forms of causal explanation were gradually substituted by general and coherent scientific argumentations (Donald 1991; Lindberg 1992), in which observations and their interpretation can be systematically differentiated. This long and by no means linear development had achieved a first high point in physics with Isaac Newton, which even today continues to represent a valid ideal for other sciences.

Though Hume was perhaps unfamiliar with the details of Newtonian physics (Hume rejected e.g. actions at a distance) he was certainly conscious of the general significance of mathematical physics. The Humean regularity thesis that particular causal event sequences comprise of instantiations of general laws, certainly draws its broad acceptance from the enormous successes of classical physics of subsuming such phenomenally disparate processes as planetary motions, tides and colliding billiard balls under a few quantitative laws. Against this background, the attractiveness of the Humean regularity theory of causation can be explained.

Normally, theoreticians of causal cognition do not discuss the cognitive pre-conditions of these scientific triumphs. Neither Hume nor his successors in philosophy of science and psychology can plausibly explain, how human beings are able to come to the abstract causal knowledge that laws of nature apply to sub and supra-lunar levels equally; that causes always temporally appear prior to their effects, and that actions at a distance are to be excluded. Such abstract causal knowledge also entered into modern definitions of causality, but such knowledge cannot have its roots in personal experiences alone. Hume's regularity theory and its modern variants place demands on a cognitive system, that are – without cognitive artefacts and external representations – practically impossible to fulfil: The Humean analysis of the observability of causal relations presupposes that prior causal knowledge is disregarded entirely although (even in Hume's understanding) this prior causal knowledge automatically penetrates everyday interpretations of observations. Mathematical notations assist the cognitive system in abstracting from the causal content of everyday language and observations. However, it ought not be forgotten how difficult most people find the application of such formal notations.

If this analysis is right, what follows for the present research in the domain of causal cognition? In my opinion mainly two lessons: Firstly, the debate between Humeans and Michotteans remains futile unless criteria for the perception and inference of causal relations are explicitely specified. The ordinary concepts of perception and inference are too loose to resolve this debate and the normative scientific concepts of observations and inferences are psychologically inadequate, because inter-subjective, objective and precise perceptions are just as unreachable for unaided human sense organs as are formal proofs for an unaided brain. Scientific observations and inferences presuppose cognitive artifacts and external representations, but in psychology we should be able to describe the cognitive processes in both cases: with and without such aids.

Secondly, and more important, it seems not only be necessary to explicate the basic concepts but also the cultural background of cognitive processes that is usually taken for granted. Lipe (1991), for instance, proposed "that all of the major attribution theories are based on the use of counterfactual information (which examines whether the event would have occurred if the proposed cause had not occurred)." (Lipe, 1991, p. 456) What Lipe did not consider was the fact that counterfactual information cannot be picked up from the natural environment. Unrealized possible worlds are capable of being described and depicted but are not observable. Counterfactuals are based on inferences that go beyond the given and are, therefore, only available in environments with mediated information. Lipe was also apparently unaware of the fact that the Chinese language, unlike English and other Indo-Germanic-Languages, has no distinct counterfactual construction, such as the subjunctive. This, of course, neither proves that Lipe is wrong nor that the Chinese cannot think counterfactually (Au, 1992). Fictions presumably play an important role in all cultures. But this example shows that theorists are liable to take their cultural background for granted: Especially their language and other forms of mediated information.

Other theorists and experimenters share this neglect of media and forms of representation. Experiments have been conducted with texts (e.g. Ahn, Kalish, Medin, & Gelman 1995), tables (e.g. White, 1995), drawings (e.g. Ferguson & Hegarthy, 1995), animations (e.g. Heider & Simmel, 1944), videos (e.g. Storms, 1973), and simulations (e.g. White, 1993). But only a few studies compare different external representations of causal information: Some with effects of presentation (e.g. Anderson & Sheu, 1995; Ward & Jenkins, 1965) and others without (e.g. Wasserman, 1990). In spite of these divergent findings and the manifold media used in everyday cognition, a comprehensive "representational analysis" (see Zhang & Norman, 1995) of the various media is still missing. The fundamental question, namely, which types of evidence can be mediated by which form of external representation, has largely be ignored (Oestermeier & Hesse, 2000).

The important role of media becomes obvious if one considers the range of experiments in human and animal causal cognition. On the one hand, there are experiments without any media and external representations. Experiments with animals on operant conditioning (e.g. Rescorla, 1968) and young children on the selection of causal rules (e.g. Shultz, Fisher, Pratt & Rulf, 1986) are performed with Skinner boxes or toys such as the "Jack in the box". In such cases, the experimental apparatus is directly manipulated and observed in all its physical aspects: Temporal cues, direct effects of interactions, similarities and generative mechanisms between parts can actively be examined by the subjects. The experiments show that causal learning is influenced by all these cues (Anderson & Sheu, 1994; Ferguson & Hegarthy, 1995; Shanks, 1991; Shultz et. al. 1986). On the other hand, there are experiments with texts, tables, and drawings. In using such abstract and static representations, all the aspects and cues mentioned, can be left unspecified: Temporal lags, the details of mechanisms, etc. *can but need not* be depicted and described. Methodologically, this is an enormous advantage because researchers can abstract from any aspect they are not interested in by choosing appropriate representations. The disadvantage, however, is also obvious: If fundamental aspects such as temporal cues and direct interactions are left out in static abstract material, experimental results obtained with such material can neither be generalized to real world scenarios nor even to interactive and dynamic media.

Thus media *add* cultural forms of information (e.g. measurements, statistics, formula, predictions, explanations, theories, criteria, counterfactuals, thought experiments) unavailable in natural environments, *reduce* the informational richness (e.g. tactile and audible cues, temporal and interactional aspects) of the real world, and selectively *emphasize* information (e.g. by highlighting certain aspects, putting distant things together, etc.). All these aspects have to be considered if one wants to clearly distinguish between the observed given information and the conclusions that are drawn from such observations. In psychological experiments on covariation processing, for instance, often modern medical problems are used. The subjects receive cards or displays with observations about the presence or absence of putative causes and putative effects. And then it is examined whether the subjects follow standard statistical rules in their causal induction or some non-standard ones. Marc Buehners study (this volume) provides an example of this kind of experiment. In his study subjects received (presumably written) information about whether a petri dish with a virus had been exposed to rays (putative cause) and whether the virus mutated (putative effect). In a modern scientific sense it is completely legitimate to describe these types of information as observations, and certainly all scientists with a medical or statistical background would consider these types of information as raw data. But neither rays nor viruses nor mutations are directly visible objects or events. In relationship to our inborn perceptual abilities they are theoretical entities that explain other directly perceivable phenomena like X-ray-photos or disease symptoms. Most of us believe in them because we learned about them in school and not because we are acquainted with them by personal observation. As long as psychological theories ignore those cultural and mediated form of causal cognition they cannot decide whether subjects believe in specific causal relations because they have perceived or inferred them on their own, or because they have adopted mediated perceptions or inferences of others.

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