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Guest-editorial

Seeing with the screen

Cornelius Borck
Institute for the History of Science and Medicine, University Lübek, Königstrasse 42, 23552 Lübeck, Germany
E-mail: borck@imwg.uni-luebeck.de

1. Introduction

The new technologies of visualization have turned the computer screen into a universal and highly versatile interface for the representation of scientific knowledge. Images, once regarded as mere illustrations of primarily theoretical and experimental advances, have moved centre stage where knowledge is generated from the confluence of vast amounts of raw and unintelligible data. The computer screen has advanced to the position of the "thinking eye," the central node where data culminate and transform into visual information. Today's sciences are "predominantly visual," argued the British art historian Martin Kemp already ten years ago and identified the emergence of computer graphics as the common cause for it [9]. Such a statement may provoke skepticism but there can be little doubt about three important shifts in relation to the significance of knowledge visualization; (a) the ascendancy of visualization as a transdisciplinary phenomenon, typical for many different knowledge domains; (b) the increased importance or dominance of visualization because of digital technologies of representation; and finally, (c) the reversal of the traditional hierarchy between theory and visualization. Taken together, these shifts account for something which comes close to a revolution of scientific knowledge; not only has the importance of visualization been rising and permeated in ever more knowledge domains, the very object of visualization, its objects, the phenomena and the knowledge do no longer exist independent of the processes of visualization. An investigation of the visualization of knowledge has to take into account that the knowledge to be visualized does no longer precede the very process of visualization but co-evolves with the image making. Strategies of data display and visualization co-construct knowledge.

2. Images as universal language of science

Scientific visualization is anything but a new phenomenon. In fact, its history dates back to the very beginning of modern science, to the scientific revolution and the invention of perspective as a mode of representation. Andreas Vesalius is still being recognized as decisive step in the emergence of modern anatomy and the life sciences, because he combined a radically empirical approach for doing science with a highly sophisticated method for documenting his findings as visual evidence in form of convincing illustrations. Without its images, Vesalius' *De humani corporis fabrica* from 1543 would still be an important anatomical treatise but hardly such a famous and seminal book, marking a turning point in the history of science. Ever since, images played an important role as supportive evidence for knowledge claims and as vehicle for the empirical soundness of scientific realism.

With the historical differentiation of the sciences into the manifold different disciplines, images obviously adapted and evolved into many different directions. Some disciplines, such as the more morphologically oriented branches of science, developed a highly nuanced repertoire of "realistic" representations, highlighting the form and shape of the common, the typical, the normal, the specific, or the particular. On the opposite pole, one could localize physics and mathematics which revived a visual mode of representation

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already present in antiquity, the geometric proof and the formula. Other disciplines would fall somewhere in between these poles, as their visualizations consist in purpose-built inscriptions, recordings or tracings that lack any resemblance with the form and shape of a body but are equally "realistic." Physiology and its armory of instruments, machines, and apparatuses, of which a large number was especially designed for the purpose of producing visual evidence of one form or another, is a particularly telling example here. And still others, such as chemistry or immunology, for example, may be best described as relying on visual models that are highly suggestive and functional but seem to come, in their ontological status, closer to simulations than to representations.

At this point, it becomes clear that the relation between visualization – and scientific visualization in particular – and the visible is far more complicated as it may have been expected at first. Of course, visualizations are visible by definition and must be so, but their epistemic value seems to be directly linked, if not derived from, the invisible. A mathematical formula or physical theory are invisible because of their conceptual nature and truthful abstractness, examples are mere instantiations. This was already Plato's argument against images as powerful means of deception, truth exists only among ideas. His philosophy may have lost some of its appeal meanwhile but his argument is still at the core of the assumption, in the philosophy of science, to regard images as mere illustrations of theoretical knowledge which in itself is conceptual, and hence, non-visual. But complicated relations between the visible and the invisible prevail even on the other pole of the scale, among morphological representations of form and shape. The object to be represented and the knowledge to be visualized are themselves visible without debate, but "truthful" or "realistic" representations have to address a whole series of issues related to the invisible, to conventions or codes of representation, to styles of visualizations, and to materialities of the media employed [12]. The three-dimensionality of the object depicted had to be translated into a two-dimensional image, for example. Some strategies of representation require also a translation of the full spectrum of colors into shades of gray from black to white. And different printing techniques allow for various degrees of softness in tone or clarity of the individual line. A scientific image is full of implicit decisions about representational strategies, including a decision about the relation of the depicted phenomenon to the exemplary or the particular specimen. Any image entails a decision about the invisible in this regard.

Already during the first hundred years following *De fabrica*, a discourse about the advantages and disadvantages of the various strategies was in full swing. How should an object be arranged for its depiction, should it be shown as if lying on the table or should it be arranged as if being alive? Should shadows be used and from where should the light come? Is space and depth better illustrated by hatching or crossing? Should a context or natural surroundings be added for creating a more natural atmosphere or would this confuse the image? Should the specimen at hand be corrected for its obvious deviations from the normal in order to illustrate the typical or should it rather emphasize the particular by highlighting such deviations? What are the advantages of hand coloring and where do colors betray the evidence? Where should the labels go, should they be inscribed on the structure named or would that confuse typographic and anatomical details? And how should images and text be lined up in order to yield the most of the visual evidence created? These are but a few of the questions debated back then [8]. The famous images in *De fabrica* set a standard for "realistic" scientific visualizations which left its imprint. With their classical postures, however, which remind the modern viewer of antique culture rather than science, the images also demonstrate how this standard evolved historically and has moved away from the solution Vesalius once offered.

If we move on to the realm of non-morphological and functional images, the relation to the invisible becomes immediately tangible. They are images of the invisible and the invisible comes in many forms [15]. An object may simply be hidden from the human eye or too small or too large for its detection, microscopy and telescopic observation are the best known examples here. Other instruments extended visualization into different domains of invisibility, opening it for registering phenomena beyond the range or type of human sensory organs with methods like X-rays, ultrasound, radioactivity, or electricity. Still other instruments translated changes over time into visual representations, thus opening the realm of developmental observation and physiological experimentation to graphical inscription. Some of these instruments anchored entire sub-disciplines in a particular mode of experimentation and image making, such as the graphic method for circulatory physiology. Some methods yielded new types of images when they traveled from their original domain into more or different applications, as in case of radio astronomy; and much differentiation in the history of science can be linked to the coupling of one method of image making with another.

A particularly striking example in this context seems to be photography which is often said to have revolutionized scientific visualization. Photography is obviously an example of a technological innovation that cut across a vast array of applications in society, daily life, technology, industry, and the sciences [5]. Especially the combination of photography with printing techniques, which allowed for the mass-reproduction of photographic images and their inclusion in standard publications, revolutionized scientific visualization. From the pricy scientific atlas as it was published in many disciplines at the turn of the century to the standardization of visual evidence for textbooks and the massive popularization of scientific knowledge and technological progress by visual means in popular weekly magazines, the photographic image played an enormous role in almost every scientific discipline. However, one should be careful not to mistake the general application of this new method of image production with a technological determinism. Photography was developed and popularized at a time when science and society already tilted towards "mechanical objectivity," as Daston and Galison [3] have shown.

The historical examples briefly introduced here have at least three important bearings for our discussion. First of all, they show that a realistic mode of representation cannot be measured by some correspondence with an object "out there" and its physical, natural characteristics. A realistic mode of representation is itself a style comprised of a set of conventions [14]. These conventions control, maintain and stabilize the "realism" of the visualization. This does not mean that realism does not exist as a marker of scientific visualizations, far from it, realism and objectivity are very powerful constructs [3]. But they are historically contingent and functionally operative in specific socio-scientific contexts. Secondly, scientific images do not only have a long history but come in many different forms and serve a great many different functions. Arguments about general trends or developments should be very careful not to ignore or obfuscate the degree of variation that seems to be crucial for specific scientific images at work. And finally third, the technological circumstances of image-making procedures impinge upon scientific visualizations. The printing technologies Vesalius had at his disposal may have been exceptional for his period, but differ greatly from those available today. One may be tempted to phrase this difference in terms of technological progress, as a gradual or stepwise overcoming of technical obstacles, material conundrums or theoretical problems. There is nothing wrong with this view as long as it does not loose sense of the fundamental nature of technical mediation. Technological progress may appear to get closer to the things themselves but is hardly a step out of technological mediation, as will be shown in the next section.

3. The computer as universal image generator

Photography may have offered its services to a great variety of scientific disciplines at a time when its mode of image making appeared to be the almost perfect instantiation of mechanical objectivity. And as a historical consequence, photographic images started to dominate many branches of science from the end of the 19th century to a degree that one could be tempted speak of a homogenization of the scientific image. For a certain period of time, the photographic image became the paradigmatic example of visual knowledge, regardless of the conventions that went into its fabrication, circulation, and interpretation. The availability of photography and the predominance of mechanical objectivity resulted in a situation where the non-photographic image became the exception requiring explanation and justification. Niches for its survival were fields which relied on typological knowledge like classification schemes and classificatory atlases where the depiction of the particular was less desirable regardless of its objectivity [4].

The widespread use of photography for scientific images and the implicit claims about its scientific objectivity make photography a welcome case for comparing it with today's universal image technology, the computer. A first difference stands out immediately. The computerized image is not so much proof of scientific evidence or an indicator of scientificity, most scientific images simply are, as a matter of fact, computer generated. And this is obviously not an exclusive aspect of scientific images. The computerized image is part of a huge picture industry that comprises private photo taking as much as trick design for movies or sophisticated imaging software for visualizing process-related brain activity. This marks a very important difference to the usage of photography in the late-19th century. Photography could be said to entail, or at least enhance, a certain moral economy of disinterestedness and of mechanical objectivity. The computerized image, in contrast, mingles the scientific image with the lure and fascination of the artificially enhanced, the fabricated and simulated image. As Timothy Lenoir [11] has shown, there are no clear boundaries and only little differences between the visualization strategies employed by military agencies, the gaming industry, and companies designing medical imaging software for diagnostic purposes – an issue requiring further discussion below.

A second difference between photography and the current predominance of computerized images is the apparent lack of an explicitly normative model of scientific visualization. The recent and massive expansion of computer graphics not only made previous computerized images look pre-historical but offers imaging without limitations. Digitization is the regime of the day, and the computer acts as universal interface between almost all kinds of visual data and visualization strategies. Digital image technologies allow a perfect fusion of animation sequences with "real" footage. Today's visual reality is the hybridization of the artificial and the real image. This de-facto integration of all available visual information has created a seamless web of data transformation, analysis, calculation, and visualization. The scientific image participates at this larger trend. The analyzing power of the computer and the versatility of modern imaging software offer their services to the sciences and the movie industry alike. The central role of the invisible in scientific visualization explains why today's sciences are so receptive. In their intrinsic dynamic to reach beyond the reality of the everyday life, modern sciences may follow a different agenda, one that is structured by scientific discourse and criteria of objectivity, but a somewhat similar fusion of the real and the artificial, theoretical predictions and raw data, characterizes their pursuit. And for this similar means prove useful.

The versatility of current visualization software has opened hitherto unknown visual possibilities. The pervasiveness of digital imaging technologies, however, resulted in an empirically observable homogenization of scientific images at the same time, in which some modes of visualization dominate others. The fairly recent availability of powerful 3D graphics and of software packages allowing free rotations, for example, is the most likely reason for the widespread usage of such tools across various branches of science, from the cognitive sciences to drug design and virtual architecture. Again, it would be a wrong oversimplification to see technological determinism at work here. Certainly, the technically possible opens and constrains the realm of visualization. These are, above all, new options for new images that enforce users and groups of scientists to make decisions about the desirability of a particular mode of visualization. New technologies do not emerge in a social vacuum but co-evolve with styles and modes of scientific practices [1].

A second set of conclusions can be drawn here. Distinctive of today's "scopic regime" [7] is not so much a particular imaging technology, such as the graphic method in 19th century physiology, the bubble chamber in turn-of-the-century physics, or photography when it dominated many sciences as the new medium. Distinctive for today's visual knowledge is the computer as the obligatory passage point [2,10]. Digitization is the universal strategy to transform all data into code which can then be fed into a range of different methods of analysis, calculation, and data corroboration. Even in cases where the original data are non-digital signals such as, for example, film, fluorescent markers, electrophoresis gels, or radioactive traces, this regime has taken command and raw data are transformed, in a first step, into a universal digital format. This integration of vastly divergent data into a homogenized digital format corresponds with the pervasiveness of computing methods for the generation of scientific images across the disciplines. Specific packages and software tools for data analysis and visual representation have been developed for converting digitized data into visualizations. In fact, many scientific projects require the additional step of data visualization and a large quantity of scientific output is today produced in form of visualizations. This is a first hint for the role of knowledge visualization in research and problem solving. Spatial and conformational information which is of crucial importance in today's most dynamic scientific areas such as proteomics, the neurosciences or the nanostructure of materials. A visual display of this information is unparalleled by other means and here emerges a powerful domain of primarily visual scientific practices. This transdisciplinary shift from a textual to a visual logic of science distinguishes the emergence of computer graphics as an epistemological and media historical break. Back in 1950, Alan Turing stipulated the computer to be a universal machine performing every possible calculation; the total integration of all data into the universal matrix of digital information fulfills his vision in form of the thinking screen.

4. The thinking eye of the screen

Visualization and data analysis are so insolubly intertwined in today's scientific practices that the temporal order of imaging and knowledge acquisition is turned upside down. In many cases, visualization comes first and becomes a prerequisite for the generation of knowledge. Visualization participates at the research process itself in many ways, and is more involved in the production than the mere illustration of knowledge. As "thinking with the eye" described Bettina Heintz and Jörg Huber this new trend in contemporary sciences for which they provided examples from the visual pattern recognition in astrophysics to the identification of particles in high-energy physics, from drug design to the evaluation of artificial landscapes [6]. And the editorial for the recent "Visualization Challenge" of the journal *Science* spoke elegantly of "pictures to think with" [13]. The image has become a powerful tool for the production of knowledge.

An intriguing detail of this new reality of visual knowledge is the massive involvement of advanced technology and sophisticated methods of transformation which nonetheless result in surprisingly "realistic" pictures. This is the paradox of the technological intervention in visualization. The artificiality of the images seems to be balanced or countered by the technological strategies themselves. Digital images are obviously the products of machines, shaped and formed by the technologies applied for their production, but with the help of an intensified usage of technology or a more sophisticated application, the distortion can be accounted for and subtracted away. This is the promise of the computerized image as the perfect visualization tool; the technology involved in the production of the image shall become totally transparent with regard to the depicted object. The dream of total transparency by means of technological mediation is problematic for various reasons, the most obvious is the implicit assumption of a non-mediated image as the true representation of the real object itself.

In the case of today's scientific images this is especially problematic. Many phenomena which are visualized by means of computerized images do not exist as objects of our daily reality but require the coordinates of the respective sciences for their generation and stabilization. And hence, there is hardly any independent measuring rod available to compare the visualizations with. Scientific images are the product of many layers of instrumental intervention and visualize objects that are the product of long sequences of material-conceptual exchanges. The objects of the modern sciences are themselves artefacts – not in the sense that they do not exist but in the sense that they are products of a complicated research process. The object and its visual representation are the product of a mutually dependent process. The new visualization tools furbish the objects of the modern sciences with a striking realism of the artefact without an original. This does certainly not mean that these tools produce counterfeits, but the differentiation between forgery and mastery is now a question of the specific form of manipulation involved. The very usefulness of visualization tools hinges upon new avenues for data manipulation accentuating a particular aspect or highlighting a hitherto overlooked detail.

This realism of the computerized image stays in stark contrast to the objectivity with which the photographic image was once legitimized as the product of nature itself. The famous "pencil of nature" has long been replaced by software. If scientific visualizations provide nonetheless "realistic" representations, they do so not because of a particularly natural mode of production. Their realism is the consequence of a specific mode of transformation, of a special conformity with particular visualization styles. The realism of computerized images is the product of established traditions in visualization that started with Vesalius. Before scientists agree about new standards for dealing with digital visual evidence have the standards of image making already shaped the rules for the new cooperation of eye and computer on the screen.

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