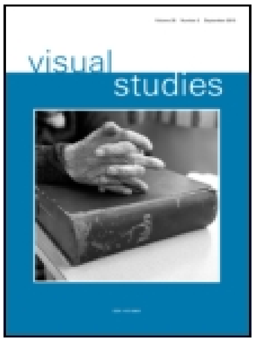

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An integrated model for conceptualising visual competence in scientific research and communication

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An integrated model for conceptualising visual competence in scientific research and communication

LUC PAUWELS

Visual representation in both natural and social sciences is an important and growing area of research and an ever-growing practice, given the rapidly developing visual imaging technologies. This article seeks to contribute to our understanding of the complex processes and decisions that go into producing and using visual representations as prime vehicles of knowledge building and dissemination. To that aim the author develops an integrated theoretical model for disclosing and interrelating the vast array of aspects in representational practices that affect the appearance and the uses that can be made of their visual end products. This knowledge will help towards developing scientific integrity and optimising expressive capabilities in scientific visual culture. In developing the model, explicit attention is paid to the diverse nature of referents in scientific research, the complex interplay across various types of 'translation processes' in arriving at legible and valid data, the imminent ambiguities and growing hybridity of visual representational methods and techniques, and the determining role of purpose and the urgent need to develop a more encompassing set of visual competencies among scholars.

INTRODUCTION

The multifaceted issue of visualisation in science involves the complex processes through which scientists develop or produce (and communicate with) imagery, schemes and graphical representations, computer renderings or the like, using various means (ranging from a simple pencil on paper to advanced computers or optical devices). Therefore, not just the result, but also how it was attained (i.e. the implicit or explicit methodology in the broad sense of the word) and the subsequent uses to which the result is put, should all be scrutinised as to their impact on the nature of what is visually represented and the ways in which this representation can be employed. Visual representations in science differ significantly in terms of how they relate to what they purport to represent (i.e. their representational and 'ontological' status), the means, processes and methods by which they are produced, the normative contexts involved, the purposes served and the many ways in which they are used and combined, to name but some of the more crucial aspects.

Scholars from very diverse disciplinary backgrounds (e.g. sociology of science, medical imaging, philosophy of science, history of science, geographical information systems, geology, biology, physics, visual anthropology, business sciences, information design, mathematics, communication studies, anthropological linguistics) have gradually taken an interest in the complex issue of visualisation in science. They have studied a broad range of types, aspects and uses of visual representations in the sciences, and each of those research traditions have contributed a lot to clarifying the huge potential as well as the many tribulations visual representational practices may implicate. Many aspects of the technical and social development of visual representations and the ways in which they are being employed have been approached from distinct theoretical paradigms and a variety of research methodologies (including, among others, ethnomethodology, phenomenology, semiotics, social constructivism, conversation analysis, interaction studies, ethnography, semiotic analysis, experiments, surveys, interviews, video-recordings, field notes). Researchers have scrutinised processes of perception and knowledge acquisition and negotiation with representations through detailed studies of practices and discourses of groups of people in different social and professional settings, such as those of fieldworkers (Lynch 1985a; Roth and Bowen 1999), laboratory scientists (Latour and Woolgar 1979; Knorr-Cetina 1981; Lynch 1985b), teachers, engineers, students, publishers, navigators and lawyers (Goodwin 1994, 1995, 1996; Pea 1994), to name just a few. A variety of products and media of visualisation have been studied in great detail, such as diagrams, photographs, drawings, and various scanning techniques. In particular, graphs and the social and technical processes that accompany their creation and use received much attention (Roth and McGinn 1997; Roth, Bowen, and McGinn 1999;

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FIGURE 1. Directly visually observable phenomena: aspects of human behaviour and material culture. Photograph by Luc Pauwels.

Roth, Bowen, and Masciotra 2002). Particularly influential are Tufte's books (1983, 1990, 1997) on the analysis and visual display of data and information and thus on the representation and use of knowledge in diverse sectors of society (see Grady 2006).

Scientific visualisation – in a broad sense – has been studied in view of its practicability in fostering educational processes and in bridging theory and practice (Gordin and Pea 1995), pointing at both unique opportunities and issues as well as obstacles. It may be seen as an enculturation device in a community of practitioners or scientists-in-process (Roth and Bowen 2001), but also as an evolving means of scientific and other areas of expression (Pauwels 1996, 2000, 2002) and a prime tool in the development of scientific literacy (Gordin and Pea 1995) among a diversity of audiences.

The many and highly divergent studies of scientific visualisation add up to an impressive body of knowledge that occasionally comes together in themed journal issues, readers and conferences, next to occupying a niche in the different disciplines and specialised journals. Synthesising the many contributions could be described, as Cambrosio, Jacobi, and Keating (1993, 663) called it many years ago already, as a 'hopeless task'. Yet, working towards integrating at least part of this knowledge and translating it into generic and more customised modules for use in many, if not most, academic curricula would be a significant step forward.

The model that I will introduce in this article essentially tries to integrate and clarify the impact of the social, cultural and technological aspects involved in the production and handling of visual representations, as well as the different normative contexts that may be at work and thus exert a determining influence on the eventual appearance and the usability of visual representations for scholarly (and other) purposes.

Each of these aspects, in my opinion, should be addressed in a much-needed project to enhance visual competency or visual literacy. Or in other words, developing knowledge and competence in these fields will help to constitute 'visual competence' or 'visual competencies' (acknowledging the highly divergent aspects and skills that are involved) in a more encompassing way.

THE VARIED NATURE OF THE REFERENT

The array of objects or referents of visual representations in science is very broad and of a highly heterogeneous nature. Visual representations in science may 'refer' to objects that are believed to have some kind of material or physical existence, but may equally refer to purely mental, conceptual, abstract constructs and/or

FIGURE 2. Referents visually observable via technical aids: fly's wing magnified through microscope (left); X-ray photograph of human head (right).

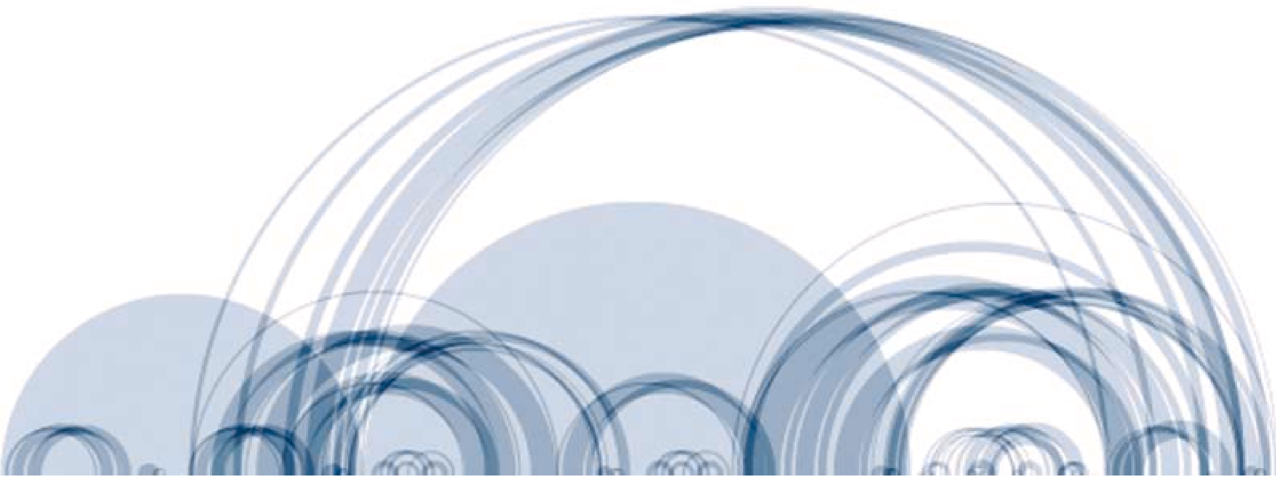


FIGURE 3. Visualising non-visual phenomena: the visual representation of Chopin's Mazurka in F# Minor illustrates its complex, nested structure. (Source: Martin Wattenberg 'The Shape of Song', http://www.turbulence.org/Works/song/index.html.)

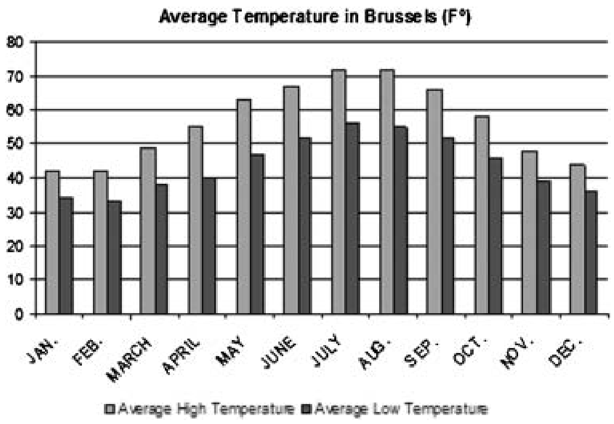


FIGURE 4. Visual representation of non-visual empirical data: a histogram of average monthly temperatures in a city.

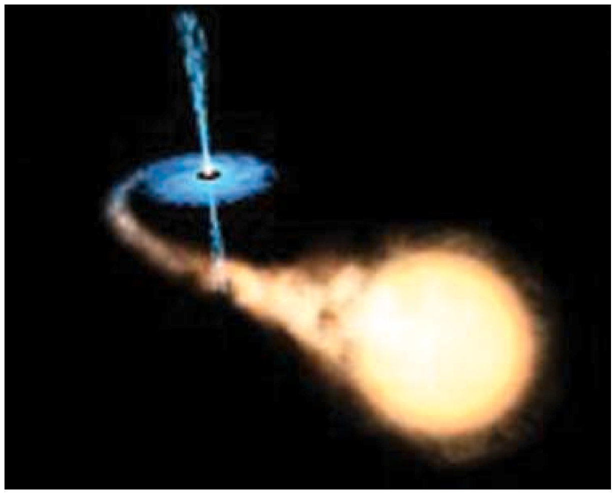


FIGURE 5. A postulated phenomenon: artist's impression of a 'black hole'. (Source: Wikipedia, *GNU Free Documentation License*.)

immaterial 'entities'. Material or physical referents may have visual characteristics that are *directly observable* to the human eye (e.g. various types of human interaction, the external structure of animals, trees; see Figure 1).

On the other hand, there are objects and phenomena with aspects that *only become visible with special representational means and devices* (e.g. they can only be observed using special techniques or instruments such as high-speed photography, satellite image transmission, a telescope, a microscope, or an endoscope). The reason is that these aspects are either too fast (e.g. an explosion, eye movements), too slow (e.g. transformations in a living organism), too big (e.g. stellar configurations), too small (e.g. microscopic organisms), too similar (e.g. colour of vegetation), too far away (e.g. planets) for the human eye to discern, or they are hidden (e.g. organs of a living body; see Figure 2) or inaccessible unless destructive course of action is taken (e.g. the dissection of an organism, the creation of a cross section of an object, the excavation of remains).

Furthermore, physical objects or phenomena may not have visual characteristics as such and still be *translated from a non-visible state* (e.g. sound waves, thermal radiation) *into visual representations* using special devices (see Figure 3).

Representational practices in science often seek not merely to 'reproduce' visual or non-visual phenomena, but also to provide *visual data representations* (e.g. charts) of aspects of these phenomena based on measurements of some kind (length, weight, thickness, resistance, quantity, temperature, verbal responses). In the latter cases, 'data' are derived from or constructed on the basis of an observed reality and subsequently represented in a visual form that allows one to discern changes or see relationships more clearly. While the resulting representations are based upon empirical observations or interrogations in the field, they are not 'reflections' of visual natural phenomena. They are, rather, visual representations of observations in the physical world that are not necessarily visual in nature. In other words, what is represented are not physical objects or phenomena, but 'data' that are constructed by observing aspects of the physical world. The relationships among the data and their representation are much more abstract/arbitrary and conventional, though some aspects may be also be 'motivated' or iconic (i.e. they may bear some resemblance to the referent). For example, graphical representations of the evolution of the birth rate within a particular population over a certain period of time, temperature fluctuations during one month in summer, or the number of murders per state do not necessarily entertain a visual iconic or indexical relationship with a physical or material referent, as often there is none. Instead, these data representations may have a 'mental' referent as far as the source is concerned, since the representations are not so much 'depictions' of phenomena in the real world as conceptual translations of aspects of it (see Figure 4). Yet they are based at least in part on quantifiable or qualifiable aspects of an observed 'reality' of some kind and thus are not purely invented or products of the imagination.

The referent of a representation may be even more *immaterial and abstract* in nature. Representations that primarily seek to visualise relations between observed phenomena visualise hypothetical relationships, postulated phenomena (see Figure 5) or effects, and even purely abstract concepts (see Figure 6). The referent of such representations may become an almost purely mental construct that has no 'pre-existence' in the physical, historical world whatsoever. Nonetheless, representations

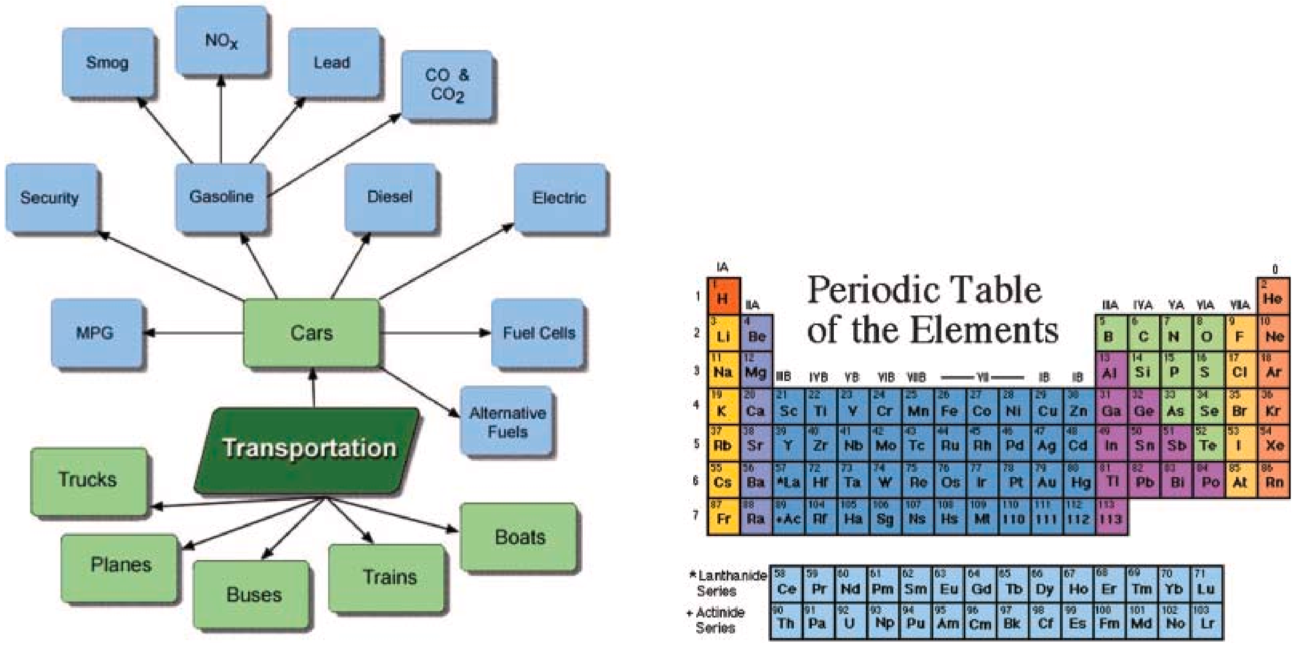


FIGURE 6. Visualising concepts, ideas and relations: mind map about transportation aspects (left); Mendeljev's periodic table of elements (right).

of these kinds of referents may play an important role in understanding or influencing that world.

Finally, it should be noted that many representations in science combine several of the above-mentioned aspects and thus have *multiple referents*. Certain aspects of the representation may, for example, refer to an observed visual reality in an iconic way (e.g. it might mimic its shape or colour) and include conceptual structures (such as metaphors) or symbolic elements (arrows, markers, colours, shapes). An edited film will refer iconically to the depicted subject matter (i.e. it will 'reflect it' to a certain extent), but at the same time it might allow scientists to express their vision or theory by means of the manner of recording and subsequent editing processes. In fact, mimesis without expression is virtually impossible. At the root of every presentation of fact is an implicit or explicit theory, a particular way of looking. In fact, visual representations may not only refer to the material world or to an abstract or imaginary world, but also may refer to a 'possible world', which may be the case when performing simulations to get an idea of what might happen when combining such and such parameters or phenomena.

REPRESENTATIONAL PRODUCTION PROCESSES: SOCIAL, TECHNOLOGICAL AND CULTURAL ASPECTS

Inscription, Transcription, Invention and Fabrication

Every 'representational' process involves a translation or conversion of some kind – a process of inscription, transcription and/or fabrication whereby the initial source (phenomenon, concept) is captured, transformed, or even (re)created through a chain of decisions that involves several actors (scientists, artists, technicians), technological devices and normative settings. This complex process of meaning-making has an important impact on what and how it can be known, on what is revealed or obscured, and on what is included or excluded.

As I have argued in the previous section, the divergent nature of the referent in science prefigures the crucial importance of the equally divergent processes of producing a visual representation. These processes not only involve technical issues but also encompass important social and cultural aspects. Obviously, technology and each of its products are part and parcel of culture (i.e. they are both a cultural product or 'result' and a cultural actor or 'force'), both in a broad cultural and a more restricted sub-cultural sense, and thus they embody specific norms and values. Apart from the characteristics of the instrumentation, which are to some degree a result of cultural processes as well, a host of other social and cultural influences at the moment of choosing and selecting the objects, samples and so on also have an important impact on how the representation will appear, as well as on the purposes it may subsequently serve.

Analysing the Social and Cultural Setting: Division of Human Labour and Different Normative Contexts

Rosenblum's (1978) sociological study of photographic styles demonstrates how the 'look of things', particularly the appearance of press, art and advertising photographs, is to a significant degree a function of various social, technological and cultural factors and constraints that are connected with their creation. The division and standardisation of labour, technological constraints, professional ethics, time pressures, as well as economic factors all play a significant role in their creation, look and value. Sociologists of science, on the other hand, have studied the complex interactions in a laboratory setting where science is being 'produced' (Latour and Woolgar 1979; Lynch 1985b), an approach that yields insight into how an object of inquiry is selected, delineated and 'prepared' to fulfil its role. Lynch has looked at the laboratory setting and the processes by which natural objects are visualised and analysed. Preparatory procedures that tend to turn the object of investigation into what Lynch calls a 'docile object' fit to be studied according to the established methods and mores of science, as well as various aspects of the instrumentation and the laboratory set-up, challenge the idea that scientific visualisation provides an unproblematic or uncompromising 'window' onto the natural world (Lynch 1985b, 43–4). Similar processes are at work when scientists make observations in the 'field'; here too, objects are selected and prepared to be subjected to scientific practices or made to participate in data-generating procedures. Furthermore, the issues of research funding, academic recognition, peer relations and societal trends must all be taken into account if one endeavours to reveal and explain the processes that lie at the heart of particular visual representations of facts or ideas. They likewise may influence what is selected and how it is selected, and the way in which it is processed.

The Varied Nature of Visual and Non-visual Transcription

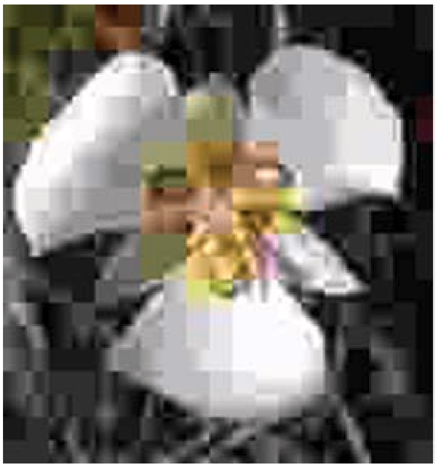
There is a fairly significant, though not exclusive or unconditional, relation between the nature of the referent and the processes through which a representation is or ought to be produced.

Obviously, *conceptual constructions* that have no material, let alone visual, substance cannot be recorded automatically or according to standardised and repeatable processes (e.g. mental images cannot be photographed or scanned electronically), as they are the result of multiple intentional acts that, first and foremost, require a suitable production technique for such highly intentional activity (e.g. pencil and paper or a computer drawing package). The involvement of the originator of the idea is paramount, and a demanding process of translating a mental image into an inter-subjective visible image is required. Aspects or dimensions that cannot in any way be visualised or verbally described are in fact lost to science.

Objects or phenomena that are *visible to the human eye* through direct observation, on the other hand, can be captured by representational devices such as a photographic camera that will produce detailed representations characterised by uniform time and continuous space. This may result in a kind of 'indifference' (some might say 'objectivity', though this may be too burdened a term to use), since all elements and details are treated equally (even though photographers have ways of foregrounding or emphasising certain aspects at the expense of others, such as through the choice of lens, film, filters, lighting, framing, viewpoint). However, directly observable phenomena can also be represented through more manual techniques, using simpler media, such as pencils and brushes, which require a more *intentional* series of acts by humans (draughtsmen, illustrators). These techniques produce images that do not have a uniform time (in fact quite some time may pass during the creation of the different parts of the representation) and that are not bound by continuous space or a uniform use of scale.

Every representation requires some kind of device or medium. Yet it is useful to make a distinction between mediation processes that are highly automated, or *algorithmic* processes (e.g. photography), and more manually and intentionally performed activities (e.g. hand-drawn or driven representations). However, these are not absolute categories and it is better to think about this useful distinction as two extremes of a continuum. Moreover, current digital technologies have blurred the dichotomy between 'machine-generated' and 'hand-made' imagery and increasingly have allowed for more complex combinations of the two (for instance, digital photographs that can be manipulated at will with the aid of sophisticated software).

The process whereby one works from a *directly visible referent to a visual representation of it* would appear to be the most straightforward, but even then a great variety of techniques are available. Moreover, even the more commonly applied techniques have their intricacies,



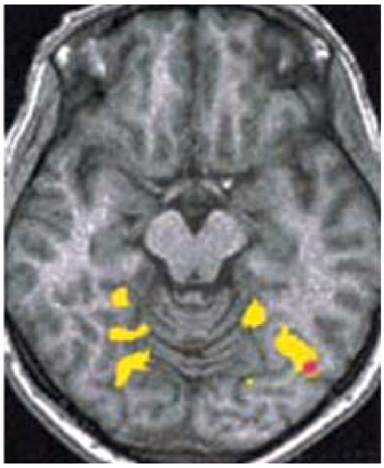


FIGURE 7. 'Artefacts of instrumentation' generated by inadequate resolution: a flower receiving a 'pattern' that does not refer to the anything in the physical world due to low resolution (left); a brain scan displaying objects that are 'produced' by the scanning device and thus may lead to a wrong diagnosis (right).

which are easily overlooked. This is true of relatively simple and ubiquitous techniques, including photography of directly observable phenomena, where one often has the advantage of being able to compare the referent (the object or phenomenon with a material existence) and the depiction (a drawing or photograph). However, as much as such devices may differ in terms of the manner in which they 'translate' an object or phenomenon into a record of it, it is important to note that both the source or the referent (the natural object or phenomenon) and its representation are 'visual' in nature and are respectively captured and constructed by methods or processes that are essentially visual as well. In such instances, there is at least the theoretical option of comparing the source and its representation in order to assess to what degree and in which respects they resemble one another. Thus, a 'check of correspondence' can be performed, albeit only to a certain degree.

A much more complex translation process occurs when the referent is visual and physical in nature (though often hidden from direct observation), while the *intermediate steps are not based on reflected visible light* waves. This is the case, for example, when ultrasound scans or X-rays are used. In these instances it is not light that is reflected by the object that is recorded, but a reaction of other types of 'invisible' waves to some characteristic or aspect (e.g. density) of the structure of the referent. These translations, while equally 'indexical' in nature, typically require a more cumbersome process of decoding and calibration (Pasveer 1992); they do not allow a simple check of 'visual correspondence'. Radiologists, for instance, need to learn how to 'read' these images, and even then they may differ on how a particular one should be interpreted.

If the translation process is not visual or if the referent is inaccessible or invisible to the unaided human eye, one has to rely on – and thus transfer authority to – the machine (Snijder 1989) in order to chart often unknown territory. In such cases, one has to be particularly aware of the possibility that one is looking at *artefacts of the instrumentation*, that is, the 'objects' and effects that are generated by the representational processes themselves and that do not refer to anything in the 'outside world' or at least not to the phenomenon that is under scrutiny (see Figure 7). In many data-generating processes, it is not always easy to differentiate 'noise' from 'data'. Artefacts or effects thus may be attributed erroneously to the outside world, while in fact they are produced in a standard way by the instruments or as a result of technical failure. Moreover, an atypical representation also may result from an unexpected and unaccounted event or coincidence in the physical world.

So, especially if the referent is of an uncertain nature, the problem of artefacts of instrumentation may arise. This may be the case when the existence of the referent is postulated rather than confirmed by fact and the process of representation serves the purpose of providing such evidence; or when complex instruments are being used; or when aspects of reality can only be seen through the instruments – that is to say, as a 'representation'. But even with very realistic renderings of directly visible objects (e.g. simple camera images of directly observable phenomena), one should be wary of the possibility of 'effects' induced by the instrumentation. Such effects can present themselves to the uninitiated eye as qualities or traits of depicted objects (colour, shape, spatiality) while in fact they are merely properties of the instrumentation (e.g. the extremely foreshortened

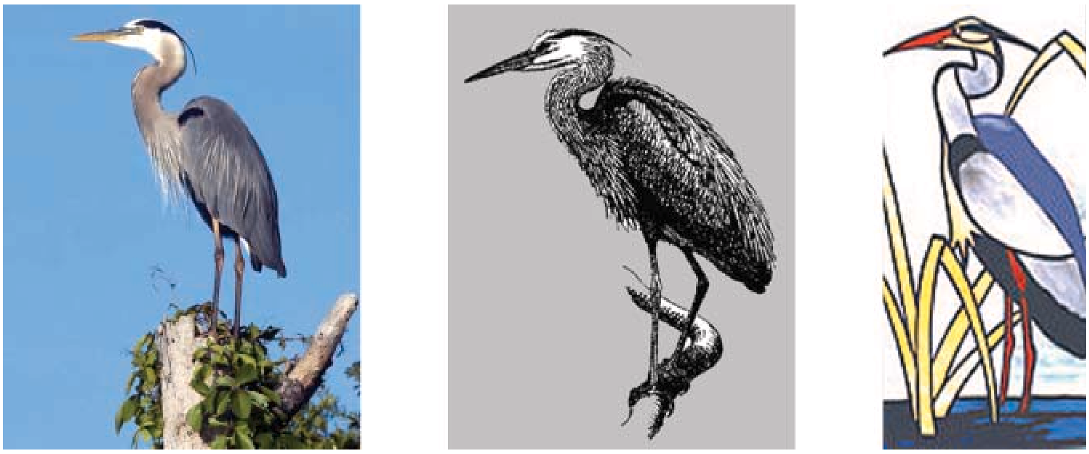


FIGURE 8. An algorithmic (photograph) and two very different non-algorithmic (hand-drawn) representations of a blue heron. The context and purpose of use should steer the choice of representational technique as well as the stylistic options within that technique.

perspective when using telephoto lenses makes objects appear much closer to one another than they are in reality; internal reflections may produce flare and ghosting; and so on). In a similar way, scientists should be aware of the possibility that important aspects of the referent might not be captured by the instrumentation (e.g. because of an inadequate resolution or insensitivity caused by a limited spectral range) or might mistakenly be weeded out as noise. Instruments, in addition to capturing or recording data, invariably both reduce (or lose) data and tend to mould (and add) data in a particular way. These two phenomena in themselves should already warn against a naïvely realistic view of the merely technical aspect of representation.

Algorithmic versus Non-algorithmic Processes

Technically sophisticated instruments that produce representations or images in a highly automated and standardised way (such as cameras and scanning devices) are generally thought of as the most suitable for scientific purposes, as they produce coherent, reliable, and repeatable representations with a predetermined level of detail. Moreover, they tend not to rely too much on personal judgment or skills in the process of image generation, unlike manual techniques such as drawing (though the interpretation of such representations may still require a lot of personal judgment and experience!).

However, in some cases more intentional processes and products may be far more convenient. This is true, for instance, if the depiction is *too detailed* for the intended purpose. This may be the case when using a highly automated and 'indifferent' process such as a camera recording. Such a recording can be indifferent in the sense that all visible elements in front of the lens receive the same treatment, irrespective of whether they are relevant to the researcher. Thus, the essence of the recording may be obscured by unneeded, distracting or irrelevant detail that can impede comprehension. Furthermore, intentional processes allow a much swifter combination of *different types of signs (iconic, indexical and symbolic) and levels of signification*. Consequently, they may yield a more functional expressive presentation of fact and vision. A third important consideration is that intentional processes may provide a much-needed *synthesis of features* rather than a simple transcript of a particular (snapshot-like) instance of a phenomenon.

For instance, ornithologists who use imagery to determine the species of a particular bird encountered in the field may be better off with well-crafted illustrations of a number of similar-looking species – such as a coloured drawing that contrasts a heron (*Ardea cinerea L.*) and a purple heron (*Ardea purpurea L.*). After all, they can derive from such a drawing how the two birds differ 'in general'. Colour photographs, on the other hand, unavoidably show a particular specimen of each type of heron in a particular stage of its development and photographed against a particular background, in particular light conditions and from a particular angle. This photographic 'particularity' may be less helpful in determining the species of an individual bird in the wild. On the other hand, purposefully simplified representations and abstractions may instil some misconceptions in people's minds if they are not duly communicated or if they are used for other than the initially intended purpose (see Figure 8).

For example, medical students may be baffled by the visual differences between stylised and simplified anatomical drawings of heart, lungs and vascular system in their introductory courses and the 'real thing'. Similarly, engineering students may be surprised by the differences between a highly stylised drawing of engine wiring and the three-dimensional reality of a dismantled engine that needs reassembling.

Scientific illustration, as a sub-discipline of science, is an interesting example of a speciality that has evolved in recognition of the fact that both scientists and artists generally lack the skills to produce renderings of birds, human anatomy or complex technical artefacts with the required level of detail and generic faculties. Using artists who are very skilled in drawing, but largely unaware of the exact purpose of the illustration, inadvertently will produce imagery that may thwart that purpose. Scientific illustrators, on the other hand, need to be well versed both in the art of illustration and in specialised fields of science. They are trained to have a thorough and fully integrated knowledge of the subject matter or concepts that they are asked to draw and of the exact scientific and didactic purposes their products need to serve.

THE VISUAL PRODUCT: THE IMPACT OF MEDIUM AND EXECUTION/STYLE

Cultural Impact on Style and Use of Media

Visualisation obviously results in a product that can be 'seen': a graphic representation, a photograph, a computer rendering. The products of a visualisation process emanate the characteristics of the (final) medium or successive operations as well as the features of the particular application or instance: the selections and choices of what and how to depict.

The end medium or medium of presentation has an important impact on the final appearance of a visual representation. Although each medium has a number of preset characteristics, within each medium there is almost always a great variety in the manner in which a particular referent may be represented (mimetically and expressively). This choice and combination of specific formal options henceforth will be referred to as the 'style of execution'. The style of execution is only partly determined by the medium. The notion of a wide variety of styles within the same medium is illustrated easily by divergent painterly traditions such as cubism and hyperrealism. Similarly, scientists may choose a variety of methods and techniques (ranging from realist to extremely stylised, to metaphorical, or even phantasmagoric) for depicting a particular subject or idea. These variations in style have to do with genre conventions, cultural schemata, scientific traditions, specific circumstances of the production process, skill, preferences and idiosyncrasies of the maker, as well as the specific purposes the representations need to serve. To complicate matters further, various media and styles may be combined in a particular representation, lending it a highly hybrid character.

Even if the referent is a phenomenon that is accessible through direct observation, this is still not a guarantee for a 'faithful' or reliable reproduction, especially if a non-mechanical process, such as hand-drawing or painting, is involved. This is particularly true if the phenomena are drawn from memory after a brief and perhaps exciting encounter (for instance, the early drawings of newly discovered animals). For representations based on first encounters or limited study, even the scientists may not know to what extent their representations have a rule-like (general) as opposed to an exception-like (deviant) quality. Even if memory is not the major obstacle, perception is always coloured by prior knowledge of other phenomena, drawing conventions, cultural representational schemata, matters of skill and mental processes. The human mind, as Gestalt psychologists revealed, seems very eager to fill in the gaps and to make us see what we want to see. Art historian Gombrich (1994 [1960]) provided a textbook example of this when he commented on Dürer's famous woodcut of a rhinoceros (1515): 'he had to rely on second-hand evidence which he filled in from his own imagination, coloured, no doubt, by what he had learned of the most famous of exotic beasts, the dragon with its armoured body' (Gombrich 1994, 70–1). But even drawings that are claimed to have been made 'from life' ('sur vif'), such as Villard de Honnecourt's 'Lion and Porcupine' (about 1235), may not provide us with depictions that are as faithful as the medium allows but highly idiosyncratic or artistic renderings, which, in de Honnecourt's case, included a quirky stylised lion that would better serve heraldic purposes than (naturalistic) representational ones. Gombrich concluded that the claim that something was made 'from life' clearly must have had a different meaning at that time: 'He can have meant only that he had drawn his schema in the presence of a real lion' (Gombrich 1994, 68).

Visual Representational Latitude: Coping with Controlled and Uncontrolled Variation in the Depicted and the Depiction

Though visual media and techniques provide many unique advantages in representing the physical world and in expressing scientific ways of thinking, as soon as a

FIGURE 9. The issue of 'visual representational latitude' exemplified: do these non-algorithmic representations of a porcupine each refer to different (sub)species or do they merely embody different artistic interpretations of the same (sub)species?

certain level of abstraction or generalisation is needed – an essential facet and phase of many scientific undertakings – some distinctive problems may arise. Verbally, for instance, one can state that a certain bird species may have three to seven spots on its wings. However, when producing a visual representation, one inevitably must draw a definite number of spots. Visuals, unlike oral descriptions, do not offer the option of indicating a range, say 'from three to seven'. Instead, a choice needs to be made out of the five possibilities when representing in a single drawing a species that exhibits that amount of variation. Moreover, if a photograph is used, one is even forced to show a particular specimen of the species (or a series of photographs of different specimens), of a particular age and sex, in specific circumstances (habitat, weather, time of day, season). Neither intentional nor more automated (algorithmic) visual images can in themselves express in a simple way the variation (in shape, colour, amount) one may expect to encounter in the real world. Nor can visual depictions fully explain the connections among the particularities of the representation (the variation in the depiction) and what they seek to refer to (the phenomenon and the different forms it can assume in reality).

This multifaceted problem of different types of justified or unjustified variation in scientific representations, combined with both the variation that exists within the species or phenomenon that is depicted and the variation in the depiction of certain phenomena or ideas, is what I would propose to call 'visual representational latitude'. This latitude will be determined partly by the capacities of the medium applied (e.g. intentional versus algorithmic media) in coping with the variation observed within the depicted phenomenon or process, but more importantly by the *manner* in which that medium is used, including the stylistic options it offers, the scientifically motivated choices and the various 'liberties' that producers allow themselves. The 'room for manoeuvre' or representational margins may or may not be purposeful, functional and understood (see Figure 9).

Visual representational latitude, therefore, is not just a producer's (or sender's) problem; that is, it is not just a matter of deciding how to express variation, of choosing the right level of iconicity or abstraction for a specific purpose. It is also a user's (or receiver's) problem: what kind of variation is to be expected in the real world, and which elements in this particular representation are 'motivated' by a perceived reality, and which others are due to specific, intentional or unintentional choices of the producer, limitations of the medium or larger production context? To what extent is every choice to be interpreted as 'necessarily so' or as just 'one way of putting it'? If, for instance, a physical phenomenon is depicted as consisting of a core with, say, 23 particles revolving around it, one is still uncertain whether this exact number of particles is a unique and thus determining trait of the phenomenon, or whether the person who produced the diagram merely meant to indicate that 'many' particles are revolving around the core. Similar questions could be raised with respect to the relative distance of the constituting parts of the drawing, their scale, colour, shape and so on.

Verbal comments (e.g. in the form of an extended 'legend') are one way of making sure that users know what they are looking at, what codes are being used, what semiotic variation is being employed and what representational claims are put in effect by the representation. Another way is to develop further a visual language of scientific representation, which in a sense restricts the ways in which visual elements may be employed, but at the same time enables a more visual and less ambiguous form of information transfer and expression.

TYPES AND CONTEXTS OF USE: MATTERS OF ENCODING AND DECODING

Representational Constraints

Representations cannot serve adequately just any purpose or intent. Various significant relationships exist between the type of referent, the production process, the medium and the types of uses and claims that can be attached to them. Visual representations must have the necessary 'properties' to comply with certain functions or uses. Properties, for that matter, refer not only to the characteristics of the medium that is employed but also to the broader contexts of both production and use.

Mitchell (1992) distinguished between two types of representational 'constraints' or, put differently, two factors that both the producer and user will have to take into account when trying to apply visuals successfully in a communication and cognitive process. First, there is what he called '*representational commitment*', by which he meant that certain techniques are (more) appropriate for recording certain things and less suited or even totally unsuited for recording others: 'different medical-imaging techniques – CT, ultrasound, PET, MRI, and so on – are committed to acquiring different types of data about bony and soft tissue diseases and physiological activities, and so are used for different diagnostic purposes' (Mitchell 1992, 221). Similarly, black-and-white photography may offer the right kind of detail to study naturally occurring phenomena in a social context and thus may be an ideal tool for anthropologists and sociologists; but in some instances this representational choice will be less than adequate. This could be the case, when documenting trends in fashion, home decoration and the like, where the use of colour embodies essential information; or when a detailed account of processes is required, which can only be achieved by means of a continuous record of moving images. A second requirement that Mitchell puts forward is that a visual representation 'must have the correct type of *intentional relationship to its subject matter*' (Mitchell 1992, 221). Some examples may help illustrate the importance of this requirement: the picture of an escaped convict may help police track down that particular individual, but his facial characteristics cannot be used to identify other individuals with criminal tendencies before they can actually commit a crime. Likewise, a scan of a pathogenic heart may serve as a diagnostic tool to help one particular patient, but that is not to say that it is the most appropriate representation for use in a general biology textbook.

However, the same medium types of representation may serve many purposes and entertain widely divergent relations with the depicted matter. Furthermore, a particular visual representation that was made for a specific purpose may be suitable for other purposes, even for some that were not envisioned at the time of production. However, in most cases one needs to know exactly how the images or visual representations came about and what their broader context of production was before one can assess their validity for those other purposes. The use one can make of a representation is determined, to a considerable extent, by its generative process (choice of visual medium and broader production aspects: choices regarding style, selection and preparation of subject, normative systems) vis-à-vis its intended use. So, in so far as this is possible, a predetermined purpose should guide the production process. Some purposes, such as the exploration of a naturally occurring phenomenon, may require an indifferent, detailed account of particularistic data in their specific context, whereas others, such as educational aims, may better be served by highly stylised and synthetic representations highlighting only the essence of a more general phenomenon. So the medium and the techniques in part will determine the uses that can be made of a representation, but even representations produced with the same medium or technique may have widely divergent intents and representational positions.

Kinds of Intents and Purposes

The intents and purposes of visual representations in scientific discourses are manifold. For one thing, natural phenomena might be visualised for the purpose of *further analysis*: to make a diagnosis, to compare, to describe, to preserve for future study, to verify, to explore new territory, to generate new data and so on. Representations that serve these primary purposes will

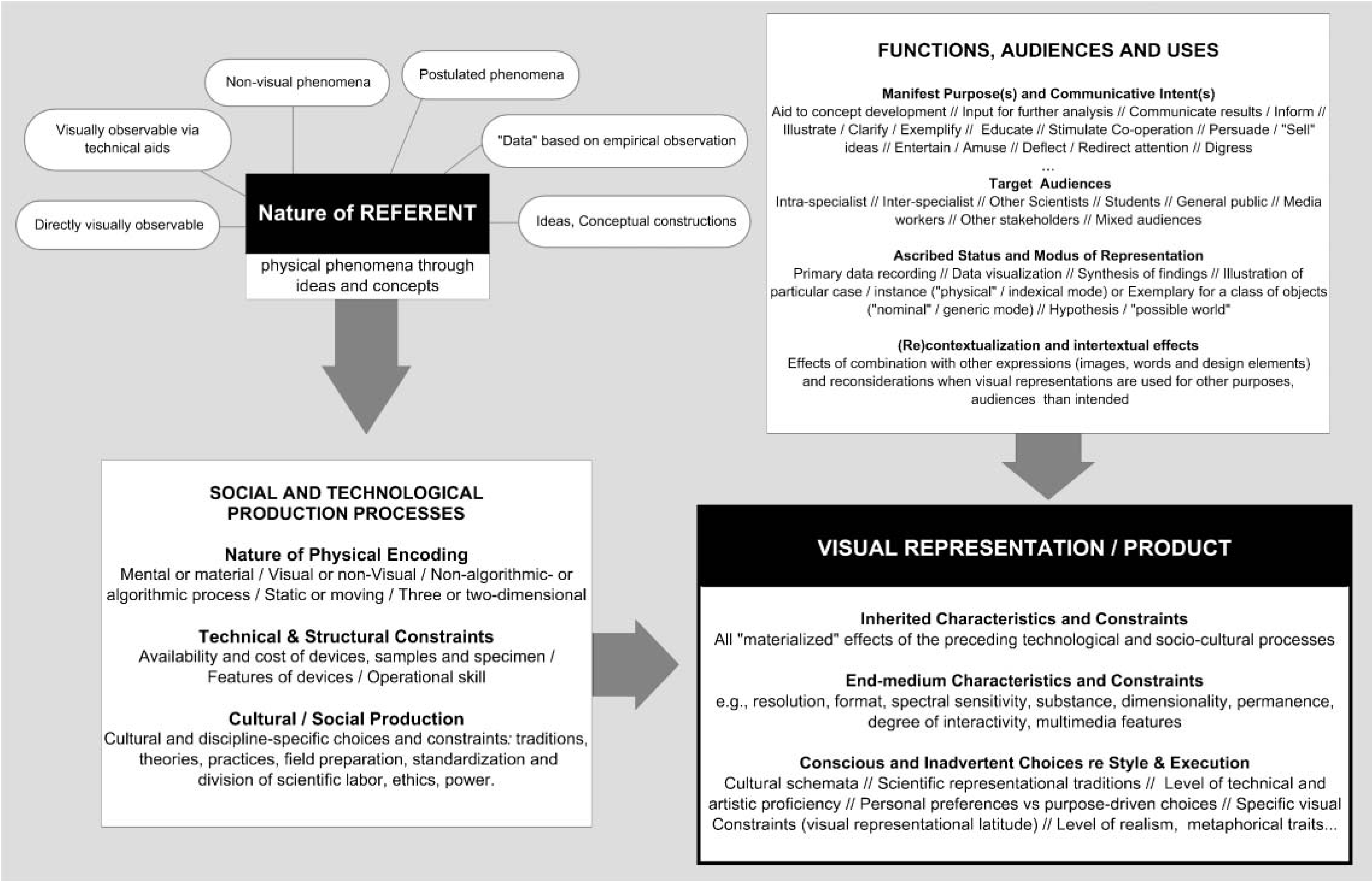


FIGURE 10. A conceptual framework for assessing and creating visual representations for scientific purposes.

often be algorithmic in nature and they may have an only 'intermediate' function, since they are primary 'data'. Visual representations that have no material referent may serve primarily to *facilitate concept development* or to uncover relationships, evolutions (e.g. through charts of all kinds) and, in general, to make the *abstract more concrete* and thus more accessible for further inquiry. Forms of externalised thinking (conceptual graphs) may be useful both on an intra-personal level (for example, to guide researchers in a dialogue with themselves) and on an inter-personal/inter-specialist level (e.g. to exchange ideas in an early stage, to invite feedback or to prompt cooperation from peers). Visual representations not only serve analytical and intermediate purposes, but they are also often used to *summarise or synthesise* empirical findings or a theoretical line of thought. Thus, they may provide an overview, display results in their spatial organisation or conceptual relations, or clarify the textual or numerical part. In science, more synthesised or purposefully assembled visual representations generally serve to facilitate knowledge transfer in a variety of ways and seek to communicate with diverse audiences. They can illustrate, demonstrate or exemplify features, relations and processes, or provide mediated experiences, in ways that are adapted to the audience (which may vary from highly specialised to lay audiences).

Many visual representations will intentionally or unintentionally embody an implicit or more explicit view on, or argument about, what is being presented visually, through the many elements and choices that make up the representation. This expressive function of scientific visualisations need not be a problem as long as it is duly acknowledged and, if required, explained. As intentional forms of communication, and through the selection and formal execution of the representations as well as by their thoughtful arrangement in the broader context of an article, a presentation or a multimedia product, visual representations will attempt to exert a certain amount of persuasion. Often, receivers or users of the representation will, in subtle ways, be invited, seduced or even compelled to adopt the views of the sender and to perform the preferred actions (to believe, give approval, appreciate, change opinions, donate money or support morally). For those reasons, but also for the more acclaimed function of cognitive transfer and education, a visual representation may perform the function of an eye catcher, a means to arouse and maintain attention and interest, or even to entertain the reader/spectator (and thus bring them into the right mood for acceptance). Some aspects of a visual representation in science may even perform no other function than to appeal to the aesthetic feelings of the receivers or just be an expression of the personal aesthetic preferences of the maker. These latter functions, though not readily associated with a scientific discourse, are not necessarily detrimental to the mission of a scientific undertaking, as long as these traits do not interfere with the more fundamental functions of data or cognitive transfer, and on condition that transparency is provided.

While we can never be complete in the listing of possible functions and intents of a scientific visual representation, this brief discussion of functions demonstrates that the idea that scientific visualisations and representations are solely meant to generate and present 'objective' data or to facilitate pure cognition should be abandoned. It should be clear that most functions and intents that are found in human communication will also be found in scientific representation, though some functions and intents obviously will serve a more central role, whereas others will not feature prominently or may be intended to perform an auxiliary function. Moreover, it should be clear that any visual representation used as part of a scientific discourse will serve and combine different functions at the same time, whether intentionally or unintentionally. These purposes may be scientific in a narrow sense, but they may also have to do with intents that lie outside the realm of the acknowledged scientific purposes, such as to serve vested interests of persons and institutions. Finally, it should be stressed that the different functions that are embodied by aspects of the visual representation may be read or 'decoded' in many different ways by different receivers (based on their intents, experience, formal background) in different contexts and over time.

CONCLUSION: DEVELOPING VISUAL SCIENTIFIC COMPETENCIES

The basic premise of this article is that representations and representational practices may be extremely helpful in developing, clarifying or transmitting scientific knowledge. However, when not produced and used with extreme care and competence, they may create at least as much confusion and as many misunderstandings. If one considers scientific representations and the ways in which they can foster or thwart our understanding, it is clear that a mere 'object approach', which would devote all attention to the 'representation' as a free-standing product of scientific labour, is inadequate. What is needed is a *process approach*: each visual representation should be linked with its context of production.

Moreover, it cannot be understood sensibly outside a particular and dynamic context of use, re-use and reception. However, given the great many types of referents, representational techniques, purposes and uses, it seems fair to assume that the vast consequences of this requirement are hardly grasped by the growing number of people who produce and use visual representations on a daily basis.

Scientists should more actively develop a sensitivity for the wide variety of visual representational practices and products and the many ways in which they can be deployed in scientific discourse. Furthermore, a real set of skills is needed in order to be able to *assess* the usability of given representations based on a thorough knowledge of their generic processes, and to be able to *produce* visual representations with the required representational and expressive properties in relation to their purpose(s). Visual representations invariably have a strong communicative function, certainly with regard to the originator (e.g. to guide his or her thinking, or to serve as data for further analysis), but often also toward a variety of specialised and non-specialised audiences. Unconsciously applied and/or unmotivated use of aesthetics and unexplained use of certain conventions are a potential hazard, whereas well-thought-out and reflexive use of aesthetics, formal choices, and well-explicated representational codes and conventions may create hitherto not fully exploited opportunities to further scientific knowledge building and communication. Modern technology offers many complex ways of generating images, but few users have a clear understanding of all the steps involved. To counter this emerging 'black box syndrome', it is clear that scientists need to keep track of new media technologies to the extent that they offer new ways of looking and (not) knowing.

This complex set of requirements involving specific knowledge attitudes and skills may be understood as a specific kind of visual literacy or competence for scientists. Visual competence for scientists can therefore be defined as a reflexive attitude (throughout the production process), a specific body of knowledge, and even a certain level of proficiency or skill in assessing and applying specific characteristics (strengths and limitations) of a particular medium, and awareness of cultural practices (codified uses, expectations) and the actual context of use (including the 'cultural repertoire' of the intended audience). In other words, a visually competent scholar should be aware of the impact of the social, cultural and technological aspects involved in the production and handling of representations, as well as the different normative systems that may be at work and how they exert a determining influence on the eventual appearance and the usefulness of representations.

Visual scientific competency should not just imply establishing a clear division of labour (every person keeping to his trade) and then linking together those various types of expertise, as in fact they need to be merged rather than developed and applied according to a separate logic for each specialised aspect. The different normative systems (e.g. scientific, technical, creative, cultural) that are consciously or unconsciously employed need to be skilfully combined with a view to the ultimate purpose of the representation. While expertise obviously cannot be accumulated endlessly in one and the same person, a serious effort should at least be made to provide a unifying framework whereby each contributor should develop a knowledge about and sensitivity for the bigger whole. What they should not do is lock themselves up in their own area of expertise, as hardly any choice that is made along the way is without epistemological consequences.

The aspects and issues that have been discussed in this article may serve as a theoretical framework for the thoughtful production of visual representations in science or they may be used as a tool to critically assess the appropriateness of different aspects of particular representations. Such a framework may prove useful in examining the complex interdependencies that exist between the nature of the referent, the social, technological and cultural context of production, the choices with respect to medium and the style of representation, and the purposes and uses that need to be achieved. Figure 10 is an attempt to summarise and – be it in a rather limited way – visualise the elements and arguments of this framework as gradually developed from section to section. Visual representations will always be used to enlighten and broaden our understanding, but at the same time, they will continue to obscure it. Concerted and integrated efforts in delineating and developing visual competencies will considerably help scholars to optimise the production and uses of visual representations in various types of research and communication.

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