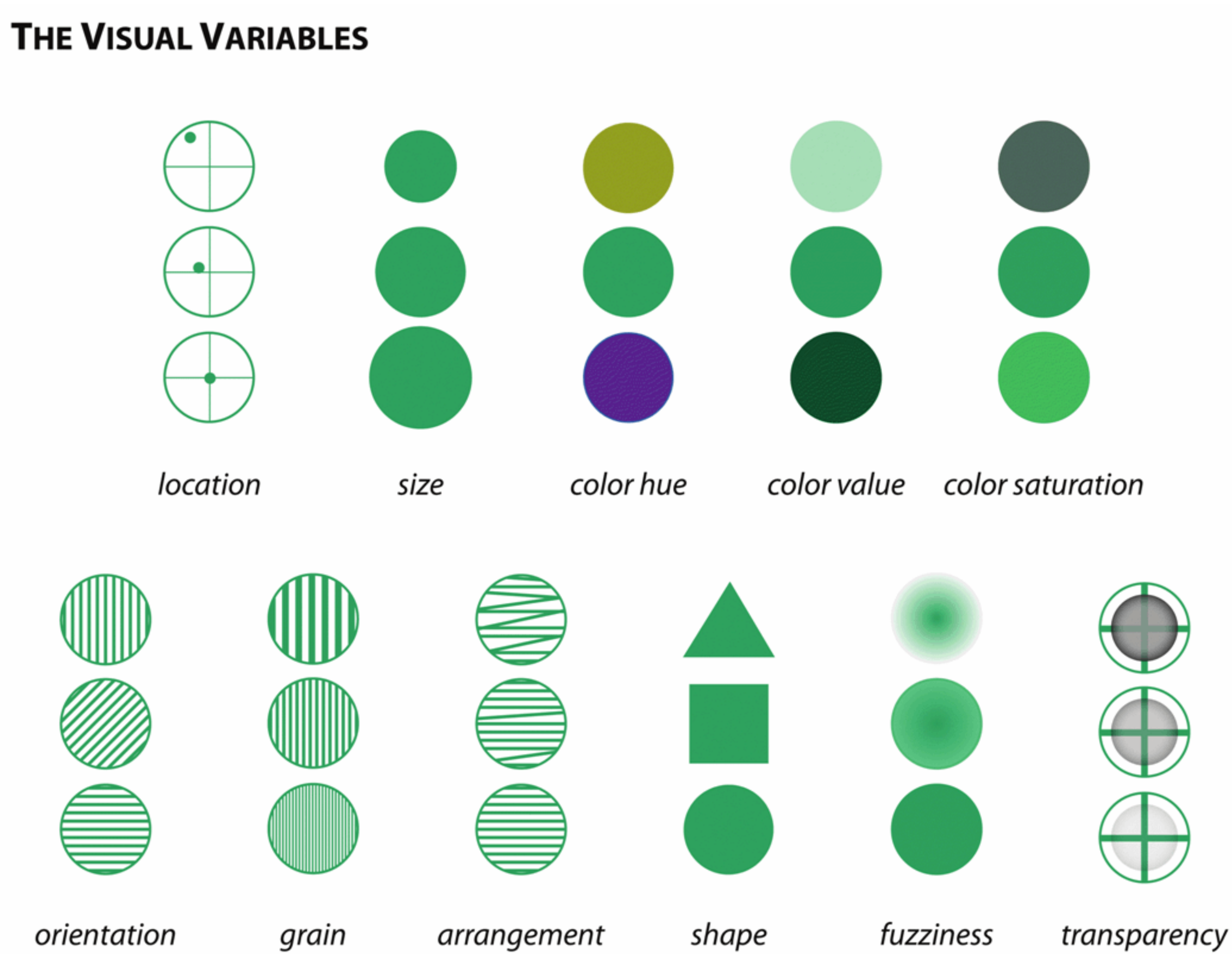

Figure 1: The Visual Variables.

Alan M. MacEachren et al., “Visual Semiotics & Uncertainty Visualization: An Empirical Study,” IEEE Transactions on Visualization and Computer Graphics 18 (12): 2496-2505 (2497). Image used with friendly permission of Prof. Dr. Alan M. MacEachren, Pennsylvania State University and Dr. Robert Roth, University of Wisconsin-Madison.

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Uncertainty Visualization and Digital 3D Modeling in Archaeology. A Brief Introduction.

Una Ulrike Schäfer

Abstract: Uncertainty is ubiquitous in everyday life; domains as diverse as engineering, finance, and insurance are increasingly aware of the far-reaching impact of uncertain data. Well-established research fields like the natural sciences are concerned with the intangible phenomenon of uncertainty, in addition to disciplines like geography, information visualization, and history. In this context, a range of disciplinary approaches were surveyed with regard to the methods and techniques developed and applied to deal with uncertainty. As a result, various efforts were made to consider suitable taxonomies, quantification methods and visualization strategies. Emphasis is particularly laid on archaeology, highlighting research in three-dimensional digital modeling and reconstruction and related archaeological discourse of the last two decades.

Keywords: uncertainty, visualization, archaeology, 3D modeling, digital reconstruction.

Introduction

> *Understanding uncertainty is one of the great scientific challenges of our time.*[1]

Uncertainty is everywhere. Not only in the philosophical sense but also in everyday life. With regard to 'data as the currency of the 21st century' virtually every existing domain of our social life is more or less affected by noise, imperfection or uncertainty. Buzzwords like big data, data mining, predictive modeling or data-driven decision making are prevalent. They indicate pervasive socioeconomic as well as technological transformations which are connected to the rapid growth of accessible information and data sets from a great many heterogeneous and often unevaluated sources (e.g. social media), facilitated by an increasing number of acquisition methods, high performance processing and seemingly infinite storage capacities.

The concept of uncertainty is by no means entirely new. In the natural sciences a wide range of defined, approved and standardized means for complex calculations and the meaningful representation of uncertainties are utilized on a regular basis (e.g. standard deviation, error bars, confidence interval, color coding, or glyphs).

Most likely, every research field is affected by or involved with uncertainty. As a consequence, a considerable amount has been published over the past decades, indicating the effort to somehow get a grip on the intangible phenomenon of uncertainty. The correlated terms thereby differ as widely as the related research fields and it seems impossible to find a generally valid definition (if this would be of any use at all). Despite this variety and diversity, these approaches share at least one general insight: uncertainty is widely understood as a heterogeneous „multi-faceted"[2] phenomenon associated with the terms error, accuracy and imperfection.

A brief historic outline

Archaeology was one of the first domains to utilize the relatively new field of 3D computer-aided solid modeling in the mid-1980s. The three-dimensional digital reconstruction model of the Old Minster in Winchester, created between 1984-86, is said to be „the earliest application in the UK of 3D computer modelling to visualise archaeological data."[3] The digital revival of such long gone historic structures in form of a 3D solid model was only made possible by the collaboration of two specialists sharing competences. Whereas the computer industry (more precisely the IBM Scientific Centre UK) provided up-to-date technology to enable the creation of highly qualitative graphic output, the necessary scientific contents where provided by archaeologists (led by Martin and Birthe Kjølbye-Biddle).

Pioneering work was also done with regard to the production of a two-minute video animation (by Andrew G. N. Walter), showing interior and exterior views as part of a virtual fly-through the reconstructed Old Minster.[4] The rapid progress in computer technology during the 1990s went hand in hand with the substantial reduction of purchasing costs, which in turn facilitated the distribution of suitable technologies and devices for digital 3D modeling. As infrastructure became more widespread and available within academic culture, digital modeling activities increased, so that „[f]or many years, photorealism was the gold standard, and the goal in visualization was to achieve renderings of scientific data that were indistinguishable from a photograph."[5]

The increasing potency of high-end computer technology helped to generate sophisticated photorealistic renderings with a number of seemingly authentic details: familiar perspective, realistic textures and proper shading and lighting conditions. Taken together, these graphic features resulted in images with the potential to convince the average viewer that they were in fact looking at a real object that had merely been photographed. „[S]cholars too will find it harder and harder to maintain any scepticism about the accuracy of the images as those images get better and better. This is all the more true because of the misperception that the images are created by unbiased automata via a mechanical process that requires no human intervention.“[6] In 1996, the Virtual Stonehenge project, sponsored by the English Heritage Company and Intel UK, celebrated the run for high tech, photorealistic and „eye-catching effect[s]“[7]. The project was special because for both institutions, as a public-facing application that implemented „the accurate positioning of stars in the night sky, the use of draping photographs in an attempt at photorealism, as well as the first ‘virtual sunrise’”[8] above the digitally re-erected site of Stonehenge.

Eventually, these developments were addressed in the criticism presented by Miller and Richards at the Annual Conference of Computer Applications in Archaeology (CAA) in 1994. Their contribution, “The good, the bad, and the downright misleading: archaeological adoption of computer visualisation” can be seen as a starting point for many of the ongoing debates regarding reconstruction and certainty that continue to the present day. Miller and Richards reason that research all too often focused on attention-getting strategies oriented to the public[9]. Instead, they argued, research should be focused on new insights that only digital tools and methods could yield. The authors additionally emphasize two fundamental problems: for one thing, they underline the lack of quality control, stating that “[w]orryingly, there is little, if any, quality control for computer graphics and they are not subject to the same intense peer review as scientific papers”.[10] The other problem relates to the lack of venues for digital three-dimensional reconstructions, even though “[m]ost archaeologists are keen to emphasise that there are many possible views of the past, and that we rarely know anything for certain”[11].

Moreover, there is a tendency to assume that detailed photorealistic computer graphics reflect one given ‘historic truth’ and that all the things shown must have indeed been there in the way that they were depicted. The same logic assumes that missing elements are not worthy of attention, if their visual absence even registers to the viewer. „The fact that many hours of discussion between computer scientists, historians, and archaeologists went into its design cannot be seen by inspecting the image, let alone can the reasons for the design decisions be [sic!] ascertained nor the uncertainties underlying the decisions.”[12]

So, since 1990s, increasing efforts have been made to find and develop appropriate methods to resolve two of these main problems widely discussed in archaeological discourse: the multilayered problem of photorealistic computer graphics and their application in archeological visualizations, as well as the considerable lack of visual empirical clarity that can be established between these visualizations and the material distributions to which they lay claim. At the same time, new practices for evaluating 3D models and workflows (and the material products dreived from them) were developed.

Standardization has also been a recurring issue. Since the beginnings of archaeology as a discipline, a range of methods have been established to deal with uncertainty. These practices and techniques were developed to address specific requirements, e.g. for visualization. Thus, they were not assumed to be standardizable conventions, or even obligatory features of a practice, as in the case of mathematical notation. „Unfortunately the standardisation of the techniques used by illustrators of archaeological material has never been fully discussed and, although there are a number of standard conventions, there are also a number of different methods in use in different parts of the world today."[13] Standardization poses an ongoing, massive challenge to digital documentation, and continues to inspire various workflows, metadata schemes and data formats[14], as well as the setup of an vast number of databases that collect, archive and provide data and information in a systematic way[15]. Moreover, a whole range of international organizations[16] and labs[17] have been founded, which in turn organize major conferences[18], contrive official charters[19] and guidelines, and explore new publication formats[20].

Standards which can document and quantify uncertainty in digital three-dimensional models and reconstructions in archaeology, in a more generalized and applicable way, are still under development. But recent activities show that the discursive landscape of archaeological method evolves fast and renewed attention is being paid to these complex issues, especially in the context of digital cultural heritage.

A brief taxonomy of uncertainty

Other disciplines tackle the problem of uncertainty with a degree of subtlety that warrants further exploration here. These approaches could be of interest for the evolving discourse of uncertainty research in archaeology. Although they widely differ in their frameworks and strategies, these approaches have some aspects in common: after shortly reviewing other relevant texts, I will show how they classify uncertainty. Within such a system we could begin by documenting a number of typological features: 'sources', or 'causes', 'types', 'categories' or 'levels'[22] of uncertainty.

The most commonly mentioned sources (or types, levels etc.) are accuracy (locational, attributal, temporal, logical), error, precision, completeness, consistency, reliability, credibility, validity, subjectiveness and data lineage. These sources (or types etc.) are assumed to generate, introduce, enhance and/or propagate uncertainty during a multi-staged workflow and to directly correspond to the quality, reliability or certainty of information. The exemplary workflow stages listed below are suspected to be focal points for the introduction, transfer or propagation of uncertainty.

- *data acquisition / collection*
  classification and categorizations
- *processing*
  filtering, transformations, sampling, approximation, interpolation, translation, decryption, quantification, simplification, extrapolation
- *visualization*
  mapping, modeling, rendering
- *evaluation & comprehension*
  human bias, incomplete knowledge
- *presentation & dissemination*
  file formats, operating systems, translations, decontextualization

Since the occurrence of uncertainty during these stages of the workflow is ubiquitous and rarely controllable, it is tremendously important to carefully observe, question and document the process in detail, including ambiguities, problems, discussions, and especially underlying decisions made during the processes. One relevant example from archeology is worth noting here. At the Digital Roman Forum Project, where three levels of certainty were assigned to the digital models[23]. A very recent approach comes from Fabrizio I. Apollonio, „Classification schemes and model validation of 3D digital reconstruction process“[24].

After the classification process, quantification inevitably gains in importance as a component of the workflow, especially if appropriate visualization strategies must be chosen. This makes it necessary to quantify the uncertainty observed in the data. For this purpose, a diverse range of methods established in natural and engineering sciences can be applied, including but not limited to Monte Carlo method, probability calculations, possibility theory or heuristic evaluation.

In archaeology, the evaluation of data and information from many different sources of varying quality doubtlessly ranks among the main challenges. The quantification of information and claims derived from human discourse—academic exchanges coordinated by numerous individuals with their own subjective preferences and biases—is an incredibly complex task. The same applies for written sources and all sorts of image material, created, processed and distributed by humans. When we try to visualize uncertainty, we are constrained not only by the repleteness of the information, but also by the instabilities and uncertainties built into the visual apparatus upon which we are relying. These optical uncertainties may of course be exaggerated or attenuated at different levels of processing in the workflow. One solution often encountered involves the creation of a visual vocabulary which can register classes, types, and sources of uncertainty.

A brief outline of visualization approaches

The representation of uncertainty is and always has been something of a dilemma for all archaeologists. Verbally, textually and visually archaeologists have had to develop means of expressing and incorporating uncertainty and ambiguity into the archaeological process and into their representations of archaeology.[31]

In this sense, archaeologists and others who undertake the creation of scientifically reputable and serious visualizations of no longer existent historical contexts are confronted with difficult questions concerning the inclusion or exclusion of information, somehow caught inbetween imaginative additions (missing parts that they assume were once there, traces of usage, or soundscapes, for instance) and a scientifically appropriate but somehow „sanitized view of the past".[32]

Throughout the 19th century, well-known artists like Alan Sorrell or Piet de Jong established a drawing technique of 'artful concealment', by arranging clouds, bushes, branches, columns of smoke and the like on particular spots in the archaeological illustration, to either subtly disguise what should remain invisible, perhaps due to a lack of knowledge or uncertainties[33]. They also lent a sense of liveliness and presence to the scene; as one scholar has argued, „In both their beauty and communicative power, such illustrations cannot be matched in quality yet by methods and tools on computer."[34] Although artists could once skillfully conceal uncertainties, digital 3D modeling technology is based on complex volumetric calculations, which require concrete declarations and values in order to work properly. That is why it is all the more important to note that „[w]hereas it is possible to speak of a tower without knowing or having to be precise about what it looks like, visualization technology forces clear-cut decisions." [35] As a result, a carefully positioned digital cloud would be of no use in a 3D environment, for one thing because the user can easily change the perspective and see everything that is supposed to be camouflaged by the cloud. But the crucial point is that all the parts in the scene have to be modeled either way, even if they are intended to be invisible or covert and even if the required information is incomplete. Thus, the problem remains, because „[i]f we show other structures, we know we are wrong. If we show nothing, we are avoiding certain error but providing a reconstruction that will be equally misleading by showing a void where there were structures." [36]

In any case, while the provision of visual or textual references and explanations to clarify the use of the chosen visualization strategy (e.g. void or reconstruction) is often criticized as insufficient or even missing, the insufficiency of evaluation methods for visualizations (particularly in regards to the visualization of uncertainty) has been identified as a problem across disciplines. „There is much space for improving the way uncertainty information is currently captured, depicted and shared. To make uncertainty visualization successful, there need to be better techniques to capture and model uncertainty data; an agreement on data and implementation; and provision of a socially-agreed system for depiction."[37] In addition to the questions already mentioned, others are arising: how to find appropriate visual representations (for specific tasks) and identify inappropriate ones (because of their ambivalent meaning, for instance)? Further, there is the problem of designing visualizations that do not distract or mislead viewers. „The sparse nature of uncertainty information, the lack of a consistent format for expressing it and the need to accommodate various display media and user expertise all pose a great challenge to the visualization designer as popular methods in the literature cannot be easily adopted in real-life applications." [38]

The development and application of various techniques to enable a more meaningful and comprehensible (re)presentation of information for different visualization types is under constant construction. Many applications are nowadays open source. In the following sections, some of these 'real-life applications' shall be briefly outlined. The options listed below are applicable for both 2D images as well as 3D models (or scenes). The first option 'visual cues' relates to visual manipulations directly on elements of the model (or image), the second option 'rendering style' affects the visualization as a whole, whereas the third option outlines some possibilities to (re)present the visualization results, e.g. renderings, 3D models or whole 3D scenes.

OPTION 1: Visual Cues

Historically the geovisualization community were perhaps the first to realise the importance of uncertainty. This community has long been concerned with issues of data quality so that the limitations of the data are understood when looking at maps.[39]

One of the many influential achievements from the pioneering field of geovisualization (and information visualization as well) is the genesis of methods and means in graphic semiology, established by french cartographer Jacques Bertin. He provides a system „that logically translate[s] information into graphic displays"[40], including his extensive work on 'graphic (or visual) variables'.[41] Bertin's initial compilation consists of the following six variables: size, value, texture, color, orientation and shape (plus the two dimensions x and y). They are used „to represent relationships, resemblance, order, and proportion"[42] and also play a vital role for immediate perceptual group selection, natural perceptual ordering (not learned), and quantitative comparisons"[43].

Because of their functionality and potential for specific visualization purposes, Bertin's system of graphic variables was used as starting point for further experimentation in other disciplinary contexts. How such an adaptation could be of use and how it could be done, was considered by Alan MacEachren in his early approach "Visualizing Uncertain Information" in 1992 (see fig. 1).[44]

Many years later, Zuk et al. also tried to adopt the concept into an archaeological framework, as described in their approach „Visualizing Temporal Uncertainty in 3D Virtual Reconstructions"[45]. The authors attempt to integrate and visualize temporal uncertainty from their data within an application called 'TimeWindow' (ArkVis), which basically combines animation, interactive elements ('time slider') and a range of visual cues based on Bertin's variables. „A visual cue can be defined as any visual encoding (color, size, animation, etc.) and used to communicate meta-data. In the current context a visual cue is any visual encoding used to distinguish levels of uncertainty"[46]. Examples of visual cues mentioned by Zuk et al. are 'rising/sinking', 'wireframe', 'transparency', 'shadow/light', 'blur' and 'depth-of-field' to express previously quantified amounts of uncertainty.

As described above, visual cues were utilized throughout the 19th century, e.g. for 'artful concealment' in archaeological illustrations, history paintings, and graphic reconstructions

Table 1: Further examples of visual cues.[47]

location	color	focus / blurriness	animation
size	color hue	contour crispness	rising/sinking
shape	color value	fill clarity	oscillation
orientation	color saturation	fog	blinking
	transparency[48]	resolution	
textures	opacity	grain	sonification
	pseudo-color	depth-of-field	
pattern	color mapping[49]	(motion) blur	haptics
glyphs			
construction lines[50]	shadow/lighting	level of detail[51]	

of ancient sculptures. In this case, they were applied, if details or parts of the sculpture were missing and commonly assumed to have been on a determined spot at the statue. These graphical additions were distinguishable from the original drawings, showing the actual remains, because a different layout was chosen for the drawing line, as well as differentiating colors.[52]

Color is a common means of representing information, particularly levels of uncertainty. For instance, uncertainty is often symbolized by the color code system of traffic lights, whereby red is used for the highest degree of uncertainty (lack of knowledge etc.) or the most speculative parts of a digital reconstruction. Color as a visual cue has long been thoroughly researched, as a mean to distinguish between material properties or different periods of time and to specifically distinguish the archaeological evidence from the computational reconstructions in an image, as described and experimentally visualized by Eiteljorg and Tressel almost 20 years ago[53]. One recent example is the „escala de evidencia histórica (or scale of historical evidence)[54] presented by Pablo Aparicio, coined as „a color scale that has changed the way archaeologists look at 3D modelling“[55]. The application is demonstrated in the illustration of a roman tower[56] and was used in a rendering of the Portus Theodosiacus showing „the port as color coded according to our current level of knowledge“[57].

OPTION 2: Non-photorealistic Rendering

...visual presentations need not always be realistic. They rather need to convey a message. As long as the user knows (preferably intuitively or inattentively) what to take as real and what not, the visualization could be effective.[58]

One of the problems related to photorealistic renderings in archaeological (or generally historic) contexts is the tendency to convey certainty about the things depicted. One simple but more effective method is to utilize the wide-ranging set of non-photorealistic rendering techniques as a form of „acceptable imperfect presentation”[59]. At least since the 1990s, the development of this visual vocabulary is constantly progressing, especially in and thanks to all fields of the creative industry, like game development or graphic design, resulting in ever improving implementations and effectiveness. „Non-photorealistic rendering (NPR) is any technique that produces images of simulated 3d world in a style other than realism.”[60] Efforts were made to imitate well-known art styles, like oil paintings or water color drawings, or for instance the characteristic style of technical drawings. Other known and often used forms are wireframe, pen-and-ink or a vast range of line or pencil styles and shaders.[61]

NPR techniques can be of use for uncertainty visualization because they „add an illustrative quality to the rendering technique...”[62], basically creating abstract visual stylizations which address different perceptive qualities compared to photorealism. They often give the impression of a more incomplete but therefore more flexible, modifiable image, open to changing processes. In this way, distraction from realistic details is considerably reduced, whereas the scope for interpretation and hypothesizing is facilitated by the abstraction.

In 1999, a concrete attempt was made by Strothotte, Masuch and Isenberg, to utilize non- photorealistic rendering techniques for „Visualizing Knowledge about Virtual Reconstruction of Ancient Architecture”[63] with the aid of their newly developed software called ‘SketchRenderer’ and ‘AncientVis’ (fig. 2). „This use of sketchiness or line saturation for various degrees of uncertainty is an attractive and intuitive way of visualizing uncertainty because it is used by artists in hand drawn pictures as well [...]. Users can interpret pictures as they are used to

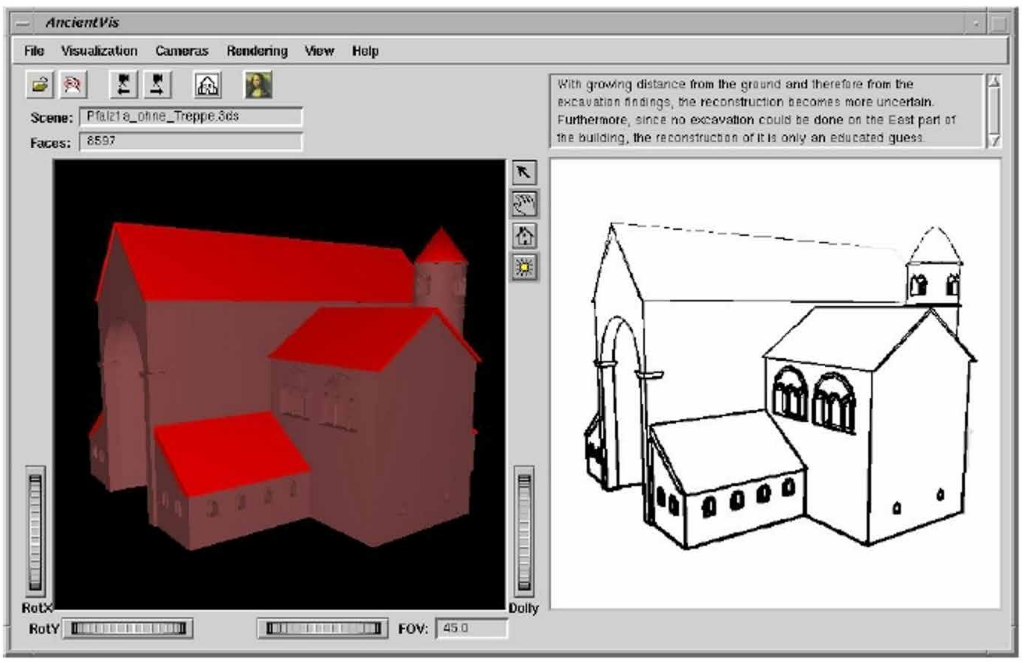

Figure 2: Interface of the AncientVis / SketchRenderer software.

Strothotte, Thomas, Maic Masuch, and Tobias Isenberg. “Visualizing knowledge about virtual reconstructions of ancient architecture.” Proceedings of Computer Graphics International (1999): 36-43 (40). Image used with friendly permission of Prof. Dr.- Ing. Maic Masuch, University of Duisburg-Essen.

doing so in conventional drawings and do not have to learn a new paradigm."[64] The functionality of the software is exemplified by the digital reconstruction of the palace of Otto the Great in Magdeburg (Germany). In this example, increased levels of uncertainty, especially in the upper parts and backside of the building, are visualized by lighter, thinner and more sketch-like lines, in contrast to the bold and straight lines used for the more certain reconstruction of the foundations. The reduction of visual information in some areas draws attention and scales the information available in others, while providing the opportunity for a user to interactively explore the (underlying) complexity of architectural reconstructions.

OPTION 3: Means for (Re-) contextualization

In this option sophisticated three--dimensional visualizations of archaeological contents are suggested to be supplemented by textual information that is embedded within or attached to it, for instance, a project description (e.g. aims, methodology, problems, decisions, debates, assumptions, sources etc.). Ideally, some explanatory notes inform about the way uncertainty was encountered during the research and reconstruction processes.

How this can be done is demonstrated at the "Digital Roman Forum"[65] project. Each 3D model selectable on the website, has its own detailed profile with all kind of information, even about the evaluated 'levels of certainty'. Unfortunately, the underlying evaluation process for these 'levels' is not described in further detail.

The possibilities to add text passages online are technically unlimited. And these web applications are predestined to be linked with data bases like Wikidata or Perseus Digital Library. Thus, further research is enabled, while providing access to additional (or different) data and information, thus generating additional value and ongoing discourse. Metadata for the provided images and 3D models shown could include but it certainly not limited to caption, production date, time and location of the displayed content, key aspects of possible debates or discussions, creator(s) of the 3D model, as well as information about involved parties.

Another frequently expressed demand concerns the expansion of the image repertoire, for instance, by providing alternative reconstructions and hypothesis to the final renderings.[66] This expansion can also be achieved by providing (a) images representing the excavation in progress, from intermediate stages (image overlays) up to the final visual results[67]; (b) images 'from behind the scenes', illustrating the digital reconstruction process as it unfolds, possibly with erroneous renderings and rejected models; (c) images with different perspectives and detail views; (d) alternative rendering styles (e.g. non-photorealism), different lighting (e.g. day/night time) or weather conditions etc. [68] Likewise, a side-by-side view[69], a sequence[70] or an image gallery[71] could be used, as well as videos with cross-fading effects, e.g. between the original record and reconstructed elements[72], image overlay[73] or merging[74], to expand the visual repertoire and make content comparison easier. Either way could help to illustrate the underlying genealogies and distortions related to multilayered project workflows which, although well documented, are often somehow locked-up, but could, if accessible, provide (further) insights.

The popularity of interactive elements is noticeably increasing. Thus, a significant shift is under way from static, inaccessible 'illustrative material' to more dynamic content generation. Therefore, this shift should be carefully observed, evaluated and critically questioned in future research. One example of a popular interactive application is the 'slider'. The main function is to process at least two images by moving a slider to merge, overlay, cross-fade or replace images with each other (for example, to compare an object's original state with a reconstruction).[75]

Another well-known tool is the '3D viewer', the most popular of which is the free plugin Sketchfab.[76] The 3D viewer can be easily implemented on websites, enabling the user to directly observe interactive 3D models by navigating in three-dimensional space, also allowing the user to change the perspective, among other options such as lighting, and rendering style.[77] Moreover, the Sketchfab 3D viewer is capable of showing 3D models directly in Virtual Reality, and also supports sound as an additional feature.

Furthermore, a wide range of interactive applications can be gathered under the term 'interface', allowing the user to manipulate the provided options and parameters. The most basic versions offer the possibility to select/deselect (or enable/disable) specific contents and information, so that the selection will be either directly mapped or removed from a given image or scene.

„Our reconstructions are also too clean and neat. The real world includes people, animals, plants, trash, signs of age and decay on structures, etc. Here again, we can only include some of these items and make mistakes or omit them and present an antiseptic world that is equally misleading."[78] In this sense, a slider could be moved between the two extremes of a range, so that the user can interactively change between images (or even changes a whole virtual scene), that is, between a 'sanitized view' (e.g. mere architectural structures without any further details like textures, etc.) to increasingly speculative scenarios, from in situ conditions to a detailed and highly speculative reconstruction.

A brief contemplation

Life is not perfect. We confront imperfection (and uncertainty) every day. Similarly, data and information as well as their representations will never be perfect. We thus need to get accustomed to and make peace with this fact, not expect decision making based on perfect data, information, and presentation. In that regard, we need to develop principles and methods of ›imperfection (uncertainty) management‹ how to get and understand imperfect information using imperfect representations and reach sound decisions in real-world conditions.[79]

Uncertainty is often perceived and communicated as a problem occurring anytime, anywhere. It requires a lot of careful work and well-prepared considerations to adequately cope with the enormous workload uncertainty entails (including detailed documentation of data, complex evaluation processes, debates, decision making and iterations). With regard to archaeological attempts to visualize uncertainty, one of the main difficulties observed is the ambition to develop images (or 3D models) according to established scientific requirements, that is, to show what is correct, verified and reliable, while at the same time, balancing aesthetic demands for clarity and repleteness. Additionally, the advent of photorealistic computer graphics predisposes us to images that are unambiguous and quickly, uncritically consumed. From this point of view, research fields like archaeology will always be confronted with the dilemma of interpreting, expecting or showing too much and at the same time too little. It is therefor crucial to develop standards and criteria for documenting (and not merely concealing) uncertainty.

Ideally, new forms of interactivity and visual communication yield new scientific insights. To do so they must integrate uncertainty into visualization. „In the end, visualizations are simply communication between people. Thus, when creating uncertainty visualizations, it may be a useful abstraction to think about just two people trying to communicate with each other."[80]

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[14] cf. e.g. Dublin Core, CIDOC CRM, VRML, X3DOM

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[16] cf. e.g. ICOMOS, ICROM, INNOVA,

[17] cf. e.g. KVL, DHRLab, CVRLab, VWHL, CultLab3D

[18] cf. e.g. CAA, ACM SIGGRAPH, Europgraphics, EVA, EuroMed, SciVis, VAST, DHd

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