# Mirror, Mirror on the Wall,
# Who Has the Best Visualization of All?
# – A Reference Model for Visualization Quality –

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**Abstract.** What is a 'good' visualization, one which leads to desired insights? How can we evaluate the quality of a scientific visualization or compare two visualizations (or visualization systems) to each other?
In the following, the importance of considering the 'visualization context' is stressed. It consists of the prior knowledge of the user; the aims of the user; the application domain; amount, structure, and distribution of the data; and the available hardware and software. Then, six subqualities are identified: data resolution quality, semantic quality, mapping quality, image quality, presentation and interaction quality, and multi-user quality. The $Q_{VIS}$ reference model defines a weight value C (i.e., importance) and a quality value Q for each subquality. The $Q_{VIS}$ graph is introduced as a compact, easy to perceive representation of the so-defined visualization quality. An example illustrates all concepts.
The reference model and the graph can help to evaluate visualizations and thus to further improve the quality of scientific visualizations.

## 1 Introduction

In the fairy-tale 'Snow White', the wicked stepmother asks the mirror: 'Mirror, mirror on the wall, who is the loveliest lady in the land?' — By what criteria does the mirror evaluate the 'loveliness' of women? Surely, 'loveliness' cannot be measured objectively. Rather, loveliness will be defined differently by different people. Similarly, in order to evaluate the quality of a scientific visualization, it is important to know who will use this visualization and for what purpose.

Good scientific visualizations are needed by scientists and engineers in many fields, but they can also be useful to managers and to the general public. Here, 'good' generally means 'meaningful', but also 'beautiful' (by artistic standards) or 'simple' visualizations can be desirable. In this work, 'visualization quality' will mainly be examined from a technological point of view and psychological, pedagogic, or artistic factors mostly have to be excluded.

Any dataset can be visualized in an infinite number of possible ways. If the visualization is to achieve its goal (e.g., lead to new insights quickly), the choice of a visualization system, of visualization techniques, as well as of visualization parameters is crucial. But what is a 'good' visualization? How well does the result of a visualization (i.e., an image or an animation) or a visualization system reach its goal? How can we compare strengths and weaknesses of such visualizations or systems? – In the following, a reference model for 'visualization quality' will be presented as a foundation for discussing such questions.

Another question is: Can an 'objective' measure be achieved at all? Surely, 'visualization quality' always depends on a 'visualization context' which includes (but is not limited to) the prior knowledge and the aims of the user.

The importance of evaluating visualization software has been stressed by Globus and Uselton in [12]. There, a number of possible evaluation methods has been proposed, ranging from the analysis of mathematical properties of algorithms to performance measurements of users. On the other hand, Robertson and Silver [29] recommend case studies. They point out that in a specific application case, it is more easy to decide if the goals of a visualization have been met and how an increased effectiveness, reliability and consistency of visualizations can be achieved over a wide range of application domains. [3] gives one example of such a case study. Here, several ways of visualizing a storm are presented and evaluated. The discussion of the quality of these visualizations also takes into account graphics design and perceptive issues.

An extensive selection of visualization examples may be found in the book 'Visual Cues' [23]. Each of them is described in picture and text on one page. These examples are ordered according to classes of visualization techniques. The number and variety of examples allow a good comparison and an evaluation of visualizations. Several appendices give fast access to these examples according to visualization techniques, visualization goals, number of visualized variables, application domains or the used hard- and software. A theory chapter of the same book gives general hints for good visualizations, including visualization goals, output media, design principles, and usage of color.

In the field of automatic generation of visualizations, much important work relevant to the question of visualization quality has been done. Starting from the work by Mackinlay [24], who introduced the two criteria of expressiveness and effectiveness, there has been a considerable number of interesting works, including [27], [2], [20], [25], [28], [4], [26], [30], and [22].

## 2 The $Q_{VIS}$ Reference Model for Visualization Quality

### 2.1 Short Definiton of Visualization Quality

Before starting to explore the 'measurement' of visualization quality, here is a definition of how the term is understood in this paper.

The quality of a visualization is defined as: the possibility and ease for a specific user to gain the insight desired by him into information that is conveyed in his data by looking at or interacting with the visualization.

The quality of a visualization *system* is defined as: the possibility and ease for an average user from a clearly defined group of users with a clearly defined goal in a clearly defined application context to gain the desired insight into information that is conveyed in an average data set of a clearly defined set of possible data sets by using the visualization system in a clearly defined hardware and software environment.

What influences the so-defined 'visualization quality'?

### 2.2 Visualization Context

The work reported, e.g., in [8], [15], [14], [17], and [13] has confirmed that we cannot speak of the 'quality of a visualization' without considering the environment in which a visualization occurs, i.e., its application context. We call this the 'visualization context'. It includes:

1. the prior knowledge of the user,
2. the aims of the user,
3. the application domain,
4. amount, structure, and distribution of the data,
5. the available hardware and software.

In [9], a similar scheme is proposed. Due to space limitations, please refer to [16] for a more detailed explanation of the visualization context[1].

### 2.3 Visualization Subqualities

Six 'subqualities' together describe visualization quality in the $Q_{VIS}$ reference model:

1. data resolution quality (dr),
2. semantic quality (se),
3. mapping quality (ma),
4. image quality (im),
5. presentation and interaction quality (pi),
6. and multi-user quality (us).

The *data resolution* depends on the number of data values in relation to the given range and to the underlying function they sample. If the quality of a visualization *system* is under investigation (as opposed to the visualization quality for a specific dataset), then the subquality for data resolution should not be considered.

The *semantic quality* stands for the semantics of the data to visualize. Four cases can be distinguished: no semantics (i.e., geometry, color, etc. only, not derived from original values); static semantics (geometry, etc. derived from static data); offline-dynamic semantics (geometry, etc. derived from initially known,

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[1] In [16], the term 'visualization background' was introduced by the author, but 'visualization context' better describes the concept and therefore will be used from now on.

dynamic data); and online-dynamic semantics (geometry, etc. derived from online simulation or online measurement, i.e., the data is being generated concurrently with the process of visualization, e.g., as response to interactive steering of the user). Thus, semantic quality comprises the degree of direct interaction of the user with the data source.

The *mapping quality* is the next important subquality. it includes the flexibility of mapping original values to visualization objects, the numerical quality of this process (interpolation, integration in vector fields, etc.), and the consideration of human perception, e.g., in the case of color selection.

The *image quality* mainly includes five subitems: image resolution (number of pixels), color space resolution, dynamic range, pixel sharpness, and rendering quality. Most of these subitems need not be explained here since they are discussed in many publications, e.g., in [7]. The subitem rendering quality (in the 3D case) distinguishes different rendering techniques like wireframe, flat shading, Phong shading, raytracing with reflections, etc. Thus, image quality in this paper only comprises technical, static image quality. Content or aesthetics are either partly covered by other subqualities (e.g., data resolution or mapping quality) or completely excluded from this reference model.

The *presentation and interaction quality* includes: temporal resolution (frames per second), latencies, field of view, stereoscopic quality, degree of immersion due to head tracking, and intuitivity of input devices. Thus, this subquality comprises all kinds of presentation and interaction starting from batch processing (latency, e.g., one day), interactive graphics (1 to 10 frames per second, latency less than 1 second) to immersive visualization (typically more than 10 frames per second, latency less than 0.2 seconds). Some of the subitems of this subquality are mainly interesting for immersive visualization[19] (field of view, immersion due to head tracking) while others are important for many more visualization applications (temporal resolution, latencies, stereoscopy).

Finally, the *multi-user quality* takes account of the number of users of a visualization (system). It distinguishes users that are interacting online with the visualization, users that are consuming online (but without interaction), and users that are consuming offline, i.e., they see the results of a visualization process after the visualization has been completed. The number of online interacting users again can be grouped in four important classes: no interacting user during the generation of a visualization (i.e., batch processing), one interacting user (most common case), two interacting users (simple CSCW[2] solution for connection and consistency), and more than two interacting users (complex CSCW connection and consistency structure). Another aspect in respect to multi-user quality is the location of users: Do all of them have to be in the same room or can they be distributed over large distances?

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[2] CSCW = Computer Supported Cooperative Work

### 2.4 The $Q_{VIS}$ Reference Model

The reference model for visualization quality defines a way to get numerical quality values for a visualization by quantifying a number of subqualities as well as their importance (as 'weight values') under consideration of the visualization context.

Each subquality is quantified by determining a *subquality value* in the range from 0.0 to 1.0. These subquality values are also denoted by Qxx (Qdr, etc.). A subquality value expresses how well the visualization under investigation satisfies the demands of the visualization context in the corresponding subquality.

One 'weight value' Cxx (Cdr, etc.) is assigned to each of the subqualities in order to express the importance of the subquality for the overall task (again depending on the visualization context). This is necessary since not all subqualities are equally important for all visualization tasks.

Weight values may be any positive number (including 0.0). It is impossible to give suitable values for all Cxx for all possible cases *a priori*, but in general, most of the weight values can be set to 1.0 and only in some cases they should be increased or decreased according to the situation. The problem of finding suitable values for the weight values is similar to finding suitable values for the subqualities: they must be guessed after a careful analysis of the visualization context.

An example may be the layman visualization of daylight intensities in a proposed building. If a single lay person is to get an as comprehensive impression of the lighting situation as possible, an immersive inspection of the data using virtual reality technologies is very important and the weight value for presentation and interaction quality Cpi will be set to 1.0. If, on the other hand, a presentation to a large public via a magazine article is needed, the presentation and interaction quality is not important at all and Cpi has to be set to 0.0.

Thus, the visualization quality $Q_{VIS}$ of a visualization according to a visualization context can be expressed by six pairs of two values each:

$$Q_{VIS} = [(C_{dr}, Q_{dr}); (C_{se}, Q_{se}); (C_{ma}, Q_{ma}); (C_{im}, Q_{im}); (C_{pi}, Q_{pi}); (C_{us}, Q_{us})] \tag{1}$$

These twelve numbers are *not* accumulated to one single number since this would mean a huge loss of information and since such an accumulated number would no longer allow one to achieve a fair comparison of different visualizations to each other.

In order to facilitate perception of the visualization quality as well as comparison of the qualities of two different visualizations, a visual representation of $Q_{VIS}$ (called the '$Q_{VIS}$ graph') is used. It shows six vertical bars (one for each subquality). The height of each bar represents the subquality value Q, the width represents the weight value C. An example is shown in figure 2.

## 3 Example: Visualizing the Space Shuttle

The $Q_{VIS}$ model and graph may be illustrated by looking at three different visualizations of NASA's space shuttle.

The following visualizations are compared:

1. a simple, static visualization created with the AVS[31, 1] system,
2. an interactive, distributed visualization done with the ISVAS system[8, 21], and
3. an immersive visualization using NASA AMES' Virtual Windtunnel (VWT)[5, 32].

Examples for the three visualizations (with user interfaces) are shown in figure 1. The image for VWT shows a plane instead of a shuttle data set, but visualizations of the space shuttle data have also been done in this system.

Comparing three visualizations done with these three systems is very difficult. The systems and visualizations differ quite a lot from each other; they were created having very diverse tasks (and thus visualization contexts) in mind.

First, the three visualization(systems) are briefly introduced. Afterwards, they are compared using $Q_{VIS}$ graphs.

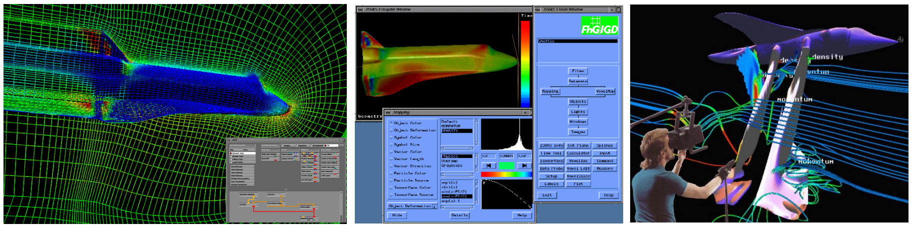

**Fig. 1.** Example pictures of the three shuttle visualizations with user interface (from left): static visualization with AVS, interactive distributed visualization with ISVAS, and immersive visualization (of a plane) with the Virtual Windtunnel (VWT) (picture with kind permission of NASA Ames).

### 3.1 The Three Visualization Systems

*Static Visualization with AVS:* AVS 5.0 is a very popular general purpose visualization system. It belongs th the class of application builders, i.e., users can configure their own visualization pipeline by arranging existing (or custom made) modules in a graphic interactive user interface.

The system can be use for interactive visualization. A PostScript output module also allows high quality static visualizations for printing.

For this paper, a static, printed visualization of space shuttle data is chosen as visualization context.

More information on AVS may be found in [31] and [1].

*Interactive Distributed Visualization with ISVAS:* ISVAS 3.2 is a flexible, monolithic visualization system which has been developed by Fraunhofer IGD since 1991. The main motivation for this work was the flexible visualization of large datasets in realtime.

The main focus of this software is on the visualization of FE (finite element) data, e.g., for structure dynamics or for fluid dynamics. System features which were introduced for this purpose include:

1. a very flexible calculator for complex operations on raw data, e.g., scaling of time varying tensor data or the combination of 3 scalar fields into one vector field;
2. interpolation in space (using shape functions) and time between given node values;
3. mapping functions of values to color, vector arrows, deformed geometry, etc.;
4. slicing, particle tracing, iso-surfaces in unstructured grids;
5. comparison of computed and measured values (e.g., strain on a steel shaft under load).

Another ISVAS data type is voxel data, e.g., medical MRI data, ultrasonic data, seismic data. Iso-surfaces and arbitrary slices are possible with this data type.

ISVAS can be coupled to simulation systems in order to allow online visualization. It also has been coupled successfully to a VR system, thus realizing immersive scientific visualization[15]. Furthermore, it allows collaborative, distributed visualization among two users.

More information on ISVAS may be found in [8] and [21].

*Immersive visualization with the Virtual Windtunnel (VWT):* In [5] and [32], a monolithic system for exploring numerically generated 3D unsteady flow fields is presented which employs virtual environment techniques. The system was designed for the very purpose of "walk around inside three-dimensional single grid steady flow tracking a streamline from the hand at frame rates" [6]. When it was presented in 1992 it was revolutionary in the way that it allows investigation of flow fields in VEs at reasonable frame rates. The fact that it has been developped by NASA Ames Research and the applications it is being used for (e.g., flow around Space Shuttle) made it clear that VE techniques indeed can be used for applicatins other than architectural walk throughts.

Yet, by trying to gain maximum performance, a very special system was designed which lacks many techniques used for scientific visualization or for virtual environments, e.g. level of detail.

### 3.2 Comparisons of the Three Visualizations

Now for a comparison of the three visualizations. Unfortunately, there is not enough space in this article to describe in detail the visualization contexts and the visualizations that led to the following $Q_{VIS}$ graphs. Still, it is important to stress that the following is *not* an objective comparison of the three systems, but it is the comparison of three very specific visualizations done with these systems according to different demands (and visualization contexts).

The basis for the following comparisons were the visualization contexts that were shortly mentioned in the previous section. Both the weight values C as well as the subquality values Q had to be guessed by the author; extensive user surveys and testing would have led to more accurate results.

Table 1 gives the weight values and the subquality values if each visualization is rated according to its own visualization context. These values are visualized in the $Q_{VIS}$ graph in fig. 2.

**Table 1.** Subquality values (Q) and weight values (C) for the three space shuttle visualizations, each according to its own visualization context. ($Q_{VIS}$ graphs in fig. 2).

| | | *AVS* | | *ISVAS* | | *VWT* | |
|---|---|---|---|---|---|---|---|
| *subquality* | | *weight* | *quality* | *weight* | *quality* | *weight* | *quality* |
| *name* | *abbr.* | *C* | *Q* | *C* | *Q* | *C* | *Q* |
| data resolution | dr | 1 | 0.9 | 1 | 0.9 | 1 | 0.9 |
| semantic quality | se | 0 | 0 | 1 | 0.5 | 0.5 | 0 |
| mapping quality | ma | 1 | 0.9 | 1 | 0.9 | 1 | 0.8 |
| image quality | im | 1 | 1 | 1 | 0.8 | 0.8 | 0.8 |
| presentat./interact. | pi | 0.2 | 0.2 | 1 | 0.9 | 2 | 0.9 |
| multi-user quality | us | 0 | 0 | 1.5 | 1 | 1 | 0.8 |

It can be seen that for the static, printed visualization with AVS (leftmost graph), semantic and multi-user quality are completely unimportant, and presentation interaction quality also does not have significance (well, maybe only for generating the visualization it is preferred to have an interactive system instead of a batch oriented one, but not for consuming this visualization). The demands for image quality are fulfilled completely, those for data resolution and mapping quality almost, only presentation interaction quality is not too good.

Similarly, for distributed interactive visualization with ISVAS, multi-user quality is very important, but the other subqualities are also important. Data semantics is not met too well, since there is just static semantics in our test case, but online visualization with steering of the simulation process would be best. This is possible with ISVAS, but not realized for the space shuttle example. Multi-user quality meets the demands of the visualization context very well.

For the Virtual Windtunnel example, it must be admitted that the author did not have all the information that would be needed to make a very good $Q_{VIS}$ evaluation. Some items had to be guessed. Semantic quality is not too important here, but it would be desirable to have online visualization in this example, which (to the knowledge of the author) is not the case. Of course, presentation interaction quality is very important and very good in this example of immersive scientific visualization.

So a look at the three $Q_{VIS}$ graphs in figure 2 easily shows strengths and weaknesses as well as different demands of the three test cases.

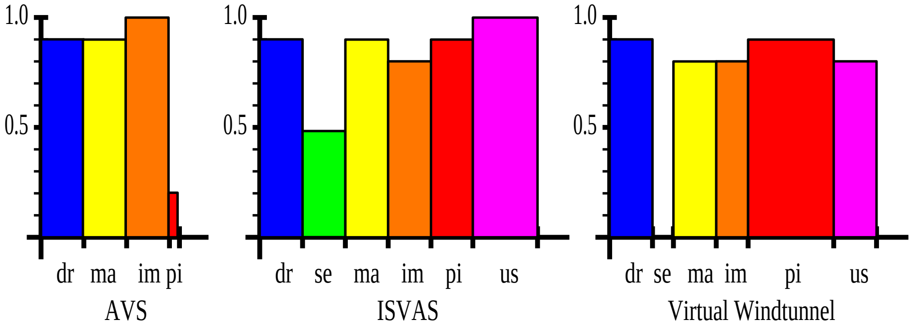

**Fig. 2.** $Q_{VIS}$ graphs for the visualization quality of the three visualizations, each according to its own visualization context (see table 1).

Fig. 3, on the other hand, shows the $Q_{VIS}$ graphs of the weight values and subquality values for the three visualizations if they are all evaluated according to a uniform, specific goal and visualization context: Two engineers want to discuss with each other on several complex vortexes in the flow field around the space shuttle.

Since the demands to the three visualizations are the same, the weight values Cxx also are equal for each of the three cases. Now, the static visualization with AVS does not meet the requirements very well. The requirements could be met much better with AVS if a different visualization would be done, but for the sake of this comparison, let's use the visualization that was done for the demands outlined for figure 2.

The graph for ISVAS has changed only a little, since the demands now are very similar to the ones of the previous example. The graph for VWT has changed more because the demands have changed. It can easily be seen in figure 3 that the described visualization with ISVAS best meets the demands that are now the same for each of the three visualizations, but this is only due to the fact that the demands are very similar to the ones that this ISVAS visualization had been designed for, and quite different from the initial demands of the two other visualizations.

## 4 Conclusion

The $Q_{VIS}$ reference model is an approach to measure and to compare the quality of visualization systems or of visualizations by quantifying a number of sub-

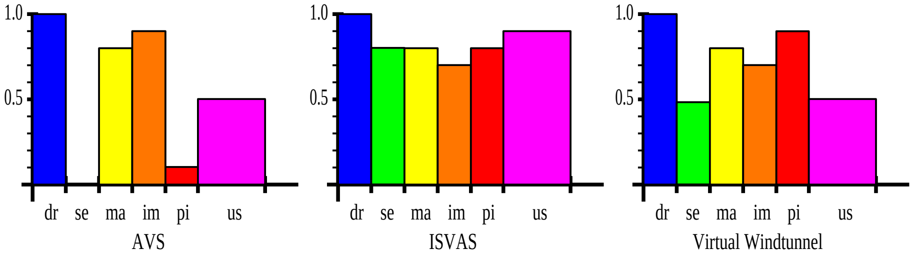

**Fig. 3.** $Q_{VIS}$ graphs for the visualization quality of the three visualizations, all according to the same visualization context.

qualities as well as corresponding 'weight values', i.e., their importance. It is emphasized that the specific visualization context must be considered.

This visualization context includes the prior knowledge of the user, her or his visualization aims, the kind of application, the amount and structure of the data to visualize, as well as the available hard- and software.

The mentioned subqualities are data resolution, semantic quality, mapping quality, image quality, presentation and interaction quality, and multi-user quality, which sometimes are an assembly of several subitems. The $Q_{VIS}$ graph is a compact, easy to perceive and to compare representation of the so-defined visualization quality.

Please note that the definition of the quality of a visualization *system* in section 2.1 does not take into account the flexibility or robustness of a visualization system to behave nice under a variety of different user demands (e.g., a variety of users with different demands). So a future extension of the reference model woud be to evaluate these aspects of a visualization system.

The reference model can help to evaluate the quality of a visualization or of a visualization system. Still, it must be stressed that the 'perfect' visualization (system) does not exist and cannot exist. The individual demands of the users, but also the changing aims of a single user and the data sets to visualize are too heterogenious. Furthermore, some requirements for an optimal visualization are contrary to each other and will never be harmonized completely. An example for such contrasting demands is the wish to achieve high frame rates in visualizing exponentially growing data sets in sometimes very high quality representation, if possible even over large distances. No matter how the performance of hard- and software should evolve in the future, it is clear that such demands always will require compromises.

Still, the proposed reference model for visualization quality does not specify a completely objective metrics – to achieve this would be an irrational goal considering the very individual properties of visualization quality – but it is a first approximation of a good tool for evaluating and comparing visualizations and visualization systems. This can eventually lead to improved visualizations and thus to more or faster insights into raw data and underlying phenomena.

Computer scientists will have to work together with users (e.g., engineers) of visualizations and they will have to learn from teachers, advertisement experts, designers, and artists who have investigated the best usage of visualization (color, shape, and many more aspects) for a long time. The findings of all of these people must not be ignored if we further want to improve the quality of our scientific visualizations.

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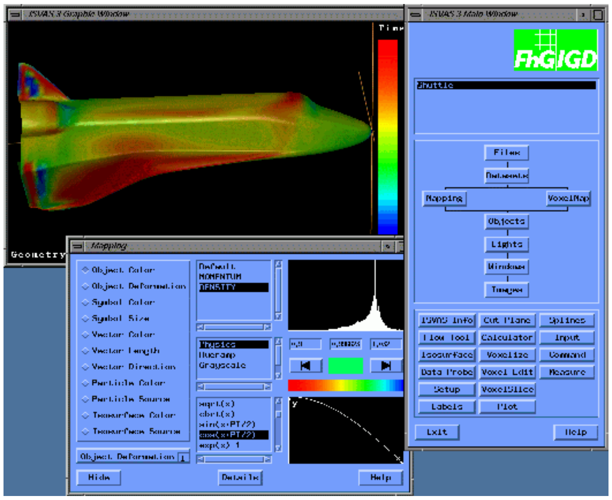
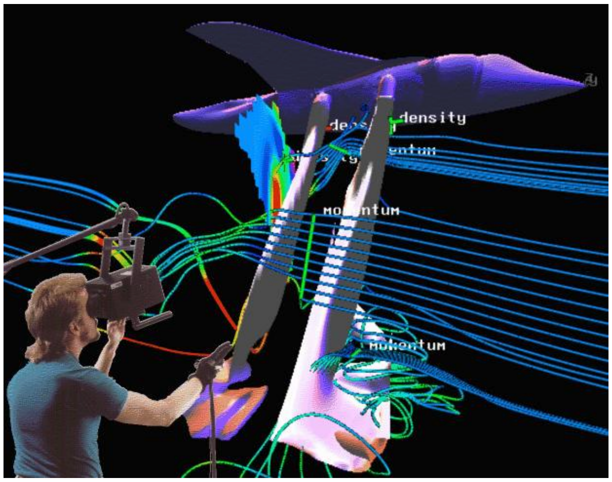


Screenshot of interactive distributed visualization with ISVAS (Haase, Fig. 4).



Example picture of immersive visualization with the Virtual Windtunnel (VWT) (picture with kind permission of NASA Ames) (Haase, Fig. 5).