

# Adaptable Visualization

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## **Abstract**

The paper suggests an approach to improving the efficiency of visualization tools developed for solving numerous applied problems. It is shown that one of the obstacles in this direction is the discrepancy between the choice of the method of visual representation of the analyzed data and the capabilities of the user using visual analytics tools. As a way to overcome the common errors of visual communication, the transition to adaptable visualization is proposed. The concept of adaptable visualization is based on the semiotic model of visualization and develops the concept of human-machine interaction in the direction of attracting the cognitive capabilities of users to solve visual analytics problems.

**Keywords:** Visualization, semiotics, visual communication, data analysis.

## **1. Introduction**

Within the framework of the approach developed by the authors to systematization of design processes of information visualization tools, the task of building a model of visual communication which is adaptable to various situations of practical use is of high importance. One of the known obstacles in this direction is the significant uncertainty in the visualization tool user's perception and actions, i.e. their subjectivity influenced by many external factors.

Considering visualization as one of the existing tools for organizing human-machine interaction, a large number of issues can be pointed out that need to be resolved when supplementing context-sensitive interfaces with the capability to adapt to the user's cognitive characteristics. Transition to the use of visual analytics tools adaptable not only to the features of the analysis problem being solved but also to the conditions of their use (including users' individual capabilities and state) will make it possible to approach important goals:

- Wide involvement in the visualized data analysis of perception characteristics of a potential visualization tool user, his preliminary awareness as well as personal cognitive models [1]. An obstacle here is the variability of the specified resource, its continuous transformation depending on a variety of external causes.

- Transition to the meaningful use of modern technical developments in the field of computer visualization [2]. The problems in this area are largely related to the formation of "digital reality", in which interpretation of visualized information is not verified by accumulated personal experience.

- Obtaining balanced visualization technologies aimed at a rational combination of visualization resource intensity levels and analysis task complexity [3].

- Increase in the speed of visual communication as one of its most significant characteristics due to the efficient coordination of cognitive and visual models.

- Expanding the capabilities of scientific visualization tools by attracting passive resources: the user's emotional states, visual perception aesthetics, movement interpretation, etc.

- Directed use of visualization teaching potential, the purpose of which may be formation of the user's new conceptual apparatus and a system of reliability criteria that are of decisive importance, for example, in the development of decision support systems based on providing the decision maker with visualized information.

The basis for the transition to the adaptable model of visual communication can be the similarity between visual and speech communications investigated at the level of their functional features and their corresponding tools. From this point of view, the dynamic characteristics of visual communication are of fundamental importance, when visualization interpretation subjectivity can be considered not as an accidental result but as a process controlled by the inherent characteristics of the visualization tools. Consequently, in Frege's classical semantic triangle, which combines three concepts: sign, denotation and sense, the informative image acquires additional meaning as a control element responsible for the representation of external data, control over the user's state and response, interpretation of data and change in the system of concepts belonging to a particular user [4].

Development of the analogy between visual and verbal (linguistic) communications necessitates to determine the meaning of some concepts, including "sign", "word", "phrase", in information visualization as objects with different purposes, properties and applicability substantiation. Introduction of such definitions will make it possible to systematize visualization tool developers' efforts as a result of the transition to a reasonable use of the semiotic approach in visualization [5].

The most obvious difference between these concepts can be associated with the information content of the corresponding objects, i.e. with the amount of new information obtained by the recipient in the course of communication. For example,

- a visual sign refers to a concept included in the user's knowledge system;
- a visual word is a sign of greater capacity, i.e. an image that possesses self-sufficiency properties, which includes both a content part and a comparison with a new visual sign;
- a visual phrase is an informatively rich image interpretation of which is accompanied by a purposeful cognitive effort associated with the interpretation of phrase structure, meanings of its individual elements, interrelationships between them, etc. based on additional perceived features.

Besides, in accordance with the systemic language properties, visual phrase interpretation results are also determined by the subjective influence of the user himself, including his awareness, ability to recognize hidden meanings and implicit indications as well as the psycho-emotional state and propensity for in-depth analysis of the reasons that led to the appearance of an interpreted visual phrase.

Information content assessment of a visual image or its individual components is an extremely ambiguous process [6]. Therefore, an alternative (or additional) basis for the introduction of definitions of visualization structural elements can be the time spent by the user on the interpretation of a visual image. From this point of view, belonging of a visual image to one of the named categories becomes dependent on visual communication participants. For example, a rich informative image, if repeatedly represented to the user, is interpreted in a way different from the initial observation. The signs of similarity with the already known image identified in the resulting one provoke a switch to retrieving the results of an earlier interpretation from memory. The purpose of switching is usually to save the user's physical or cognitive effort and associated time.

## **2. Errors in visual communication**

A common situation in visual design is when a visual phrase, which may have a voluminous informational meaning, becomes a visual sign, uses different interpretation mechanisms and most likely does not justify some of the visualization developer's efforts. Controlling this process and supplementing visualization tools with options for promptly making the neces-

sary changes to their operation provide opportunities for reducing resource consumption, including increase in speed of visual analytics tools.

In other situations, visualization based on representation to the user of individual images (a visual word), sufficient to establish a correspondence between an information event (fact) and a visual image, may depend on the current characteristics of the user's perception. For example, in case of the user's insufficient preliminary information awareness, it becomes necessary to accompany the visualization with additional explanatory elements, and the visual word becomes more capacious, acquires the capabilities of a learning tool and goes into the category of visual statements.

In the opposite case, the user becomes confident that the presented visual image is familiar to him and, even in the absence of a verified interpretation, the user stops detailed study of the image and simply establishes a correspondence between his knowledge and the new image. Thus, the visual phrase becomes a sign again, which can lead to many interpretation errors. The indicated difficulties accompanying visual communication make it mandatory to adapt visualization tools to the user's current state and general capabilities.

There are many examples of using visualization tools to solve highly specialized applied problems (medicine, geology, engineering, education, etc.), in which the discrepancy between the purpose and the means used discredits the value of visualization. For example, in the design of many decision support systems, excessive information arises, the influence of which on the result of visual communication is rather difficult to control. In this case, there is an unreasonable attraction of resources from the point of view of the goal of visual communication. The manifestations of over-informing include visual elements with re-informing (visual tautology), unjustified display variations that require additional cognitive efforts from the user, etc.

A characteristic feature of visualization used in educational processes is the accompaniment of the main content with elements that repeat previously stated information to form the necessary sequence of inferences with the student. Adapting visual communication to the conditions of its implementation can solve two common problems: distraction of users' attention [7] who already have a sufficient amount of preliminary knowledge, or building alternative interpretations, verification of which requires additional resources.

As an example, there are two alternative situations encountered in education [8]. In the first case, a student who does not have the necessary motivation to actively participate in the educational process is focused exclusively on memorizing the incoming visual information. Lack of cognitive effort in the communication process leads to passive fixation of new information, which is easily replaced by new data in the near future. In the opposite situation, the process of interpreting the visualized data can go in a completely unexpected direction or cause the emergence of many hypotheses that are insignificant for the problem being solved and corresponding to the randomly arisen interest of the communication participant; this will become a significant obstacle to achieving the initial learning goal.

A positive solution to these problems may be to change the goal of visual communication. It is about replacing the process of informing the user with the process of cognitive research [9]. In this case, the lack of personal knowledge, which prevents the interpretation of a data image as a previously known sign, initiates generation of assumptions about its meaning which have signs of novelty for the user. The source of the generated hypotheses about the meaning of the perceived image are visual elements, the context of communication, subjective experience and the purpose of interpretation. Achieving this goal involves testing the validity of hypotheses, establishing new relationships between known facts, accumulating both positive experience and rejected erroneous judgments. In this case, the cyclical nature of the approach to the correct interpretation allows considering visual communication as a process corresponding to the results of the directed training of the user.

### 3. Control

Transition from one type of visual communication to another occurs as a result of selection or change of the way for representing analyzed data. This enables considering visual communication as a tool with adjustable functionality; the opportunity to control it becomes an independent task for visualization tool developers. The purpose of such control is not only the choice of the required type of interaction with the user but also the suppression of unwanted choice or switching made by the user under the influence of uncontrollable factors.

Within the framework of the semiotic approach to the development and use of visual analytics, it is necessary to consider the interdependence of all its components: interpretation problems, communication goal, visualization tool user's characteristics, visual representation method, means of influencing the user.

Based on this, control of visual communication properties can be carried out in several ways:

- Interface, software for selecting the properties of data visual representation (sigmatic control).
- Means of achieving proportionality, compatibility, conflict-free visual metaphors used for different data and problems (visualization semantics)
- Means of attention control organizing and changing the sequence of communication (visualization syntactics)
- Tools for adapting visual representation to the needs of a particular user; or means of influencing the observer, forming necessary, from the point of view of the problem posed, psycho-emotional state (visualization pragmatics).

Expanding the range of visual communication capabilities becomes the applied meaning of its controllability. Consequently, inclusion of visual analytics tools by developers into their functional set of adaptation tool becomes an additional but necessary action. The indicated ways of managing visualization are inter-complementary in their capabilities and implementation options, and the decision to use them depends on practical expediency. Therefore, it is important to develop a theoretical model of adaptable visual communication and the rules for its error-free adjustment.

The goal of the communication model is deriving and studying internal visualization processes and their features. The directed organization of such processes in the ways proposed by the developers will lead to systematization and predictability of the results obtained in the practical use of visualization tools. Within the framework of the semiotic model, the following processes can be distinguished (Fig. 1) associated with the application of visualization: definitions of acceptable notations (compliance with technical capabilities and the existing tradition), choice of a representation metaphor (compliance with data characteristics), organization of a discussion (cyclical hypothesis formation and verification), making and preservation of the achieved decision (compliance with the original problem and the prospective application of the results obtained).

For the visualization tool user, the same processes can be correlated with his own actions (Fig. 1) aimed at solving the problem at hand. These actions usually represent a search for answers to local questions, some of which, being quick patterns of perception, are not even formulated explicitly. The processes of perception, interpretation, analysis and decision making are compared to the corresponding elements of the semiotic model and therefore can be realized by comprehensible linguistic means.

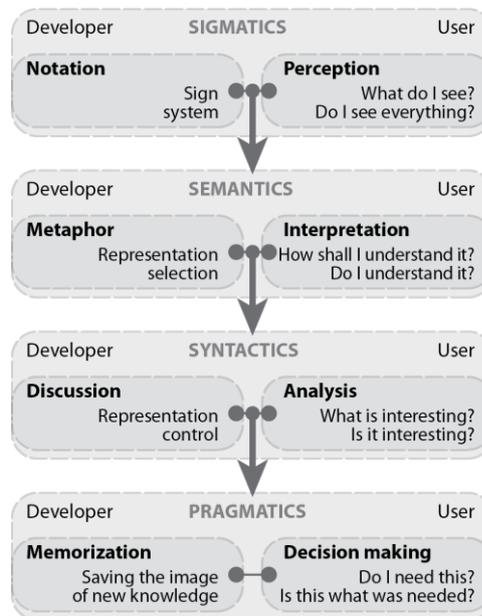


Fig. 1. Correspondence between visual communication stages, visualization tool developer's goals and user actions

#### 4. Conformity assessment in visual communication

Assessment of uncertainty (errors) in actions or reactions of communication participants is proposed as one of the ways to test the proposed model of user interaction with visualized data, i.e. communication between data, the user of visual analytics tools and their developer. To obtain such an assessment, an observation of the user's actions in simulated practical situations of interaction with unfamiliar objects has been carried out.

The subjects were asked to determine the purpose and capabilities of an industrial design object relying on assessment of its appearance (Fig. 2). It was assumed that this was a model version of the problem of interpreting visual data by a visual analysis tool user. The point of modeling such a task ensuring the necessary cognitive problem for the subject was the observation of a conceptual design object that had a well-defined set of functions, but the appearance, consistent with the functional content of the device, had significant novelty. In other words, the visual image acted as an unfamiliar semiotic object but with a given meaning.

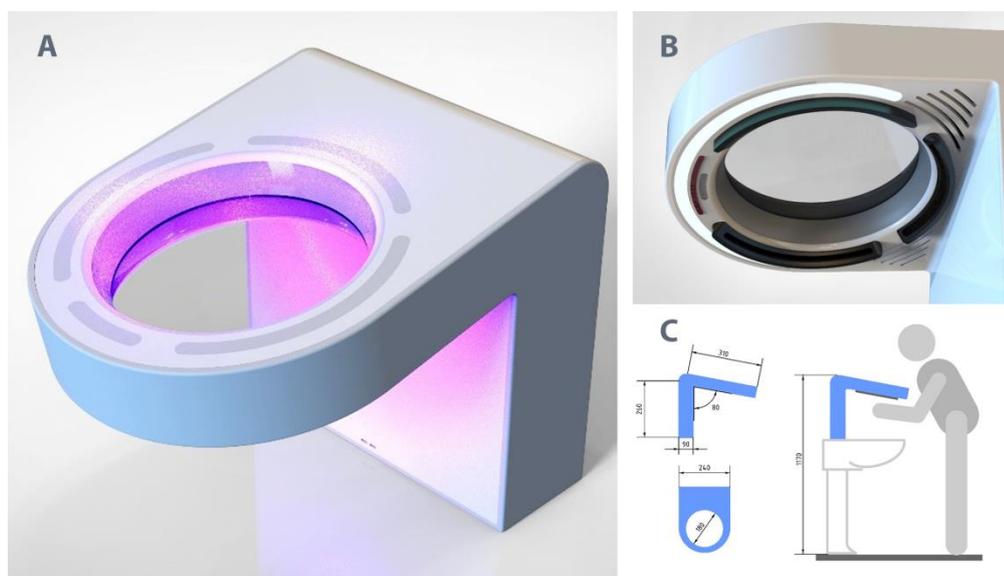


Fig. 2. Interpretation of the appearance of an industrial design object by levels of contextual information

When interviewing the participants in a group of subjects (40 people), the following goals were pursued: determining visual image elements that were significant for the observer, assessing their information content, identifying the reasons for misinterpretation, selecting visual communication features that contributed to its efficiency increase. Within the framework of the experiment, the subject's interaction with the unknown object was limited to visual observation in three-dimensional space. Kinesthetic, auditory and any other perception were excluded from the communication process. A limitation artificially introduced when testing the proposed interaction model was the need for the subject to make a final decision (interpretation of visual data) with a minimum number of erroneous hypotheses.

In one variant of the experiment, the user was asked to evaluate a new device and determine the purpose of its controls. The obstacle for the subjects was the fact that the device appearance was completely unusual from the point of view of everyday experience. The conditions of such an experiment corresponded to the situation of using visualization tools in which the user would see for the first time a data image formed within a representation metaphor unknown to him. As expected, the correct interpretation of visual information occurred only in a small number of cases (<10%).

*“What is it?”* (Fig. 2, A) If the initial data for the user are information about the field of application of the device and therefore the associated subjective experience then the situation, according to the correspondence scheme (Fig. 1), will be characterized by the choice of a specialized sign system (sigmatics). The significant error level (~65%) at the sigmatic level is due to the lack of connections between experience, purpose and representation of information.

*“How does it work?”* (Fig. 2, B) The transition to the next level (semantics) occurs after adding contextual information to the information available to the user. In this case, the user selects simple information structures in the analyzed image that make it possible to establish the necessary connections between the purpose and individual experience (through representation). The number of erroneous judgments formulated by the user is reduced to 40-45% according to the obtained rough estimates.

*“How to use it?”* (Fig. 2, C) The error level reduces significantly after changes are made to the observation conditions, that is providing interpretation with feedback. As a result of the procedure of repeated visual communication the number of formed and tested hypotheses increases; this corresponds to the accumulation of subjective experience by the user.

The reduction in the number of erroneous decisions at this stage (syntactics) is the result of coordination of the communication goal and the interpretation results. Detailing the initial data (analog, operation principle, device characteristics) changes the user's understanding of the problem being solved, reduces the error level (almost to 20%) and leads to the emergence of new knowledge for the user corresponding to the study of a new symbolic object.

*“What will it give me?”* Finally, the most significant results in reducing the interpretation error level made by the user (~5-10%) are obtained when three semiotic components (experience, purpose, representation) are consistent due to the interaction between the user and the object of study (Fig. 3).

It should be noted that, as a result of the research, the thesis about the possibility of manipulating the process of user interpretation by the visualization tool developer was confirmed. This means that the results of practical application of visualization tools that use metaphors of visual representation unfamiliar to the user can form both new knowledge and persistent false associations that can influence the effectiveness of the use of visualization tools.

## 5. Manipulation and reframing

The need to comply with the listed correspondences is fulfilled at the design stage of visual analytics tools and leads to changes in methods used both when creating visualization tools and when applying them. The main goal of the proposed changes is to shift the efforts towards actively attracting user competencies at all stages of solving a research problem – from

preliminary analysis of conditions to final decision making. This corresponds to the reasonable refuse to use decision support systems based on machine learning capabilities in situations where the development resource intensity of such systems does not correspond to their practical application.

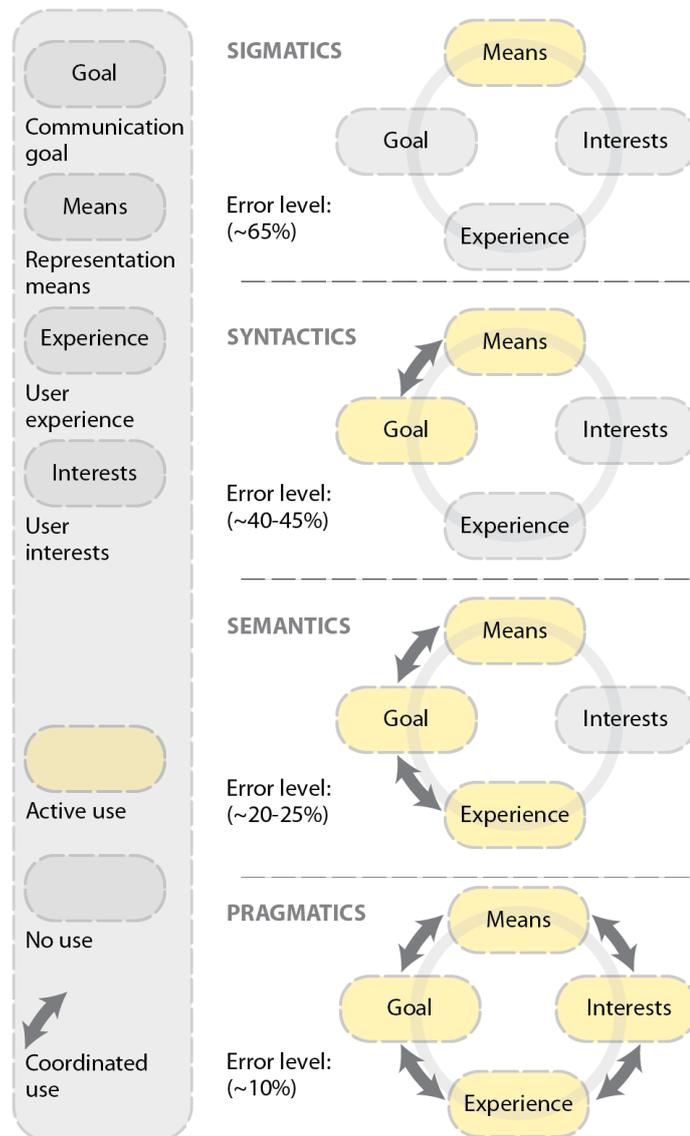


Fig. 3. Coordinated functioning of the semiotic model elements and its impact on visual communication efficiency

Thus, the problem arises of identifying a set of tasks of visual data interpretation for which the user's own knowledge is sufficient to obtain the correct solution. An example of a possible modification of traditional visual data interpretation method from the user point of view is appearance in the visual communication process of operations of initial problem statement modification (reinterpretation). The ultimate purpose of manipulating the conditions of the problem and the process of its solution is to reduce the volume of optional (redundant) operations with the data under study.

An analogy can be drawn using a technique called "reframing" [10], which is used at the stage of setting the goal of visual research. In this case, reframing is a technique for changing the interpretation context based on the selected representation metaphor in order for the user to achieve new or operational understanding of the visualized data meaning. The meaning of the actions performed by the user within the framework of the semiotic approach to visualization is to achieve the closest possible consistency between the components: data representation (sigmatiks), user's own knowledge (semantics), research problem (pragmatics), decision

hypothesis connecting data, i.e. creating a model of the event under study (syntactics). For the visualization tool user, such consistency looks like an opportunity, supported at the level of the involved tools, to look at the task from another (various) perspective(s), evaluate its goal from a different angle, identify features in the initial data that are not available when using the traditional or familiar representation metaphor.

Reframing methodology implementation poses a task for the visualization tool developers to provide the user with a technical opportunity to create a variable data representation in the course of visual communication. Consequently, it becomes mandatory to add to visualization tools the capability to control interactively both the represented data (filtering, scaling, coordination, etc.) and visual display methods.

## **6. Adaptation of visual communication levels**

A useful consequence of the proposed scheme for coordinating semiotic model elements (Fig. 3) is the opportunity to increase the efficiency of visual analytics functional definition of the adaptable visualization concept proposed in the paper, which considers visualization as a process efficiency of which depends on the consistency of all its elements. First, adaptation of visual communication implies coordination of expressive means used by visual analytics tools both with the properties of initial data and with the goal of communication being performed. Second, communication control aimed at achieving consistency between user perception and visualization properties must ensure that the visualization tools perform their role without errors. Otherwise, the use of decision support tools in an unusual role of learning tools and, therefore, the unattainability of the set goal may result from an incorrectly chosen visualization metaphor.

Based on the considered features of visual communication, it can be argued that their reasonable organization is capable of expanding the applicability of visualization tools including their use as standalone tools with a number of unique advantages.

For example, the results of experimental assessments of consequences of using interactive visualization tools [8] allow for asserting the existence of two-way consistency within which not only the user's knowledge is used to interpret and analyze the initial data, but also his experience is actively manipulated.

The cognitive effort made by the user while forming intermediate hypotheses and verifying them corresponds to the iterative learning effect consistent with the considered semiotic approach. A useful result of the continuous accumulation of experience by the user is reduction in the time it takes to solve similar problems because memorized visual sequences of visualization tool states or their fragments, due to the capabilities of perception, also become new signs (or their combinations) and take part in interactive visual communication at the next step.

However, as follows from the correspondence scheme (Fig. 1), transitions between the levels of the semantic model can occur under the influence of many external factors which are not always controlled by the user. For example, transition to the pragmatic level can be performed without going through the syntactic level in the presence of strict time constraints for visual communication. In this case, absence of consistency between subjective experience and communication goal can become a source of erroneous decisions.

Understanding the reasons why visual analytics tools can perform a function different from the one for which they are designed or involved in the task at hand will allow for making timely adjustments and avoid misconceptions. Analysis of the visualization semantic model and the results of experimental assessments allows for the following conclusions (Fig. 4):

- Adaptation of visualization tools to visual communication goals can be realized both when using the capabilities of interactive control and as a result of changes in the external conditions of communication.

- The task of informing (sigmatics), using a certain sign system, in the case of expanding this system or changing (clarifying) the area of its application, goes into the class of learning tasks, which, in turn, leads to different organization of the communication process.
- Acquaintance with a new visual metaphor defining the meanings of unfamiliar images leads to a change in the user's interpretation of visual data, complementing the previous experience and knowledge. This initiates the formation of subjective interest and new hypotheses explaining contradictions present in the image. To solve the problem of analysis (syntactics) becomes the communication goal. It implies directed cyclical communication.
- Ambiguity of hypotheses formulated by the user based on the capabilities of the selected sign system and the goal of visual communication can be supplemented by the capability to save and compare verification results of these hypotheses. The level of selection or decision making about optimal compliance with the desired result (pragmatics) should also differ in its organization from the other levels in order to preserve the goal of visual communication and prevent transitions to simpler levels.

The findings are in good agreement with the experience of designing visualization tools [11] for interpretation and analysis of heterogeneous data [12-13]. For example, the same data, being the basis of visual images using different representation metaphors (Fig. 5), correspond to the tools of informing (A), research (B) and selection (C). In the informing problem (A), the goal is to transmit the initial data to the user with minimal distortions arising from the transition to the visual representation. In the research problem (B), visualization options are proposed that focus the user's attention on the features of the data that are relevant to the purpose of the analysis. In the selection problem (C), the initial data visualization is supplemented with visual images of the hypotheses being formed, for example about the internal dependencies necessary to select one of the possible solutions. The visualization option offered for decision support systems assumes the capability to visualize not the initial data but only the results of intermediate interpretation.

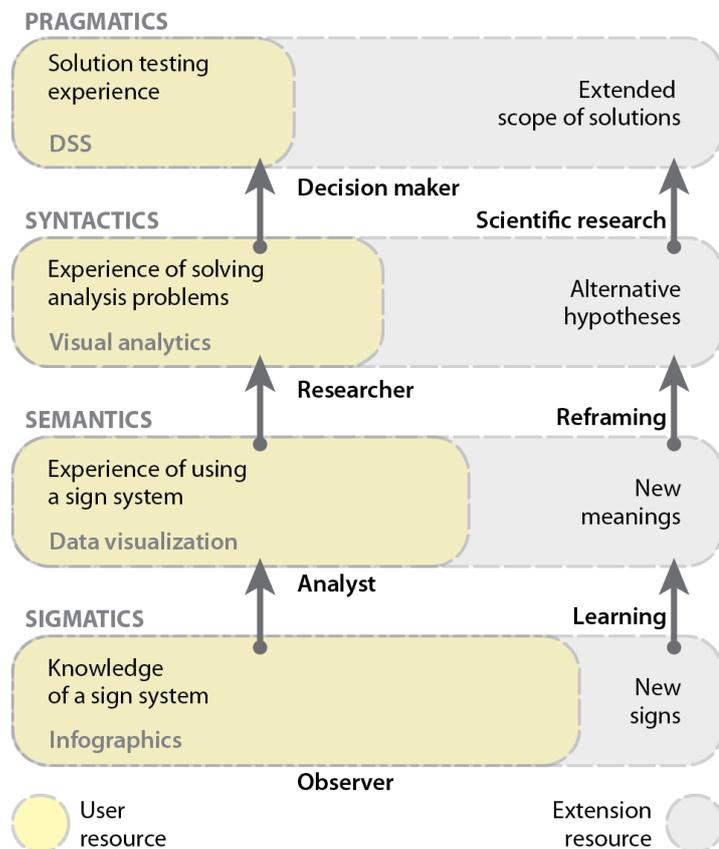


Fig. 4. Changes in the levels of visual communication occurring as a result of coordination of its goals, user capabilities and visualization tools used

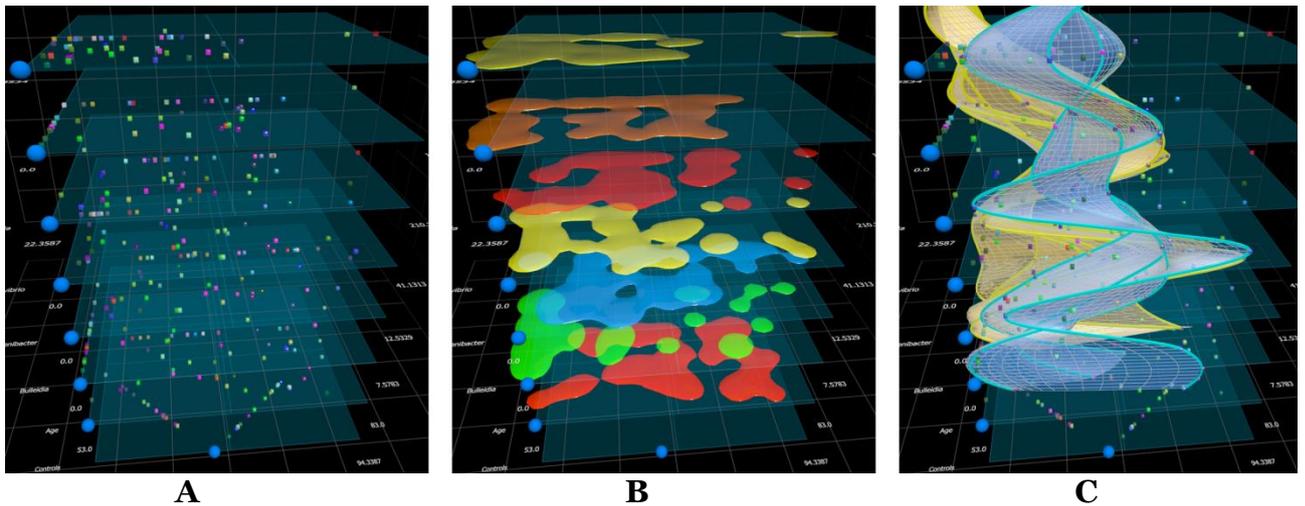


Fig. 5. Visualization options with different functional purposes

## 7. Conclusion

Thus, the paper proposes a scheme for adapting visualization tools to the specifics of the tasks for which they are developed. Analysis and interpretation of significant volumes of multidimensional data, including those obtained as a result of computational experiments, should be considered as one of the promising areas of visual analytics development, to which the results obtained in this work may be valuable [14]. Application of adaptable visualization techniques will reduce the level of interpretation errors and increase the efficiency of existing and developed visualization tools in their practical use.

## References

1. Zakharova, A.A., Shklyar, A.V.: Informative Features of Data Visualization Tasks. *Scientific Visualization*, 7 (2), 73–80 (2015).
2. Bondarev, A.E., Galaktionov, V.A.: Generalized Computational Experiment and Visual Analysis of Multidimensional Data. *Scientific Visualization* 11 (4), 102–114 (2019). doi: 10.26583/sv.11.4.09
3. Bondarev, A.E.: On the Construction of the Generalized Numerical Experiment in Fluid Dynamics. *Mathematica Montisnigri XLII*, 52–64 (2018).
4. Solomonik, A.: *Ocherk obshhej semiotiki [Essay on general semiotics]*. URSS, Moscow, Russia (2018). [in Russian]
5. Averbukh, V.L. Approach to Semiotic Theory of Computer Visualization. *The Advances in Computer Science: an International Journal (ACSIJ)*, 4 (1), 44–54 (2015).
6. Ware, C.: Foundation for a Science of Data Visualization. In: *Information Visualization. Perception for Design (Third Edition)*. 1–30 (2013). doi: 10.1016/B978-0-12-381464-7.00001-6
7. Green, T.M., Ribarsky, W., Fisher, B.: Building and Applying a Human Cognition Model for Visual Analytics. *Information Visualization*, 8 (1), 1–13 (2009). doi: 10.1057/ivs.2008.28
8. Zakharova, A.A., Vekhter, E.V., Shklyar, A.A.: The Applicability of Visualization Tools in the Meta-Design of an Educational Environment. *European Journal of Contemporary Education* 8(1), 43–51 (2019). doi: 10.13187/ejced.2019.1.43
9. Sacha, D., Sedlmair, M., Zhang, L., Lee, J.A., Weiskopf, D., North, S., Keim, D.: Human-Centered Machine Learning Through Interactive Visualization: Review and Open Challenges. In: *ESANN 2016 proceedings, European Symposium on Artificial Neural Networks, Computational Intelligence and Machine Learning*, pp. 641–646. i6doc.com publ, Bruges, Belgium (2016).

10. Martin, B., Hanington B.: *Universal Methods of Design: 100 Ways to Research Complex Problems, Develop Innovative Ideas, and Design Effective Solutions*. Rockport Publishers (2012).
11. Zakharova, A.A., Vekhter, E.V., Shklyar, A.V., Pak, A.J.: *Visual Modeling in an Analysis of Multidimensional Data*. *J. Phys.: Conf. Ser.* 944 012127 (2018). doi: 10.1088/1742-6596/944/1/012127
12. Zakharova, A.A., Shklyar, A.V.: *Visual Presentation of Different Types of Data by Dynamic Sign Structures*. *Scientific Visualization*, 8 (4), 28-37 (2016).
13. Zakharova, A.A., Podvesovskii, A.G., Shklyar, A.V.: *Visual and Cognitive Interpretation of Heterogeneous Data*. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, XLII-2/W12, 243-247 (2019). doi: 10.5194/isprs-archives-XLII-2-W12-243-2019
14. Bondarev, A.E.: *On Visualization Problems in a Generalized Computational experiment*. *Scientific Visualization*, 11 (2), 156-162 (2019). doi: 10.26583/sv.11.2.12