

Dimensional Congruence for Interactive Visual Data Mining and Knowledge Discovery

Sebastian Baumgärtner¹, Achim Ebert¹, and Matthias Deller

Competence Center for Human-Centered Visualization

German Research Center for Artificial Intelligence (DFKI), Kaiserslautern, Germany

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{Sebastian.Baumgaertner | Achim.Ebert | Matthias.Deller}@dfki.de

Abstract

Many authors in the field of 3D human computer interaction have described the advantages of 3D user interfaces: Intuitive metaphors from daily life, immersive workspaces, virtual environments that closely resemble natural environments, and the usefulness of the third dimension as an additional visualization scale. Nevertheless, there are still few or no successful applications for complex information spaces that make use of it in a natural human-centered manner. In this paper, we propose a novel hybrid user interface for knowledge workers to support document spaces and corresponding visualizations. We propose a combined 2D + 3D interface to support both visualization approaches and interaction metaphors to their maximum potential. Interaction is matched due to the principle of dimensional congruence and a thorough investigation of previous approaches and problems is given. Finally, a user study to evaluate the effectiveness and usability of the proposed system is presented.

Categories and Subject Descriptors (according to ACM CCS): H.5.2 [Information Interfaces and Presentation]: Graphical User Interfaces I.3.6 [Computer Graphics]: Ergonomics I.3.7 [Three-Dimensional Graphics and Realism]: Virtual reality C.2.4 [Computer-Communication Networks]: Distributed Systems-Distributed Applications

1. Introduction

Today, almost everyone uses a personal computer in some form or another. They're used at work, for personal purposes, leisure and entertainment, as tools to leverage our knowledge and intelligence, or to better support scientific research and development. Usually, one is expected to operate it by means of a graphical user interface. Primarily a mouse is used to click on icons, to launch programs, to position and manipulate a variety of windows together with belonging menus and graphical controls. This is well known as WIMP (windows, icons, menus, and pointing device) paradigm and has dominated personal computer systems over the last decades. However, user interfaces for visual data mining did not rest in this state. Graceful 3D visualizations and representations were more and more used [CRY96] [SCL*99] [WCC05].

In order to keep pace with visualization possibilities, computer and graphics systems evolved according to Moore's law, being more powerful than ever before. Display tech-

nologies and graphical output devices got more and more mature and affordable in the past years. There has been a clear shift from CRT monitors to LC displays, three dimensional displays and virtual environments. Nowadays, they are more widely available and it is likely that suitable displays or display combinations might replace traditional ones. Virtual Reality applications do not have to be treated as niche applications any longer.

However, there are still many unsolved questions in the area of 3D user interfaces and many detours are taken to establish a rich set of functionality which is already available in today's familiar 2D interfaces. While others try to find best-practices to embed information such as text or meta-information into virtual environments [BNC*03] [PB05], to integrate complicated textual input or system control mechanisms within a virtual world [CRF97], we try to identify affordances and match them to an appropriate input or output device. This results in a superior user interface, being more intuitive and more natural to use.

In this paper, we present a hybrid 2D + 3D visual data mining approach using mixed-dimensional visualization. Thereby, interaction is adapted to complement visualization dimensionality in order not to sacrifice task performance. We use the concept of *dimensional congruence* to find best-matches for the dimensionality of interaction techniques with the demands of visualizations and tasks. This concept was introduced by Darken and Durost [DD05], who define the term as:

[...] a condition whereby the spatial demands of a task are matched directly by the interaction techniques that is used to execute it.

The remainder of this paper is organized as follows. The state of the art is reflected in a first step. With the task analysis and the definition of dimensional congruence in hand, an appropriate system configuration is derived. The implementation of our proposed system framework is elucidated and evaluated afterwards. Finally, future work and conclusions are presented.



Figure 1: The proposed visual data mining system.

2. State of the art

2.1. 2D and 3D user interfaces

Visual interfaces have become the de facto standard for human-computer interaction. The 2D WIMP paradigm has been extended towards three-dimensional user interfaces (3DUIs) in the past years. There has been a huge discussion on 3DUIs and many empirical studies have revealed contradictory evidence of their value. Robertson's *Data Mountain* [RCL*98] tries to leverage natural human capabilities,

particularly cognitive and perceptual skills. Results show that users are able to exploit spatial abilities and to transfer organizational knowledge to a 3D virtual environment (VE). However, users complained that navigation controls were '...confusable or not grouped properly by function'.

Tavanti and Lind compare a hierarchical layout to a spatial metaphor as well [TL01]. Results show that realistic 3D displays better support cognitive spatial abilities and memory tasks, thus confirming Robertson's results. However, they argue that it is still unclear, to what extent visual properties of the 3D space affect this performance.

Contrary to this are the results of Cockburn and McKinsey [CM02]. They compared the effect of 2D and 3D interfaces, tightly resembling *Data Mountain*. They report that subjects' ability to relocate web pages deteriorated as their freedom to use a third dimension increases in both virtual and physical environments. The overall user satisfaction was negatively assessed as users found the 3D interface less efficient and more cluttered.

To understand this divergent result, another study was conducted [Coc04]. While Cockburn's experimental setup was heavily based on that of Tavanti and Lind, he tried to eliminate untreated factors of their experiment to determine if the positive effects of 3D are still reproducible. Results suggest that spatial memory is fairly unaffected by the presence or absence of 3D interfaces in regular monocular static displays. It remains unclear, whether a 'perfect' virtual 3D implementation would produce spatial memory advantages or disadvantages.

2.2. Natural representations

A further outcome of Cockburn's study is the fact that locations are better learned and memorized when the underlying information is meaningful to the user and visually distinctive. Questions and doubts on over-reliance of spatial memory have already been noted by Jones and Dumais [JD86].

Ark et al. examined the effect of more 'natural' GUI representations through which users might find it more intuitive to navigate through virtual spaces [ADSZ98]. They examined target acquisition times by four different layout possibilities extending traditional WIMP metaphors by an ecological office-like metaphor, resulting in the best overall-performance. Ecological considerations are important as people draw important cues from their immediate environment, develop knowledge of the space over time, and through the experience of interacting with it.

2.3. Hybrid approaches

Bornik et al. use a Tablet PC in front of a stereo wall (375cm diameter) in the medical application area [BBK*06]. The authors' objective is to combine direct 3D interaction with 2D system control and precise 2D interaction. A new input device - a kind of *flying mouse* - is introduced by the authors to establish hybrid interaction. The device is connected via

cable to the Tablet PC and uses markers for optical tracking. Half of the users had problems with focusing between the larger stereo wall and the desktop. Mixed dimensional interaction introduced by their novel input device did not place any problems.

These problems are also reported, however, to a lesser extent, by Narayan et al. [NCQ04]. They investigate the usability of a Tablet PC as a remote control device comparing (1) a single desktop computer to (2) a Tablet PC in combination with it and (3) a Tablet PC with a large screen display. The authors argue that peripheral vision provided by the large screen display resulted in fewer problems with context switching as it occurred with the regular PC. Moving the Tablet PC next to the monitor ameliorated context switching costs.

3. Towards a dimensional congruent system

Our investigations are settled in the project @VISOR (Adaptive Dynamic Visual Semantic Organizing). Its objective is to combine human capabilities with artificial intelligence (AI) to create a system for interaction with documents, meta-data, and semantic relations. Human capabilities in this context are spatial memory and fast visual processing of attributes and patterns. AI techniques assist the user e.g. in searching documents and calculating document similarities.

3.1. Tasks to be supported

A human-centered design approach demands for a requirements analysis as a first step. To carry out daily work, a decisive mission of @VISOR, several tasks have to be supported:

- Document management
- Overview + Detail
- Investigation of additional meta information
- Text entry and submission of search queries
- Task switching functionality

Whenever one of the above mentioned tasks or a series is performed, it is important not to hamper the flow of interactions. If this happens, user dissatisfaction is likely to occur and task performance decreases.

3.2. Dimensional congruence and natural interaction

While interacting in virtual environments, situations that desire 2D input, 2D output, or both usually come across. It is necessary to match the dimensionality of interaction with the dimensional demands in order not to sacrifice task performance. This is referred to as *dimensional congruence*, a term coined by Darken and Durost [DD05]. The authors demonstrated that 3D interaction techniques were preferable on 3D dominant tasks, purely 2D interaction techniques were preferable on 2D dominant tasks, and their hybrid interface where 2D and 3D interaction techniques were matched to each individual task showed the best performance. In order to construct interfaces that can both handle equally well, an

adequate combination as well as a prioritization might be thought of.

3.3. Usability guidelines for multiple views

Considering a system with both 2D and 3D visualizations, not only interferences due to mixed-mode interaction have to be considered. Effects caused by multiple views have to be taken into account as well. Therefore, Baldonado et al. [BWK00] proposed usability heuristics to avoid intricacies in systems using multiple views. They postulated eight rules, where a few are of special interest in our context.

The *rule of diversity* stipulates the usage of multiple views where a diversity of attributes or levels of abstraction are available. This is particularly the case in our information rich environment. An Overview + Detail approach might be a reasonable solution for the realization of abstraction levels. The *rule of complementarity* and the *rule of decomposition* fortify this. In order to account for a coordinated management of the user's attention, the *rule of attention management* asks for the focusing attention on the right view at the right time.

3.4. Cognitive issues

The previous section outlined guidelines for multi-view visualizations. They can be established using a single display or multiple devices. However, there must be a foundation for the proposed heuristics. Ryu et al. [RYC*03] [CCY*03] put some work on the investigation of cognitive issues in multi-view visualizations. These aspects include:

- Time and effort to learn the system is needed
- It puts load on the user's memory
- Mental work and costs for comparison tasks and context switching is needed
- Increased cognitive attention is needed to account for changes of another view

Contrary to what has been suggested in previous literature, the authors of [RYC*03] [CCY*03] found out, the time costs for context switching between different types of visualization (views) may not be significant and further merits might be achieved. Herein, orthogonal views play an important role, since displaying the data in the same type of visualization might cause interference. Especially this fact is addressed by Baldonado's *rule of complementary*. Using a multi-view visualization the right way, overall task performance might be increased and the following points leveraged:

- Unforeseen relationships might be discovered
- Unification of the user interface can be established
- By displaying the data in multiple ways a user may understand the information through different perspectives, overcome possible misinterpretations and perform interactive investigative visualization through correlating the information between views.

3.5. Stereo vision and the effect of immersion

One particular task of @VISOR is the illustration of relationships among documents. Therefore, studies comprehending visualization of network structures and graphs are of particular interest. Sollenberger and Milgram tried to investigate the effectiveness of stereoscopic and rotational displays for the purpose of establishing human factors guidelines for 3D interfaces [SM93]. Depth perception was evaluated by examining accuracy in a 3D path-tracing task. Results indicate that performance increased using either technique relative to pure static 2D viewing. In addition to that, the authors found super-additivity between the rotational display and stereo-enabled one. It is questionable if this outcome can be applied to systems providing motion parallax through head-coupling. In the latter case, rotation usually occurs to a slower and lesser extent and the scene is usually not entirely turned.

Ware et al. conducted several comprehensive studies in order to explore the benefits of stereo vision and motion parallax. One of the first experiments [WAB93] involved tracing a path from a leaf of a 3D tree to the correct root. Error rates were least using either stereo (14,7%) or head-coupling (3,2%). Therefore, the authors concluded that head coupling producing motion parallax was probably more important than stereo cues in 3D visualizations and that the combination of both was best. In a follow-up study [WF96], they slightly changed the task. It involved the comprehension of 3D graphs for the purpose of information net visualization and therefore generalizes tree structures to arbitrary graphs. The size of an abstract graph to be understood increases by a factor of three using both stereo and motion parallax. Stereo and head coupling alone produced an increase of 1.6 and 2.2 respectively.

3.6. Conclusion and summary

The previous section reviews many pros and cons of mixed-mode interaction, multiple views, and stereo viewing. They have to be balanced in a thorough manner. Bearing tasks and demands to be supported in the context of @VISOR in mind, we decided on the deployment of an auto-stereoscopic monitor in combination with a Tablet PC and data glove for the following reasons:

- There is a well-known preference for 3DUIs.
- There is evidence that larger structures can be better understood using additional depth cues [WF96].
- Positioning the Tablet underneath the monitor is a native way for writing and organizing documents. It resembles typical desks of information workers, hence resulting in a familiar feeling.
- Using the data glove for gesture input and a pen for writing is straight-forward; it does not hinder each other. Mixed-mode interaction is used in sequential order and interference due to parallelism is not to be expected.

- The Tablet PC is used as a complementary device. Orthogonal views are used in compliance with [BWK00].
- Overview + Detail is in our bipartite ensemble facilitated using the 3D display as overview and the Tablet as detail display.
- Textual input for search queries or annotations are very fast and intuitive using the Tablet's soft-keyboard or handwriting-recognition.
- Traditional 2D elements like buttons and sliders are better displayed on the 2D output device.
- The Tablet PC has a crisp high resolution display providing superior text legibility.
- Switching focus between both displays is not a major concern, since they are placed next to each other.

Our design results in a small change of visual focus. Slight changes on the 3D display can even be recognized due to peripheral awareness. For similar applications involving tasks analog to @VISOR's, this proposed setup might be a promising alternative.

4. Designing a dimensional congruent system prototype

In accordance with the aforementioned guidelines and after several user studies with earlier demonstrators, we designed and implemented a prototype for dimensional congruent visualization and interaction with personal document spaces. We allocated the different visualization and interaction metaphors to a two-dimensional and a three-dimensional display environment, dependent of the usefulness or hindrance of a stereoscopic view on the data.

4.1. Hardware setup

Our hardware setup consists of a stationary desktop PC containing the actual electronic documents. The PC runs DynaQ [ARD06] as information retrieval backend as well as the stereoscopic visualization framework. To display an immersive stereoscopic virtual environment, we used a SeeReal C-I auto-stereoscopic monitor (<http://www.seereal.com>).



Figure 2: Illustration of the auto-stereoscopic monitor displaying our 3D visualization environment.

To facilitate interaction within the three-dimensional workspace, we use a P5 consumer hardware data glove. For a more natural interaction, we have devised a gesture recognition framework for this and similar data gloves [DEBH06]. The recognition framework is based on defining gestures as a sequence of postures and orientations, allowing a fast yet reliable recognition without generating much load on the running system. In addition, it is easy to add new gestures to the library as well as adopting existing gestures and postures to different users.

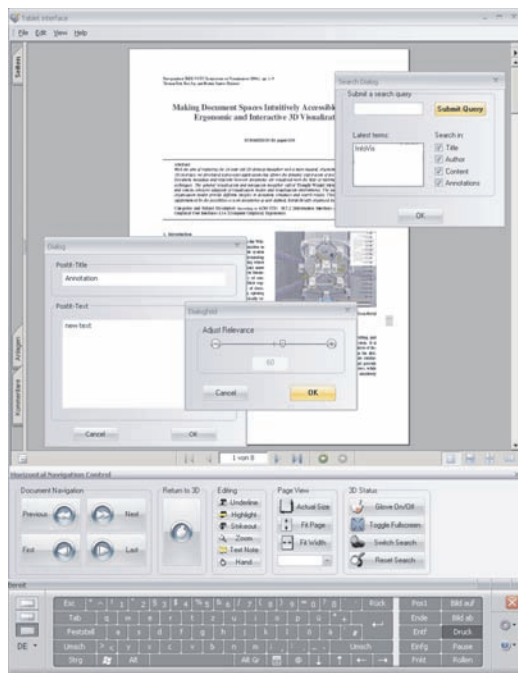


Figure 3: 2D Tablet PC interface.

As a device for both displaying and interacting with two-dimensional data we use a Tablet PC, lying or being carried in front of the stereoscopic screen. By using this device, 2D interaction can be done directly on the Tablet's surface using the pen, thus providing a quick and intuitive interface to two-dimensional visualizations. Also, there is no need for an additional keyboard; text can be entered either by using a soft-keyboard or by handwriting recognition, both provided by the Tablet PC's operating system. This is especially useful since text entry using a keyboard is somewhat hampered by the data glove.

Both machines are connected via Ethernet or WLAN, using a networking framework that allows the Tablet PC to access necessary data on the host machine as well as controlling and interacting with the application.

4.2. Interacting with virtual document spaces

The principle part of the demonstration scenario takes place within the VE on the stereoscopic display. The virtual workspace consists out of a desktop in the lower visual region of the displayed environment, and a virtual pinboard to the right of the virtual viewpoint. When interacting with each of these objects, the virtual camera is moved from the original perspective to provide a full view on the table or pinboard. The desktop provides a surface to spatially arrange single documents and document clusters. Normally, most of the visible region of the stereoscopic screen is filled by a view on the cover pages of all available electronic documents (figure 4).



Figure 4: 3D document corpus overview and working desk.

Initially, all documents hover in space at the same distance from the user supporting the demanded overview of the document corpus. The user can interact with individual documents in different ways using the data glove and our gesture recognition framework [DEBH06]. A virtual hand avatar allows to grab documents, drag a copy to the virtual desktop, stack them in an own meaningful fashion, or attach intelligent PostIts as used from the real world. Visual cues provide valuable feedback to the user. He can also put documents on top of each other, thereby manually creating document clusters which are in turn represented as stacks on the virtual desktop. Document management is naturally facilitated this way.

Of course, there's the need to provide views inside a document stack or to view an entire document. Clusters are examined by performing an opening gesture on the stack, causing the stack to move to the left side of the screen and the rest of the environment to blend out. Browsing through the stack can be either done by means of the Tablet PC or according gestures. Thereby, the documents on the stack fly first towards the user to provide a detailed view of the document and then to a second stack to the right, representing browsed documents. Because of the higher

resolution and the crispness of the 2D screen, browsing as well as editing of documents is done completely on the Tablet PC. After completion, the view changes back to the 3D representation.

More abstract interaction possibilities like changing the search mode or displaying all PostIts attached to a single document can be invoked by a three-dimensional ring menu. A pointing gesture at a virtual object triggers a ring menu to appear at the object's spatial position. By moving his hand up, down, left or right, the user can select entries of the according menu.

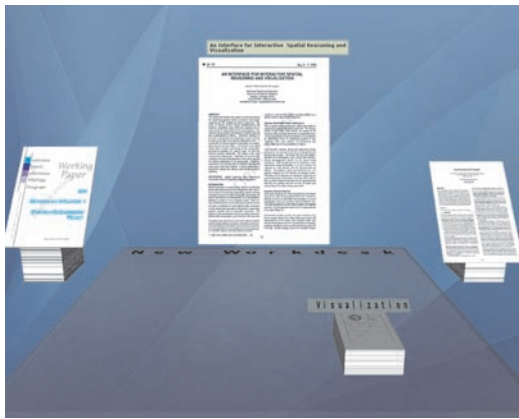


Figure 5: Browsing a stack of the virtual workdesk.

Searching through the document corpus is triggered via a 3D widget inside the VE (figure 4, top). The user can then enter a sequence of search terms via the Tablet PC, causing individual documents to leave their original position. They move towards or away from the user, depending on how good his search queries are matched. In this manner, the user gets a preattentive clue on which documents best match his current search. The user can manually redefine the importance of documents by touching their representation and pulling it towards him or pushing it away. Documents, identified by the information retrieval backend as of similar content, are also rearranged to represent the user's focus of interest. This can be influenced by a context pool which acts as a relevance feedback element. The user can add documents being particularly important for a search. In addition, the intelligent PostIts can be included into an inquiry.

The user is able switch between different tasks, e.g. from searching documents for writing a paper to assemble documents for a meeting. To change his active task, the user can activate either a 3D widget in front of the virtual workdesk or on the 2D GUI on the Tablet PC. When a new task is created, the current workdesk is saved, complete with all stacks on the workdesk, current search terms, and documents' arrangement. An empty workdesk is created and the search as well as document representations are reset to the initial state.

5. Evaluation

The overall evaluation of the developed interface was done following the sequential evaluation approach of Gabbard et al. [GHS99]. In a nutshell, it is a four-step iterative process employing application-specific guidelines, domain-specific representative users, and application-specific tasks to produce a usable interface. @VISOR is a three-year research project and an in-depth task analysis was performed at the very beginning. Starting from this point, tasks and requirements have been adjusted during the whole development phase and finally led to those presented in 3.1. Expert-guidelines based evaluations were conducted during two annual workshops (<http://www.hciv.de>) with well-acknowledged experts in the domain of HCI, InfoVis, and computer graphics. Their way to use and comment the system gave early feedback and helped to iteratively improve the system.

5.1. Formative evaluation

Two formative evaluations were performed early in the project. More than twenty subjects (60% female) were introduced to a very first system prototype in an initial informal evaluation. A broad majority of the users gave encouraging feedback: 74% accepted the visualization and interface metaphors. The spatial information item layout was reported to be intuitive by nearly 90%. The movement of important documents to the front was selected as the best choice by 72%.

A second (informal) formative evaluation was performed with VE geeks from a computer graphics class. This time, the evaluation did not include an active part but rather a fictitious scenario. Results suggest that subjects would search for important documents mainly in the front of a spatial layout (72%) and in the middle (40%) rather than in the peripheral region (20%). When asked which gesture they would perform for moving a stack, 65% answered they would use some kind of drag'n'drop by grabbing a virtual object, 16% would perform this in a 'mouse-like' fashion.

5.2. Summative evaluation

Ten subjects volunteered for a final summative evaluation study, six males and four females. All of them were between 21 and 30 years old and most of them had a solid computer science background. The subjects were first asked to fill out a pre-questionnaire which mostly focused on demographic data. Subjects were shown a training video to get to know all system features and interaction possibilities. Afterwards, they had the chance to explore the system, to ask questions, and to play around. The actual summative evaluation included a real-world scenario in which subjects were asked to write two different reports on the soccer World Cup 2006. This included subtasks like searching for keywords (e.g. 'final'), clustering of results, annotation of documents,

and switching between tasks. All participants had to fill out a post-questionnaire focusing on the user's satisfaction. The main points included visualization metaphors, functionality of virtual menus, text entry via stylus, and the extent of switching focus between the Tablet PC and the 3D visualization part. All factors were rated on a five point Likert scale (1 indicated strongly agree, 5 indicated strongly disagree).

5.3. Results and discussion

Due to the application specific experimental design, definitive and generalized statistical conclusions based on the data recorded cannot be made. However, the overall system was assessed very well and the average results of the post-questionnaire lie between 1.3 and 2.7. The most important results of the outperformed evaluation are:

- The decision if 2D or 3D document views perform better is extremely dependent on the user and task. 60% of the users preferred the Tablet PC's 2D view over the 3D view. Some users commented that the 3D view is well suited for a fast overview and the Tablet PC for a detailed view.
- The search-mode in which the user can manually redefine the importance was rated 1.45 ($\sigma = 0.49$). The context-sensitive search provided by the context pool was judged almost identical (1.55 with $\sigma = 0.31$).
- The familiar 2D interface of the Tablet PC led to the result that almost all users found it very intuitive and self-explanatory.
- The average result of assessing the pen for text input was 2.7. The high standard variance of 0.98 confirms that some users were not conversant with this input technique and did not come to grips with it.
- 80% of the users did not have problems with switching context between 2D and 3D.
- The questionnaires, videotaping, and think-aloud protocols reveal that major problems of the user interface were caused by the 3D stereoscopic monitor. Some users felt dizzy and could not establish a real 3D feeling.

The conducted evaluation demonstrates the usefulness of the proposed 2D + 3D visualization and interaction framework. Comments like '...that's nice, I did not expect it to work that well!' or '...the 3D arrangement is cool!' are encouraging and show the direction for further developments. Most of the problems with the system were related to current hardware and are likely to be eliminated by future technological improvements.

6. Conclusion and future work

In this paper we have presented a novel 2D + 3D interface for visual data mining. We identified tasks to be supported and derived a dimensional congruent system matching task, interaction, and visualization demands. By doing so, we created a more natural and intuitive interface. Some of the usability issues arising with the proposed framework were explored, discussed, and detailed solutions presented.

One of our next endeavors is to use a lightweight Tablet PC in combination with a 3D projective system in order to explore the benefits of large screens and to investigate interaction issues resulting out of this combination. The large screen scenario could bring problems concerning context switching to light. Since our utilized data glove is optically tracked, an alternative solution would have to be found. We are interested in the transfer of the proposed system configuration to other applicable areas, such as software or process visualization.

A further extension would incorporate the available camera system of the utilized monitor in order to account for the effects of motion parallax. This possibility has not been regarded yet. We further want to use the Tablet to display additional meta data, either retrieved from the information backend or virtual objects themselves.

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