The Data in Your Hands: Exploring Novel Interaction Techniques and Data Visualization Approaches for Immersive Data Analytics

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In this paper, we describe a concept for visualization and interaction with a large data set in an virtual environment. The core idea uses the traditional flat 2D representation as a base visualization but lets the user transform it into a spatial 3D visualizations on demand. Our visualization and interaction concept targets data analysts to use it for exploration and analysis, utilizing virtual reality to gain insight into complex data sets. The concept is based on the use of Parallel Sets for the representation of categorical data. By extending the conventional 2D Parallel Sets with a third dimension, correlations between path variables and the related number of items belonging to a specific node can be visualized. Furthermore, the concept uses virtual reality controllers in combination with a head-mounted display to control additional views. The purpose of the paper is to describe the core concepts and challenges for this type of spatial visualization and the related interaction design, including the use of gestures for direct manuipulation and a hand-attached menu for complex actions.

CCS Concepts: • **Information systems → Users and interactive retrieval**; Search interfaces; • **Human-centered computing →** *Interaction paradigms*; *Information visualization*; *Virtual reality*;

Additional Key Words and Phrases: Data Analysis, Information Visualization, Human Computer Interaction, Virtual Reality, Immersive Analytics

1 INTRODUCTION

Virtual Reality (VR) offers potential to develop new visualization and interaction techniques. As a powerful tool it enables users to work in an encapsulated environment, without external influences, in which they can go through the most personal and immersive experience [1]. This kind of experience can be used to support human perception, as it focuses on natural visual representations that offer potential to communicate faster and more effective than traditional 2D visualizations. In opposite to real environments, there are no spatial limitations: the visualization and interaction space can be infinitely large, displaying millions or billions of items. Especially in the industrial context with e-commerce and business intelligence, these potential data sizes are of special interest. In our example use case, we look at product data distributed within a time dimension. Possible questions for analysis include revenue or price developments.

Our approach for improved Immersive Analytics is two-fold, focusing on both visualization and interaction. The basic visualization technique for our concept and considerations are 2D Parallel Coordinates, more precisely Parallel Sets, due to their capability to represent multidimensional categorical data, hence, supporting the analysis of distributions. Basic techniques for 2D planar data visualization are extended with spatial 3D features, thus, aiming to facilitate the understanding of complex data relationships. In addition, the concept of an interactive hand-attached menu combined with a linked view is presented (cf. Fig. 5). The purpose of this paper is to discuss these concepts based on a work-in-progress prototype and the observations made during the concept and implementation process.

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2 RELATED WORK

The core idea of the presented visualization concept is to combine the strengths of 2D and 3D representations (cf. Sec. 4.1) and take advantage of their inherited benefits. Additionally, we want to explore advantages and challenges of immersive Virtual Reality environments as a visualization medium in the given context. In order to give an overview, the following section describes the comparably new research field of Immersive Analytics in the context of industrial analysis of large data sets followed by a short overview of work on Parallel Sets.

2.1 Immersive Analytics

Due to the increasing amount of data and the demand for intuitive and efficient solutions to access data, several new concepts and tools using new technologies such as VR have emerged in recent years. Olshannikova et al. propose that visualization techniques need to be improved based on the complexity of big data, and identifies three main challenges in this context: human cognition, adopting mixed reality towards Big Data and targeting issues of visualizations regarding cognition and perceptual properties as well as interaction [21]. West et al. also demand to use the benefits of Virtual Reality, since it allows the user to accomplish or display things that are usually not possible within a real environment, e.g. deforming structures or walking through solid formations, and adopt it for a data-driven experience [28]. In addition, research shows that interactive systems can significantly influence and improve the user experience [9]. The newly emerged research field *Immersive Analytics* addresses these challenges to develop efficient visual analysis tools for immersive environments [2] while emphasizing the combination of 2D (statistical and abstract data) and 3D (physical science, engineering and design data) visualizations. Various work is also dealing with research questions targeting interaction with 3-dimensional visualizations from egocentric viewpoints [26], visualization optimization regarding clutter and occlusion with head-mounted displays [20], spatial perception in regard to depth cues and cognition [4], as well as movement in 3D environments [24] in the context of Immersive Analytics.

2.2 Parallel Coordinates and Parallel Sets

The technique of Parallel Coordinates was first introduced by [13] to represent high-dimensional structures and multivariate data. In this case, the coordinates do not run at right angles but parallel, which means that theoretically any number of data dimensions can be visualized. Objects are plotted as polylines based on their values, which intersect each axis. Detecting relationships between distant axes is difficult and barely differentiable unless there is further support for interaction [23] or dimensionality reduction [3, 25, 29]. Further research is dedicated to multiresolutional views, for example in combination with Scatterplots [3, 6, 27] to help connect certain data points visually and mentally. For large data sets, Huang et al. developed further dynamic interaction for specific data selection in an 2D environment [11] while Heinrich et al. added supplementary analytic features and rendered the density of lines instead of individual ones to reduce visual clutter [10]. While [5, 15] investigated Parallel Coordinates showing 2D relationships in a 3D visualization, [19] developed the visualization technique of Parallel Sets due to the growing amount of data and to prevent overplotting. Parallel Sets divide each axis into categories and the number of items is mapped to the line thickness. Hence, the number of lines and their overlap can be decreased, and the item distribution is also visualized. In a comparative study, [14] and [16] found that Parallel Sets are better suited for analytic tasks such as cluster analysis and determining correlations, whereas Parallel Coordinates are more suitable for ordinal data, especially numerical data that can not easily divided into few categories. Thus, we focus on the use of Parallel Sets in the process of concept development.

3 USE CASE AND RELATED DATA STRUCTURES

The role of a data analyst in sales and marketing is to plan the selling of products, collect revenue data, and maintain data sources. Thus, the main task is to transform data into a form that provides meaningful insight

Type	**Description**
Product	Name, release date, category, image and further product specific information
Segment	Information about the product segment, like segment name, associated categories, etc.
Platform-dependent values with temporal component	
Sales	Sales numbers on the corresponding platform, e.g. *10,000*
Price	Price value on the corresponding platform, e.g. *5,99*
Rating	Customer rating in the range from 1 to 10 on the corresponding platform, e.g. *6 of 10*

Table 1. Data structure according to the required values with temporal component depending on the platform. For each of the temporal components, values of specific points in time are available, these can be daily, weekly or monthly.

and recommendations. In our use case, the data analyst wants to understand how customers perceive products and segments on different sales platforms to control the efficiency of price changes and marketing campaigns to increase revenue through targeted adjustments. At this correlation, the main investigation targets revenue progress, price changes on specific platforms or the comparison of price developments across several platforms. For these targets, the representation of a temporal component is significant to meet these needs.

Thus, we want to address these challenges in our concept to provide a data analyst tool using emerging technologies to adopt for data exploration and analysis. Targeting this use case, we need to consider a data structure with multivariate data consisting of different time stamps (see Tab. 1) to target the required goal.

4 GENERAL CONCEPT

The proposed concept is based on [12] and [17] regarding the use of Parallel Sets for visual data exploration in 2D and 3D. The findings suit as a foundation about the applicability of a dynamic on demand extension of a 2D (flat) to 3D (spatial) visualization. In a previous work, we proposed a animated transition to transform the 2D representation into a 3D visualization [12] (see Fig. 1). The novel aspect is the adaptation of the core concepts to be used in a VR environment and the use of suitable interaction techniques within this context. The overall concept therefore consists of two main components: the visualization of Parallel Sets in VR and the hand-attached menu to provide additional information and interaction. In the following sections we will first discuss the terms immersion and emersion and how they relate to our concept. Subsequently, concrete aspects of this concept are explained, including the core features related to visualization and interaction. Finally, we outline the technical setup and development.

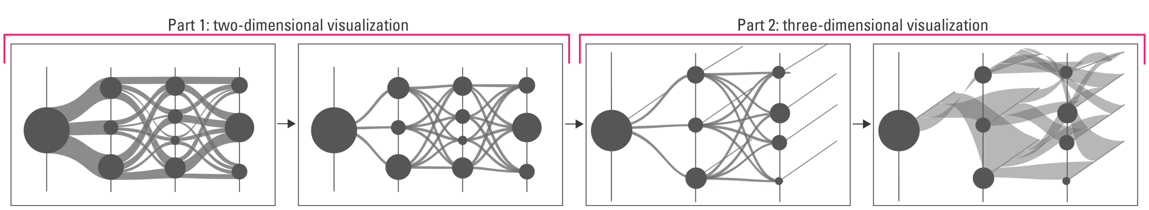

Fig. 1. Continuous transition animation [12]. From left to right: Initial 2d view, 2d view with unified paths, beginning of the transition into depth, and expanded 3d view.

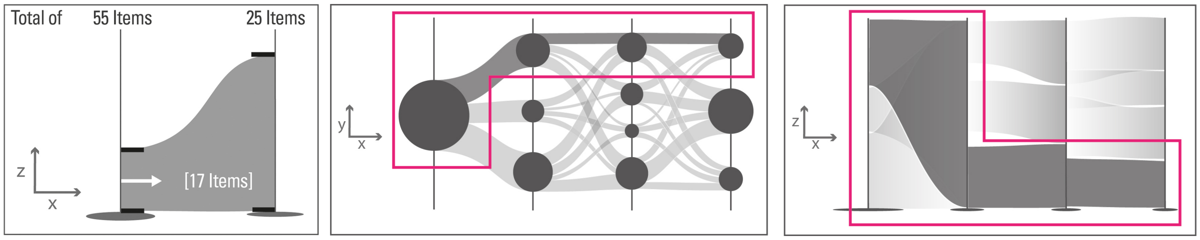

Fig. 2. Concepts from [12] Left: Schematic representation of the unification of parameter axes. Center: Front view with X- and Y-axis. Right: Top view with Y- and Z-axis and representation of the unification of parameter axes. Corresponding areas in center and right images are colored.

4.1 Emersive and Immersive Visualizations

When dealing with interactive data visualizations, Shneidermans *Visual Information Seeking Mantra - "Overview first, zoom and filter, then details-on-demand"* [22] - is often mentioned. The first and the last part, can be related to the idea of emersive and immersive representation. The concept of Emersion describes a representation in which the views from specific distance to gain an overview, like a commander observes the battlefield from an elevated point. The idea of Immersion refers to the opposite: The user is positioned *inside* the visualization and therefore is able to perceive all the details that surround him. [8]

Further attributes that can be derived from the properties of an emersive visualization: Different elements are (mostly due to missing or reduced perspective distortions) comparable, the visualization is rather static and clean / clearly ordered, because relative item positions are preserved when viewing direction or the view point changes. Due to the large viewing distance, the emersive visualization behaves like a 2D visualization - the importance of depth information is minimized. Therefore the amount on perceivable information in terms of data dimensions is smaller than in an immersive environment.

Where an emersive visualization offers an overview and depicts mainly global relationships, the immersive representation shows more detail and can reveal local relationships between elements relative to the current view point and direction. Due to this dependency, it feels more dynamic and allows for perspective-based comparisons, e.g. alignment to a certain viewing direction. By using the third dimension for data visualization more data

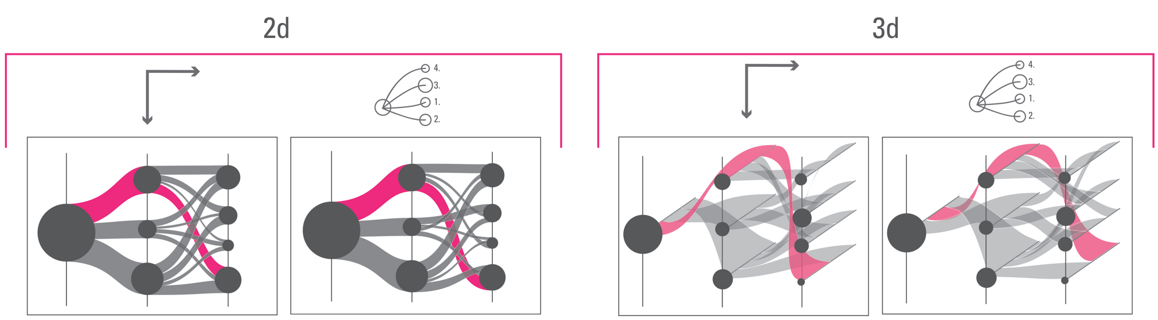

Fig. 3. Illustration of the sorting modalities of paths in comparison after [12]. Left: 2d (flat) visualization of top-to-bottom sorting (left) and next-neighbour-sorting (right). Right: 3d (spatial) visualization of top-to-bottom sorting (left) and next-neighbour-sorting (right).

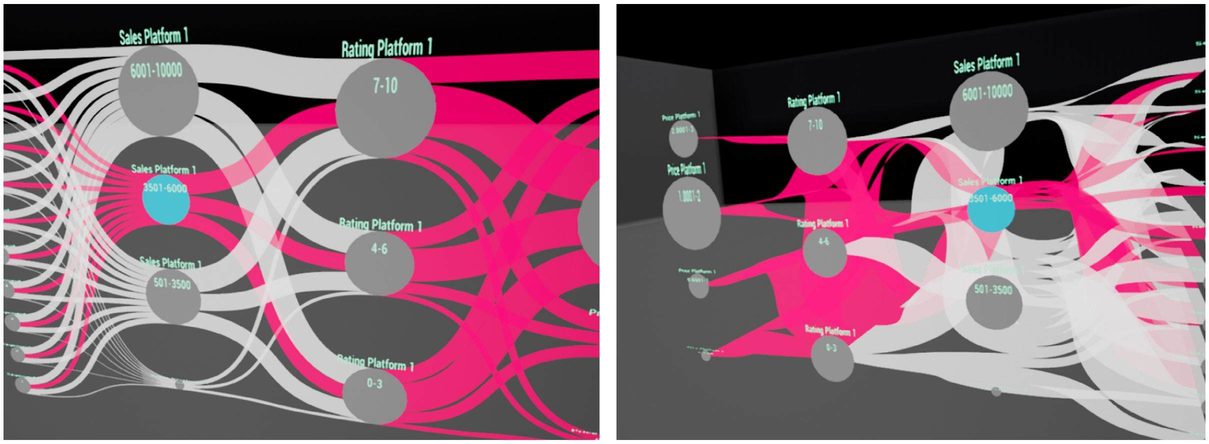

Fig. 4. Parallel Sets with one selected node and highlighted paths as well as different sorting algorithms. Left: 2D (flat) visualization with standard path sorting (top-down) active. Right: 3D (spatial) visualization with next-neighbor sorting of paths active.

dimensions can be visualized. However, the drawbacks are more visual clutter, occlusion, size and position ambiguity which makes comparison more difficult.

Based on these observations, the presented concept focuses on two characteristics of flat-emersive and spatially-immersive visualizations: 2D can be utilized to gain a quick overview of the whole problem space, whereas 3D is more suitable for detailed investigations on specific points. The visualization starts with a flat 2D graph visualization using Parallel Sets (see Fig. 4, left) to enable an assessment of the complete data space - to get the big picture. From there, the user may zoom into a specific area or Point of Interest - which relates to the zoom and filter idea of Shneidermans mantra. From this point, we started to explore benefits of an extra dimension: the user can expand the Parallel Sets into a spatial visualization - details on demand by revealing an additional data dimension.

The characteristics of this 3D representation has the typical drawbacks of 3D visualizations: overlapping paths, occlusion issues, inaccuracies derived from the perspective projection (see Fig. 4, right). On the other hand new opportunities are available: more possible relations between data dimensions can be visualized and detailed spatial structures are revealed. If the user really gets *into* the visualization, a new perspective can be obtained: the *inner* view of a single data set and its relations to its neighbors through a combination of complementary views on different visualization techniques (cf. Sec. 2.2). Additionally, it is possible to follow the path of a data set and see how these relation changes over the course through the whole visualization. In its core, the presented concept tries to combine these two different perspectives in one single interactive visualization, primarily by switching between visualization modes in combination with immersive travelling *inside* the visualization.

4.2 Extending Parallel Sets into Depth

The visualization concept initially consists of a flat Parallel Sets graph, which visualizes the categorical distribution of the data and can be expanded into depth. Thus, this visualization supports the unification of paths from [12] (see Fig. 2). Basically, every axis has a different scale when extended into the depth direction. Unification visualizes relative size of the path to the current axis instead of absolute size over the complete visualization. The motivation behind this approach is again related to the immersive view: local dependencies and relative size are more important than global relations and absolute numbers. These aspects are of particular interest to data analysts,

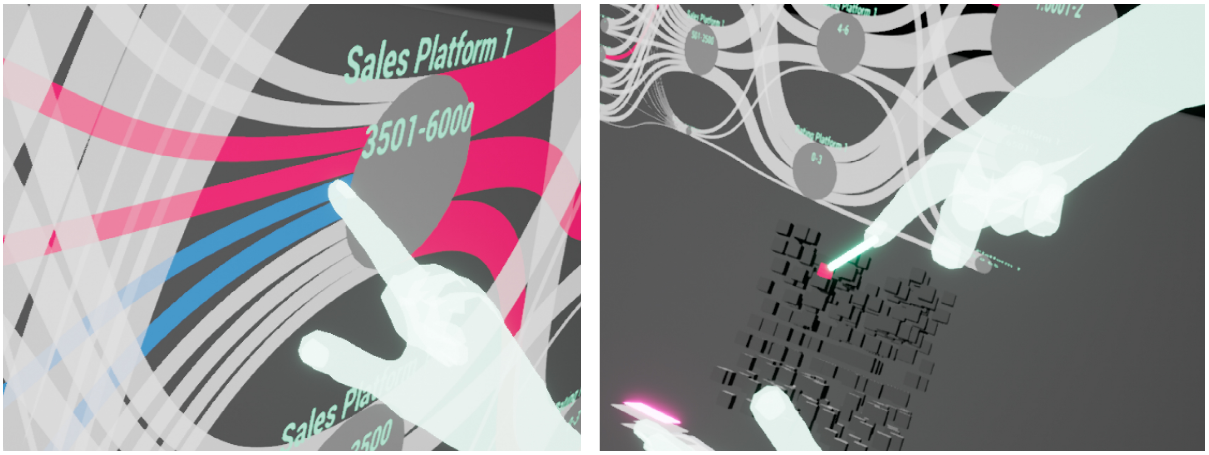

Fig. 5. Left: Highlighting of active selection (magenta) of paths while the hand is hovering over additional paths (blue). Right: Selection of item in hand-attached 3D Scatterplot visualization and brushing same item in 2D Parallel Sets visualization.

as they enable them to quickly move from one view to the next (flat to spatial), while preserving the context, at the same time adjusting to depth increases the weighting of each individual path. Thus, this supports the comparability of parameter trails and volume ratios within sections of parameters

Furthermore, this depth expansion results in different options for the sorting algorithm (see Fig. 3 and Fig. 4). While the 2D visualization seems more arranged with the standard sorting (*top-down*) for the categorical distribution, the 3D visualization seems clearer when applying the approach path weighting (*next-neighbor*) resulting in less visual clutter due to reduced overlapping paths. Here, the paths of nodes which are closer to the same height level, are visualized in the foreground of the axis. This feature is important to support tracing lines along the graph and supports the correct assignment of values.

4.2.1 ***Version control.*** Another facet is the depiction of different versions alongside to quickly visualize changes, or to highlight developments. For data analysts, it is important to view and examine data flows in order to understand specific trends. Here, visual data exploration is particularly helpful when little is known about the data and the analysis goals are vague [18]. Thus, comparing data from different points in time (cf. Sec. 3) is reasonable and allows the analyst to retrace developments. When displaying multiple data versions, they initially have a spatial offset to one another and can be moved to all axes, thus, this allows to sort and place them as required. In the 2D visualization, both visualizations can be overlaid or displayed close to each other in order to be able to compare the categorical distribution of the data without perspective leverage. Although this is also possible in 3D, it creates a different visual representation. In the overlaid 3D representation, the distribution over the time course can be followed based on the unification of the axes (cf. Sec. 4.2) to compare both graphs and can be modified by the dynamic change from 3D to 2D, without losing context. However, it may be practical to separate both graphs spatially and look at them using the perspective leverage and spatial offset to compare both graphs like the idea of a picture puzzle as a contrasting juxtaposition. Thus, to reduce memory effort for the analyst [7], the selection of paths and nodes is highlighted in the other graph by brushing to visualize the time distribution and changes of an item. In addition to selecting ranges of values, certain items can also be directly highlighted using the hand menu (cf. Sec. 4.3) to track the development of a single item or a set of items.

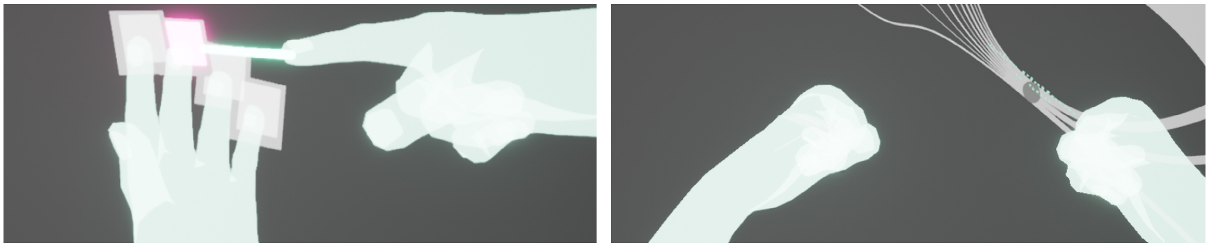

Fig. 6. Hand interaction. Left: Hand-attached menu tile is selected by pointing ray. Right: Scaling the visualization using a natural scaling gesture by using both hands in a grabbed state and pulling apart.

4.2.2 ***Virtual Interaction.*** By means of interacting with the visualization, the data analyst preserves the ability to look deeper into the data, and thus, to draw new conclusions. It is important to integrate the human into the data analysis process to take advantage on the benefits of human perception while using today's technical capabilities to analyze large data sets. Therefore, the interaction should be as intuitive and natural as possible to achieve the most immersive data-driven experience claimed by [28]. This is realized by the use of a head-mounted display for the immersion and virtual reality controllers serving as the users hands in the virtual environment. Here, it is important to recap the challenges mentioned by [21] and include the advantages of Virtual Reality presented by [28]. On one hand, the user receives the power to move freely in a (delimited) space that is not only limited to the hands, but also to the position and rotation of the body and head (*virtual camera*). On the other hand, through the use of virtual hands, whose Position and posture corresponds to the real hands of the user, it is possible to adjust and interact with the visualization. The analyst can naturally select or deselect paths and nodes by touching them (see Fig. 5, left) comparable to reshaping a fabric in the real world. At the same time, grabbing and dragging a node creates a new range of values on the parameter axis or merges values ranges. The simple gestures replace complex menu operations. Furthermore, the entire visualization can be scaled using the hand interaction as well as changing the position and rotation (see Fig. 6, right). As a result, an overview of the entire data space can be obtained quickly in form of a miniature, which can then be enlarged to dive into the data to a specific view point.

4.3 Hand-attached menu

Interacting with large and complex data sets require sophisticated interaction techniques. While selecting and deselecting items for filtering purposes can be done directly on the graph, brushing and linking several supplementary or independent visualizations represents be a helpful tool.

By mapping the menu selection directly to the hand in form of tiles (see Fig. 6, left) and dispensing button input, creates an easily accessible and natural interaction. In the concept these interaction tiles can be placed on every fingertip except the thumb. The following interaction options are provided: axis interaction mode, selection of data items, Scatterplot visualization mode and query history.

The *axis interaction mode* allows the user a menu-based assistance to manipulate axes. Additionally to moving and replacing axes, it also includes adding new or already existing axes as well as to remove them. This offers the opportunity to compare different parameters side-by-side. Furthermore, the *direct selection mode* of individual data items or specific data records with the help of a further interaction tile is possible. The selection is performed using a list of data items from which the user can select appropriate elements.

4.3.1 ***Scatterplot.*** Another part of the hand-attached tile menu is the Scatterplot graph providing a complementary visualization as proposed by [3]. Here, the data analyst can display a 2D or 3D Scatterplot graph from previously selected axes. If required, the corresponding value range of the Parallel Sets nodes can also be specified here to limit the axis values. The menu is anchored to the palm of the user's virtual hand so the visualization is firmly anchored to the user's spatial position and movement. In addition, the user can select a data item using a laser beam, which is generated by a pointing gesture of the user's hand. This selection also brushes the course of the data item in the paths of the Parallel Sets (see Fig. 5, right). By synchronizing changes between both representation, the visualizations complement each other: The Scatterplot provides enhanced object visibility, whereas the parallel sets emphasize attribute visibility. A combination of both allows for better transferability.

4.3.2 ***Query history.*** An selection or specific configuration of the Parallel Sets can be saved and used to compare with another query. Thus, a subset of information objects can be extracted based on selected parameters. The stored query histories are displayed as miniature thumbnails within a scrollable list and are then displayed similar to mapping different versions of data as a stand-alone graph visualization. Thus, both selection queries can be visually and spatially compared additionally to the version control described in Sec. 4.2.1. The data analyst can then view both graphs from different perspectives, on the one hand as a flat or spatial representation and on the other hand from different viewing angles and positions.

5 PROTOTYPICAL IMPLEMENTATION

The technical setup for the development of our work-in-progress prototype consists of an Oculus Rift CV1 and Oculus Touch Controllers. Unreal Engine 4 (UE4) serves as a software development environment as the Blueprint system of the 3D Engine is perfectly suited for rapid prototyping, especially for interaction and visualization. UE4 also offers the ability to use C++ in combination with the development environment Visual Studio for data manipulation and computational tasks. Specific C++ macros for properties and functions exposes them to the Blueprint system of Unreal Engine 4, offering a great level interoperability between the visual scripting environment and the low level programming components. The engine also offers the option to refactor Blueprint scripts into C++ classes to increase performance.

The example data record used for our prototype consists of corresponding data from 10,000 products. Besides different multivariate categorical properties, the data set contains a temporal determinant to different temporal variants of the data (see Tab. 1). In addition to the product characteristics, the product data record also contains information on different sales figures, ratings and prices, which were obtained on different sales platforms. The data is available in json format, which can be called and deserialized by an annotated C++ function within Blueprints. Since data initially is available as individual data items within a json array, it must be preprocessed first. For this purpose, an initial specification of parameter axes and value ranges triggers a creation of the categories to be used. After deserializing the json array, the data elements are mapped to the categories. In the next step, paths are generated according to the data items assigned to the categories. This indicates which data item corresponds to which category or path and can be dynamically adjusted at runtime.

6 CONCLUSION

In this paper, we presented a concept with a prototypical implementation for analysis of large data sets by a data analyst. Our focus was on the usage of virtual reality as an interactive medium and the visualization of large data sets. Our concept serves as a first step in the direction of abstract data visualization and usage of inherited properties of virtual reality to allow a more natural and intuitive interaction with data, especially when the concrete analysis goals are not yet specified and different views and filter configurations are evaluated in rapid succession.

In addition to the presentation of Parallel Sets, we have also linked a Scatterplot graph visualization, as these visualization types nicely complement each other. Furthermore, any number of additional Parallel Sets graphs can be added to the virtual environment, allowing the comparison on a global and detail scale. The basic concept of the hand menu shows potential for future extension and enhancement of existing functionality. One important challenge is related to the question of overview and orientation in abstract virtual environments. When navigating inside the Parallel Set visualization on a very close perspective, the user may lose the overview of the whole visualization. Observations show that this issue is less significant than in other visualization types, e.g. Scatterplots. However, with growing amount of data or increasing zoom factor this aspect may represent an issue. In any case, an important aspect is the investigation of the immersion on the user and the consideration of the application of emersive visualization concepts within the immersive environment, e.g. a map or providing directions to significant points inside the visualization. Comparable to landmarks (Buildings, Surface formations, Points-of–interest) in a natural virtual environment, specific values on the nearest values axis could be used for orientation in the immersive visualization. Another factor may be to restrict movement directions or offer additional navigation modes, e.g. *surfing* in a specific data item. Regarding visualization, the extension of the concept in terms of subtle assistive components is reasonable, such as the support of depth perception by using color perspective elements or the use of cutting planes on the spatial depth axes in order to filter the data space even further. The arrangement of data axes in the spatial representation is another open question. In the current concept, we did not adapt the position of the axes - they stay aligned to the x-axis when extending the graph into depth. However, spatial arrangements of coordinate axes allow to compare more than two axes, providing another advantage of the spatial visualization. Hovewer, it also widens the visual gap between flat and spatial representation, which bears the risk to lose orientation when switching between both visualizations or being confused by the transition. One aspect of the selection within the Scatterplot representation and Parallel Sets is the extension of the pointing beam for the selection in form of a resizable sphere to capture not only one but multiple data points within a certain radius. Additionally, it is conceivable to work co-located and cooperatively, thus, allowing multiple users to interact and collaborate in this environment. This includes questions for highlighting regions, specific data sets or structures in the visualization. Further collaboration concepts aim at roles between users, and how they navigate together through data, share their position, view point or current perspective on the data.

However, the paper serves as a basis for the investigation of further presentation and interaction possibilities in connection with virtual reality in order to carry out future studies on the basis of minimal prototypes and staked problem areas. Furthermore, technical considerations have to be made to determine in what way the concept is feasible in its current state.

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REFERENCES

[1] Ejder Bastug, Mehdi Bennis, Muriel Medard, and Merouane Debbah. 2017. Toward Interconnected Virtual Reality: Opportunities, Challenges, and Enablers. *IEEE Communications Magazine* 55, 6 (2017), 110–117.

[2] T. Chandler, M. Cordeil, T. Czauderna, T. Dwyer, J. Glowacki, C. Goncu, M. Klapperstueck, K. Klein, K. Marriott, F. Schreiber, and E. Wilson. 2015. Immersive Analytics. In *2015 Big Data Visual Analytics (BDVA)*. 1–8.

[3] Jaegul Choo, Hanseung Lee, Zhicheng Liu, John Stasko, and Haesun Park. 2013. An interactive visual testbed system for dimension reduction and clustering of large-scale high-dimensional data. In *Visualization and Data Analysis 2013*, Vol. 8654. International Society for Optics and Photonics, 865402.

[4] Grégoire Cliquet, Matthieu Perreira, Fabien Picarougne, Yannick Prié, and Toinon Vigier. 2017. Towards HMD-based Immersive Analytics. In *Immersive analytics Workshop, IEEE VIS 2017*.

[5] Elena Fanea, Sheelagh Carpendale, and Tobias Isenberg. 2005. An interactive 3D integration of parallel coordinates and star glyphs. In *Information Visualization, 2005. INFOVIS 2005. IEEE Symposium on*. IEEE, 149–156.

[6] Ying-Huey Fua, Matthew O. Ward, and Elke A. Rundensteiner. 1999. Hierarchical Parallel Coordinates for Exploration of Large Datasets. In *Proceedings of the Conference on Visualization '99: Celebrating Ten Years (VIS '99)*. IEEE Computer Society Press, Los Alamitos, CA, USA, 43–50.

[7] Michael Gleicher, Danielle Albers, Rick Walker, Ilir Jusufi, Charles D. Hansen, and Jonathan C. Roberts. 2011. Visual comparison for information visualization. *Information Visualization* 10, 4 (2011), 289–309. arXiv:https://doi.org/10.1177/1473871611416549

[8] Rainer Groh. 2017. *An Iconography of Interaction* (1st ed.). TUDpress.

[9] Marc Hassenzahl and Noam Tractinsky. 2006. User experience-a research agenda. *Behaviour & information technology* 25, 2 (2006), 91–97.

[10] Julian Heinrich and Bertjan Broeksema. 2015. Big data visual analytics with parallel coordinates. In *Big Data Visual Analytics (BDVA), 2015*. IEEE, 1–2.

[11] Mao Lin Huang, Tze-Haw Huang, and Xuyun Zhang. 2016. A novel virtual node approach for interactive visual analytics of big datasets in parallel coordinates. *Future Generation Computer Systems* 55 (Feb. 2016), 510–523.

[12] Natalie Hube, Mathias Müller, and Rainer Groh. 2017. Additional On-Demand Dimension for Data Visualization. In *EuroVis 2017 - Short Papers*. The Eurographics Association.

[13] Alfred Inselberg and Bernard Dimsdale. 1990. Parallel Coordinates: A Tool for Visualizing Multi-dimensional Geometry. In *Proceedings of the 1st Conference on Visualization '90 (VIS '90)*. IEEE Computer Society Press, Los Alamitos, CA, USA, 361–378.

[14] J. Johansson and C. Forsell. 2016. Evaluation of Parallel Coordinates: Overview, Categorization and Guidelines for Future Research. *IEEE Transactions on Visualization and Computer Graphics* 22, 1 (Jan 2016), 579–588.

[15] Jimmy Johansson, Camilla Forsell, and Matthew Cooper. 2014. On the usability of three-dimensional display in parallel coordinates: Evaluating the efficiency of identifying two-dimensional relationships. *Information Visualization* 13, 1 (2014), 29–41.

[16] Mandy Keck, Martin Herrmann, Andreas Both, Dana Henkens, and Rainer Groh. 2014. Exploring Similarity. In *Human Interface and the Management of Information. Information and Knowledge in Applications and Services*, Sakae Yamamoto (Ed.). Springer International Publishing, Cham, 160–171.

[17] Mandy Keck, Martin Herrmann, Dana Henkens, Severin Taranko, Viet Nguyen, Fred Funke, Steffi Schattenberg, Andreas Both, and Rainer Groh. 2014. Visual Innovations for Product Search Interfaces. In *1st International Workshop on Future Search Engines at INFORMATIK 2014*.

[18] Daniel A. Keim. 2001. Visual Exploration of Large Data Sets. *Commun. ACM* 44, 8 (Aug. 2001), 38–44.

[19] R. Kosara, F. Bendix, and H. Hauser. 2006. Parallel Sets: interactive exploration and visual analysis of categorical data. *IEEE Transactions on Visualization and Computer Graphics* 12, 4 (July 2006), 558–568.

[20] A. Moran, V. Gadepally, M. Hubbell, and J. Kepner. 2015. Improving Big Data visual analytics with interactive virtual reality. In *2015 IEEE High Performance Extreme Computing Conference (HPEC)*. 1–6.

[21] Ekaterina Olshannikova, Aleksandr Ometov, Yevgeni Koucheryavy, and Thomas Olsson. 2015. Visualizing Big Data with augmented and virtual reality: challenges and research agenda. *Journal of Big Data* 2, 1 (01 Oct 2015), 22.

[22] B. Shneiderman. 1996. The Eyes Have It: A Task by Data Type Taxonomy for Information Visualizations. *1996. Proceedings., IEEE Symposium on Visual Languages* (1996), 336–343.

[23] Harri Siirtola and Kari-Jouko Räihä. 2006. Interacting with parallel coordinates. *Interacting with Computers* 18, 6 (2006), 1278–1309.

[24] Mark Simpson, Jiayan Zhao, and Alexander Klippel. 2017. Take a Walk: Evaluating Movement Types for Data Visualization in Immersive Virtual Reality. (2017).

[25] Alexandru Telea. 2015. Data visualization principles and practice /. (2015).

[26] Jorge A Wagner Filho, Marina F Rey, Carla MDS Freitas, and Luciana Nedel. 2017. Immersive Analytics of Dimensionally-Reduced Data Scatterplots. (2017).

[27] J. Wang, X. Liu, H. W. Shen, and G. Lin. 2017. Multi-Resolution Climate Ensemble Parameter Analysis with Nested Parallel Coordinates Plots. *IEEE Transactions on Visualization and Computer Graphics* 23, 1 (Jan 2017), 81–90.

[28] Ruth West, Max J Parola, Amelia R Jaycen, and Christopher P Lueg. 2015. Embodied information behavior, mixed reality and big data. In *The Engineering Reality of Virtual Reality 2015*, Vol. 9392. International Society for Optics and Photonics, 93920E.

[29] Xin Zhao and Arie Kaufman. 2010. Multi-dimensional reduction and transfer function design using parallel coordinates. In *Volume graphics. International Symposium on Volume Graphics*. NIH Public Access, 69.