THEME ARTICLE: Immersive Analytics

Comfortable Immersive Analytics with the VirtualDesk Metaphor

Case Studies and Perspectives

Jorge A. Wagner Filho
Federal University of Rio Grande do Sul

Carla M.D.S. Freitas
Federal University of Rio Grande do Sul

Luciana Nedel
Federal University of Rio Grande do Sul

The VirtualDesk metaphor is an opportunity for more comfortable and efficient immersive data exploration, using tangible interaction with the analyst's physical work desk and embodied manipulation of mid-air data representations. In this paper, we present an extended discussion of its underlying concepts, and review and compare two previous case studies where promising results were obtained in terms of user comfort, engagement and usability. We also discuss findings of a novel study conducted with geovisualization experts, pointing directions for improvement and future research.

Immersive Analytics applications are growing exponentially with the latest technology advancements, with promising results reported in numerous data domains, including spatial and non-spatial datasets.[1] They represent a clear opportunity to tackle long standing perception and interaction limitations of 3D data representations.[2] However, much is still unknown in terms of design guidelines, and frequently adopted navigation approaches have drawbacks that complicate the use of such applications in real-world data analysis scenarios. Common implementation choices include flying through virtual scenes, which demands time to reach different viewpoints and often induces severe simulator sickness, and physically walking around the data, which requires a large space free of obstacles.

Our proposal for a more comfortable and efficient Immersive Analytics is the VirtualDesk exploration metaphor,[3] where the user remains seated in front of a virtual reproduction of his/her real work desk, and interacts directly with data representations positioned at arm's reach using only natural hand gestures (see Figure 1). Requirements and characteristics of analytical environments and activities impose the adoption of different solutions to tackle the comfort issues faced by all Virtual Reality applications.

In this article, we present an extended discussion on the fundamentals of this approach, and perform a cross-domain analysis of the results from two different case studies. In the first, multidimensional abstract data are projected to three dimensions and explored as a 3D point cloud. In the second, movement trajectory data is visualized in space and time simultaneously through an immersive Space-Time Cube representation. Our purpose is to identify common trends regarding user comfort, presence and efficiency. For specific results and details regarding each case study, we refer readers to the specific publications.[3,4] We also discuss novel qualitative results obtained in recent interviews with Geovisualization experts, and our perspectives for future developments of the VirtualDesk metaphor.

THE FUNDAMENTALS

In this section, we describe the fundamental characteristics we aimed at with the VirtualDesk metaphor, and discuss how they overcome the drawbacks perceived in alternative approaches.

Figure 1. In VirtualDesk, interaction is a combination of mid-air natural gestures and tangible contact with the real-world work desk. Viewpoint changes are only possible by manipulating the dataset or through head movements, greatly reducing simulator sickness.

Rendering Data at Arms' Reach: Embodied Interaction, Proprioception and Stereopsis at Short Distance

One of the main fundamentals underlying the VirtualDesk metaphor is the rendering of data representations at small scale and at arm's reach. This allows direct manipulation through natural mid-air gestures using virtual hands, leading to a series of advantages. The resultant one-to-one mapping between actions in the real world and in the virtual one reduces the mental workload associated to interaction tasks, freeing cognitive resources for the data comprehension (this concept has been called spatio-temporal coordination[5]). Moreover, it enables more precise manipulations by profiting of the human proprioception sense, implementing gestures relative to the user's own body. Last but not least, the stereopsis depth cue is long known to be much more useful when comparing objects positioned at short distances from the user.[6] Therefore, rendering data at arm's reach increases the contribution of this technical aspect of VR displays to data exploration tasks, for example through a better estimation of distances and depths, while large-scaled environments minimize its benefits.

Direct Data Manipulation through Natural Mid-Air Gestures

Gestures for data manipulation should correspond to expected affordances of real-world objects. Some of our main gestures correspond to very common natural actions: grabbing with one or two hands to move, stretching with two hands to scale, spinning two hands to rotate and tapping with the point of the index finger to inspect. Some actions also borrow from known desktop-based interactions, such as applying a double-tap to select a data point, mimicking an expected double click. Haptic feedback, for example, in the form of different hand controller vibration patterns, increases the intuitiveness of these mid-air interactions. Visual feedback, such as slightly changing the color of objects upon tapping are also recommended to stimulate interactivity. On the other hand, unnatural behaviors like applying different gesture interpretations for each hand, or constraining degrees of freedom, have led to user confusion and errors in our previous studies,[3,4,7] and should be avoided when possible.

Virtual Reproduction of the Analyst's Desk: Tangible Interaction and Simultaneous 2D and 3D Data Views

The VirtualDesk serves three different purposes. First, it provides a real-world reference inside the virtual environment, easing the user's adaption and increasing the feeling of presence in the immersive world, possibly leading to higher engagement and concentration.

Second, the desk allows tangible interaction with controls positioned on its surface, as in a mixed reality environment (see Figure 1). The front part of the desk constitutes a comfortable and intuitive location to position tools such as buttons, sliders and data annotation mechanisms. Similar solution was proposed in VRRRRoom.[8]

Finally, the desk's surface can also be used for displaying 2D associated data views simultaneously to the mid-air 3D representations. These can assume the form of small legends or reference maps, used as combinable interactive filters, such as in our first case study, or even the complete table, such as the base map of a space-time cube in our second case study. We believe this approach thus provides an excellent natural metaphor to answer the question of how to combine 2D and 3D views in immersive environments.

Seated Exploration and Viewpoint Changes through Head Movements: Comfort and Easy Workspace Integration

Besides offering a different perspective and potential efficiency benefits, we believe two key system requirements for an Immersive Analytics application that aims to be adopted in a real-world analysis scenario are for it to be comfortable, avoiding simulator sickness, and to be easily integrable into the analyst's typical work environment. Applications that require the user to walk around a data representation, for example, will typically demand the user to move to a different environment free of obstacles, complicating its usability for quick data exploration tasks.

In VirtualDesk, the user remains seated[9] throughout all exploration activities (except for the uncommon event of standing up to obtain a different perspective, depending on the data representation), and all viewpoint changes are obtained by moving his/her head or by manipulating the data position. This reduces physical demand and simulator sickness resulting from conflicts between real body position and virtual movements, for example, when employing flying navigation metaphors. In previous experiments, our approach has led to very satisfactory user comfort results, as will be discussed later on.

DESIGN SPACE

A series of factors are left undefined in the outlining of the VirtualDesk metaphor, and this design space can be explored to find most suitable choices.

Interaction Devices

Although a hands-free approach for mid-air interaction would be preferred and most realistic, we believe current technology still favors the use of hand controllers for hand tracking. In pilot studies, we noticed that the Leap Motion tracking system performed poorly with most gestures used in our framework. Other authors have already observed that last generation devices such as the HTC Vive Controllers are more stable, more accurate and, surprisingly, still pose a lower learning curve to users.[10] In our experiments, we have opted to use the Oculus Touch controllers which accompany the Oculus Rift HMD. Despite not being able to track the position of each finger, a series of touch and near-touch sensors and triggers allow a satisfactory estimation of hand gestures. Hand positions are permanently tracked with a high level of accuracy and six degrees of freedom using the Constellation tracking system. Additionally, the controllers offer a tradeoff for their apparent decreased realism: they allow the presentation of haptic feedback during mid-air interactions with data, increasing the perceived realism of such representations.

An additional consideration regarding the choice for interaction devices is how the desk position will be tracked by the system. In our current implementation, the hand controllers are placed on a predefined position on the front edge of the real desk upon application start, and their positions are used to obtain the desk location.

A challenge when using such an approach, however, is the eventual size difference between real and virtual hands, especially regarding the length of the index fingers, used for selections. In our observations, this has caused some users to clearly notice the difference when trying to tap mid-air points, affecting their proprioception sense, and others to have difficulties to reach the surface of the VirtualDesk despite being touching the real one. This latter issue has been improved in our second case study by asking the user to touch the desk and readjusting its vertical position according to the virtual fingers. Overall, however, in both studies, a majority of users have had no issues even without this enhanced calibration.

Interaction Gestures

Even when using hand controllers, we argue that selected interactions and gestures should be as controller-agnostic as possible, for three different reasons. First, it is expected that, with the advancement of technology, the controllers tend to be removed, and so the system should not permanently rely on them, for example by using buttons for specific actions. Second, the VR market is divided among a series of major manufacturers, and this increases the generalizability of the approach and decreases device dependency. And, third and most important, ideally the controllers should be abstracted by users after a few moments, assuming the form of virtual hands in their minds. Although this also implicates in not benefiting from any controller-specific facilities, we are convinced that most required actions can be satisfactorily implemented by gestures, while more complex interactions will be clearer when assigned to the table controls.

In our studies, grabbing and stretching gestures are easily learned, whereas the double tapping action initially leads to difficulties. This changes with training, and usually participants rate this form of interaction at the same level as in a common desktop application. It is also expected to be improved with a better tuning of parameters such as the expected interval between taps. The purpose of this gesture is to allow the system to differentiate between temporary inspections and permanent selections, such as a Desktop system would do with mouse over and mouse double click, respectively.

Desk Size

An interesting question is whether the VirtualDesk should precisely replicate the dimensions of the real one, to increase fidelity, or instead be rendered in larger scale to accommodate more content. Upon empirical testing, we have selected a larger size of 2m x 3m for our implementation. This takes advantage of the virtual environment infinite space and, by offering a larger notion of available space, stimulates the use of a larger area to scale and translate data.

Moreover, in some cases, this also provides a focus+context visualization approach. In the case of the space-time cube, for example, the user can closely inspect movement trajectories displayed at short distance (over his/her actual desk), while a larger area provides spatial context.

Obviously, the real desk size must always be used as the limits for positioning interactive content.

Desk Surroundings

In our current prototypes, for evaluation reasons, the VirtualDesk and its contents are the only objects in the virtual environment. This surely leaves much space left, with potentials to be explored in future research. For example, the space behind the user can be used to display alternative contents when he or she rotates the chair. In the same way, the space around the desk can be used for different purposes. In the case of our second case study, for example, grid walls around the desk indicate different moments in the space-time cube. In the first one, on the other hand, it remains empty.

Another potential to be carefully explored is the ability to stand up and walk during exploration, what could offer a different perspective relative to the desk. This was observed, for example, by a few users in our space-time cube application. However, this should not be assumed as a standard exploration form in the application, since it may contradict the objective for an easy-to-integrate approach, and requires more control over the remaining environment and possible obstacles. It also requires a larger tracking area, what can be a limitation for current sensors.

Virtual, Mixed or Augmented Reality

A frequent question in Immersive Analytics applications is what position in the Reality-Virtuality spectrum is most appropriate or helpful for a given analytical application.

A common belief is that Augmented Reality (AR) approaches, introducing virtual objects into the real world, would be more convenient and easily adopted, allowing the use of Immersive Analytics while still being able to use other tools such as Desktop systems and to see and discuss with other people in the same space. However, AR head-mounted displays, at this moment, are still much behind their VR counterparts, and results of experiments with such devices do not reflect the true potential of these approaches.

VirtualDesk is a Mixed Reality (or Augmented Virtuality) metaphor, bringing objects from the real world into the virtual one. One first argument for experimenting with this approach would be precisely that, in the absence of appropriate AR devices, such environment could be simulated with an environment like VirtualDesk. Nonetheless, there are other factors which justify the usage of VirtualDesk even when novel AR devices are available. VR environments offer infinite space, allowing the representation of a larger, more useful desk, as discussed, and the scaling of the data to sizes much larger than any room. They also allow the isolated exploration of the data, completely removing any distractions in the environment – arguably, also a part of the concept of immersing oneself into the data. Moreover, besides not preventing local collaboration (since multiple collocated people can join the virtual environment in the form of avatars), it also facilitates the implementation of remote collaboration, since there is no difference between people who are in the same space or in different countries, for instance.

CASE STUDY I: MULTIDIMENSIONAL DATA PROJECTED TO 3D SCATTERPLOTS

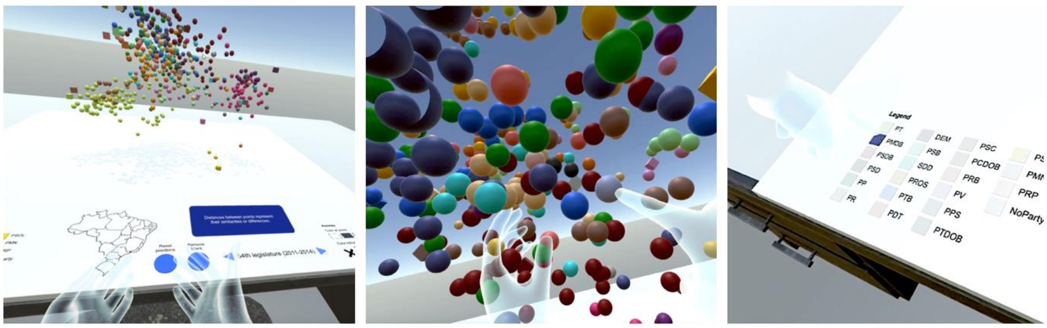

Figure 2. In our first case study, VirtualDesk is used to explore a 3D points cloud representing projected multidimensional data. 2D coordinated views displayed on the virtual desk allow the application of combinable categorial and geographical filters.

Our first case study evaluation of VirtualDesk was dedicated to the exploration of 3D scatterplots of multidimensional data, obtained through multidimensional projection techniques such as PCA.[7] We specifically selected a use case of roll calls voting data in a Chamber of Deputies, where the projection results in a political spectrum representing similarities and differences in votes between different deputies during a four-year legislature. As we have previously discussed elsewhere, the third dimension in this kind of application can offer a more accurate representation of the original multidimensional space configuration, increasing efficacy in some analytical tasks and for some datasets.[7]

Besides intuitively manipulating the 3D point cloud using mid-air gestures, the 24 participants in this study could apply combinable filters using interactive coordinated 2D representations of categorical and geographical data relative to politicians, which were conveniently positioned on the surface of the desk (see Figure 2). A series of nine tasks was defined in terms of four different competencies: point-based distance perception, class-based density perception, clustering and interaction.

When comparing against a desktop-based comparable implementation, quantitative results indicated that VirtualDesk was always at least as accurate in the performance of perception tasks, and significantly better for two of them: identification of the closest politician (neighbor data point) and identification of the time period in which a given party (group of politicians) was densest. Completion times were similar for tasks which required only the comparison between points in the point cloud – participants were much faster using the intuitive manipulation gestures, but were also more engaged in data exploration, performing 5.8x more dataset rotations than when using the mouse and contributing to their better understanding of the spatial distribution. Tasks which required the application of filters or commands using the desk, however, were significantly slower. This is partially due to the need to change viewpoints (while, in Desktop, all information is on the screen), but mostly due to initial interaction difficulties by users with a large hand size deviation from the virtual models.

Regarding interaction tasks (i.e. application of filters and selection of data points), the mouse was still faster and more accurate, with less unintended selections, particularly in cluttered areas of the scatterplot. This was already expected, considering its known precision and vast amount of previous training, and the unfamiliarity of participants with the double tapping gesture, and stimulates the continued research of novel selection approaches for this environment.

The immersive exploration of the data was subjectively favored by the majority of participants. Out of 24, all considered it more engaging, 21 more intuitive, and 15 faster. They were divided, however, in terms of accuracy: many reported that Desktop was most accurate for selection, while VirtualDesk was much more accurate for manipulation. 46% more participants agreed that it was easy to find the required information when immersed.

Comparison with Flying Metaphor

In this case study, results were compared against a previous experiment[7] that used a common immersive flying navigation metaphor. For the four point-based distance perception tasks shared between both studies, participants were consistently more accurate in the desk scenario, and significantly faster in all tasks, reaching a 51% improvement rate. Most important and impressive, however, were the results for user comfort: in a similar 15 minutes immersion session, participants using VirtualDesk reported a 7x smaller simulator sickness score (measured by the standard Simulator Sickness Questionnaire), without any reports of discomfort during or after the execution of tasks. These results confirmed VirtualDesk's potential as a more comfortable and efficient data exploration approach.

CASE STUDY II: THE IMMERSIVE SPACE-TIME CUBE FOR MOVEMENT DATA

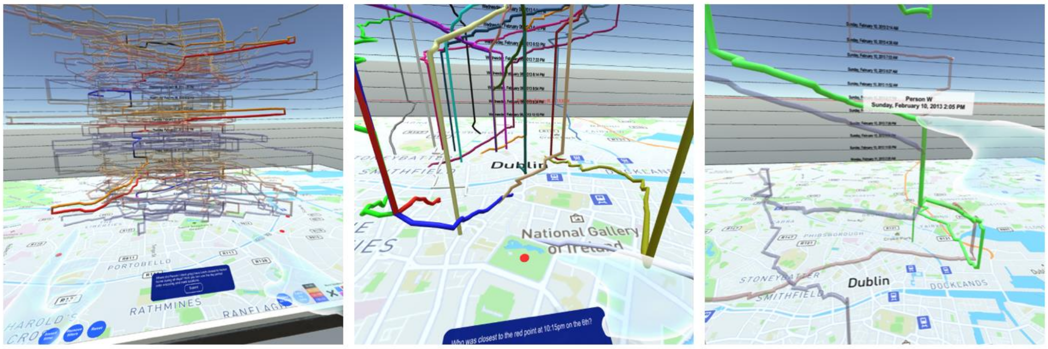

Figure 3. In our second case study, VirtualDesk is adapted to a Space-Time Cube representation, allowing the immersive exploration of movement trajectories and reducing the known steep learning curve of this geovisual representation.

For our second case study, we changed our focus from abstract information visualization to spatio-temporal data, proposing the VirtualDesk as a suitable metaphor for the immersive exploration of the Space-Time Cube (STC) geovisualization representation.[4] This important inherently 3D representation allows analysts to more clearly observe movement trajectory features and patterns in space and time simultaneously, but is usually associated to a difficult interaction, difficult perception of depths and a steep learning curve.[11]

In our VirtualDesk prototype (see Figure 3), the base map of the Cube is coupled to the desk, and trajectories are rendered as three-dimensional tube meshes. Using similar mid-air gestures as before, the user can move and scale trajectories in time or space, and rotate the map. Tapping gestures are used for inspection of different instants and for the selection of complete trajectories.

In a user study with 20 participants, two scenarios with trajectories followed by 3 or 24 people over a 3-day period and 7 different spatio-temporal tasks were investigated. Results indicated that quantitative performance is similar in the majority of tasks, possibly due to the sample of subjects, which were unfamiliar with the data representation, but large differences appear considering the subjective results and the analysis of interactivity patterns. The immersive environment resulted in a 32% higher system usability score, and 32% smaller mental workload score, indicating a potential significant improvement to the acceptability of the Space-Time Cube. Sixteen participants considered it easy to find the required information in this condition, compared to only six in the Desktop alternative. The VR system was also less susceptible to the presence of clutter, maintaining similar correct rates for all tasks in both data scenarios.

The natural interaction provided by VirtualDesk also completely modified the interaction patterns. Participants performed many more data translations and scalings by intuitively using their hands, and constantly moved their heads to change the point of view. Meanwhile, users in the desktop-comparable implementation performed much more map rotations, to benefit from structure-from-motion depth cues.

An interesting difference in this case study was that VR exposure times increased to an average of 25 minutes, due to the need for more training and more complex tasks. Nonetheless, simulator sickness results were still low and similar to the previous study (see next section).

Experts Feedback: Informal Evaluation with Geovisualization Researchers

While user studies with general users, such as employed in our two case studies, are an excellent resource to evaluate perception and interaction differences between different approaches to a same problem, focused applications such as the Immersive Space-Time Cube typically will only achieve their true potential when used by particularly interested and familiarized users, such as the data domain experts, or data owners. For this reason, we decided to conduct demonstrations and interviews with Geovisualization experts to determine next steps in our Immersive Space-Time Cube project.

During a workshop at the Laboratoire d'Informatique de Grenoble, France, fifteen different spatio-temporal data analysts (professors, researchers and PhD students), from various backgrounds, including Computer Science, Geomatics and Geography, performed free exploration sessions and provided feedback on our VirtualDesk prototype. With the exception of one participant, who felt uncomfortable and interrupted the session after 5 minutes, most were able to quickly familiarize themselves with the environment regardless of previous experience with VR devices, and spent considerable time (often more than 20 minutes) exploring different possibilities, comparing to their previous experiences with GIS software and providing suggestions for improvements. At this stage, we opted not to conduct a systematic task-based evaluation, allowing each expert to freely explore features related to his/her research interests.

All participants demonstrated interest in applying this approach to their data domains, and considered that immersive exploration allowed them to minimize the effect of typical shortcomings of the Space-Time Cube representation such as occlusion, difficult interaction and difficulty to clearly distinguish overlapping trajectories.

Some of the most frequent provided suggestions are summarized below. While some are in line with our previous observations with regular users in the second case study, others are directly related to usual exploratory procedures and interests particular to the data experts.

In terms of visual design features, the following suggestions were provided:

- Improvements to data presentation, such as the option to hide or modify the degree of transparency of unselected trajectories.
- Provision of coordinated and interactive 2D map views for easier identification of spatial patterns and application of regional filters.
- Inclusion of standard features such as semitransparent cutting planes for comparisons.

In terms of the interaction design, experts recommended new features such as:

- Inclusion of interactive tools to allow easier comparisons between trajectories.
- Inclusion of advanced interactive filtering mechanisms based on spatial, temporal, demographic and semantic information.
- Enhanced annotation tools to mark periods of time and locations on the map during the formulation of hypotheses, which persist after the end of the session.

Finally, some recommendations also concerned to system flexibility:

- Inclusion of changeable base maps including 3D terrain, satellite images and importable information layers for different analysis.
- Data enrichment with semantic attributes about trajectories.
- Inclusion of mechanisms for generation of analytical reports and output of conclusions, for example including statistics about specific trajectories selected during the data exploration.

These contributions will be integrated in upcoming versions of VirtualDesk, and illustrate the importance of permanently conducting such informal qualitative studies with domain experts.

DISCUSSION: VIRTUALDESK CONTRIBUTIONS IN USER EXPERIENCE

Current results indicate that, in fact, a large part of the contribution of Immersive Analytics is linked to subjective criteria, such as engagement, usability, comfort and workload. Comparing results across the previous two case studies, it is possible to identify patterns in contributions of the Immersive Analytics approach and in user experience results. In both cases, generally tasks were performed in similar times in the immersive and non-immersive implementations – some tasks were slower due to implementation issues or, in the case of the simplest STC task, due to the ability to select objects at distance in Desktop. In terms of accuracy, results were generally similar as well. In the first case, 2 out of 7 tasks presented significant improvements using immersive exploration, while, in the second, no differences were observed – although this still must be evaluated with trained analysts.

The VirtualDesk scenario was preferred to the desktop comparable implementation in terms of engagement by a vast majority of participants: 24/24 in the first case study, 19/20 in the second. This is partially related to the novelty of VR applications, but also to more specific factors also reported by participants: VR often makes it easier to find the desired information and makes interaction more intuitive and easier to learn. This can also be observed in terms of quantitative data exploration metrics, such as scatterplot rotations in our first study and trajectories movement and scaling in the second one. In terms of usability, measured scores using the System Usability Scale (SUS)[12] also indicate advantages for the immersive environments, especially in the case of the more complicated STC representation (Figure 4).

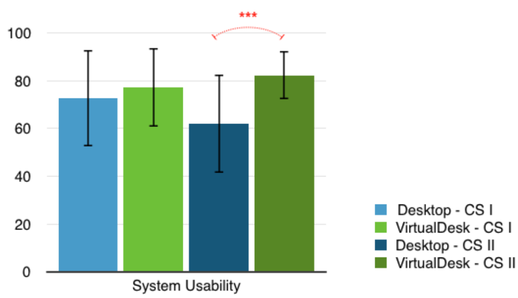

Figure 4. System Usability Scores (SUS) obtained in both case studies indicate consistent improvements using VirtualDesk, especially for the more complicated Space-Time Cube representation. Asterisks mark pairwise statistical significance at $p < .001$.

Workload

In terms of workload as measured by the NASA Raw Task Load Index (TLX),[13] other interesting observations are possible, and indicate an apparent difference between the two case studies (Figure 5). We hypothesize that these are likely related to the different complexities involved, with the second evaluated representation being much more difficult to explore in a standard desktop environment – it must be noted, however, that this is a between-subjects comparison, and different participants may have adopted different criteria in their answers.

While in the scatterplot scenario the average task load index and the mental workload are slightly increased using immersive exploration, possibly due to the novelty of the environment and experienced difficulties, in the STC case they are reduced. Similar trends are observed for the perceived performance and effort – the latter possibly dominated by the physical effort in the first case, but by the Desktop interaction difficulty in the second. A much larger difference for the STC is also seen in the frustration score. In terms of physical workload, a similar and expected trend is observed, noting the inherent physical demand of immersive environments.

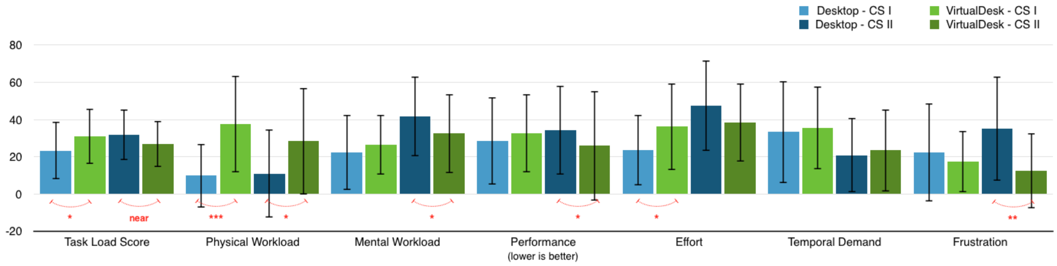

Figure 5. Measured workload factors (NASA TLX) indicate that the contribution of immersive exploration using VirtualDesk is clearer in the case of more complex representations such as the Space-Time Cube, which demand great effort and cause great frustration to manipulate in a Desktop environment. Asterisks mark statistical significance at the following levels: * for $p < .05$, ** for $p < .01$ and *** for $p < .001$.

Comfort

One of the key benefits hypothesized in the development of VirtualDesk was repeatedly validated in our case studies. Knowledgeable readers are aware that most works in the field report high incidences of simulator sickness after small VR sessions, and that participants interrupting experiments due to discomfort is not uncommon. In our studies with this metaphor, however, only occasional, mild symptoms were reported. Importantly, our second case study increased significantly the exposure times and still was able to obtain a very similar average, with only a larger overall standard deviation – but we note that no user asked for interruptions or reported any severe symptom at any moment. Comparing these results to our own previous results employing a flying navigation metaphor (see Figure 6) also illustrate this difference – that study was scored 7x higher, with several complaints.

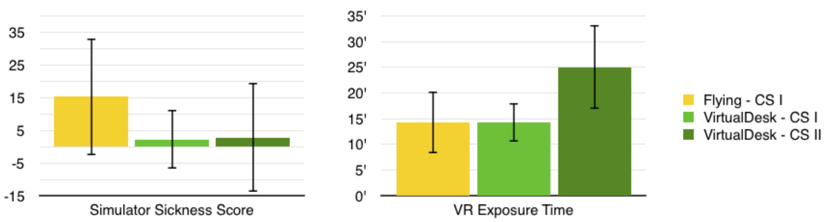

Figure 6. VirtualDesk consistently obtained excellent results regarding Simulator Sickness Scores (left) across the two evaluation studies, despite long VR exposure times (right). Compared to a previous implementation using flying navigation, sickness scores were seven times smaller.

Presence

Another important feature of Immersive Analytics applications is the feeling of experienced presence, hypothesized to increase the engagement of the user in the analytical activity. In our studies, presence was evaluated using the Igroup Presence Questionnaire (IPQ),[14] subdivided into four components: spatial presence in the virtual space, involvement (related to absence of awareness of the real environment), experienced realism of the virtual world, and a general item related to the sense of "being there". It is important to note that in both studies participants were allowed to constantly communicate with the experimenter, what kept them partially aware of the external environment.

Figure 7 illustrates similar results for the first three components and a significant decrease of general presence in the STC application. We attribute this difference to implementation choices and limitations of this prototype, and that serves as a warning for future developments. In our STC application, due to the larger amount of data visualized and the concern to preserve a high frame rate (low frame rates are also cause of simulator sickness), some interaction gestures were

This is the author's version of an article that has been published in this journal. Changes were made to this version by the publisher prior to publication.
The final version of record is available at http://dx.doi.org/10.1109/MCG.2019.2898856

constrained to avoid multiple simultaneous transformations. For example, two hand gestures were dedicated only to scaling and rotation, and translations were blocked, causing confusion since this grabbing with two hands is an intuitive action to move large objects. In the same way, scalings were performed only on the spatial or temporal dimensions at once, while rotations required both hands to be kept at a similar height, also breaking intuitiveness. These results clearly illustrate that such restrictions to degrees of freedom and expected natural behaviors affect the general experience of presence, and should be avoided.

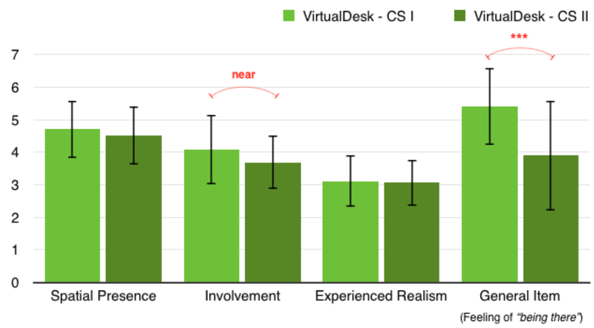

Figure 7. The Igroup Presence Questionnaire (IPQ) scores indicate that spatial presence and realism were similar, but the second case study indicated a reduced feeling of "being there" for participants. This is possibly related to implemented interactions constraints that contradicted participants' expectations, and should be taken into account in future developments. Asterisks mark pairwise statistical significance at $p < .001$.

VIRTUALDESK PERSPECTIVES

Research related to the VirtualDesk immersive metaphor can continue in several directions. In our view, the most relevant ones concern the creation of more flexible environments, through its combination with non-immersive desktop environments and alternative immersive perspectives, the creation of comfortable environments for collaborative data exploration, and long-term evaluations to assess the impact of long exposure sessions.

Desktop-VirtualDesk Integration

Even with the expected advances of VR technology, it is reasonable to imagine that most tasks in the work of a data analyst will continue to be performed in a traditional setup, involving the use of desktop applications and real interaction with other people. In this context, we believe a key perspective for VirtualDesk is its seamless integration to a desktop counterpart application. The idea is that the analyst should be able to seamless transition between both according to his/her data exploration needs, without losing context or any aggregated information such as selections or annotations.

In our case studies, desktop comparable implementations were based on a two-panels interface, where the upper, main panel offers a perspective projection of the 3D data view, while the lower panel replicates controls and 2D views situated on the surface of the desk. Manipulation is done using the mouse and keyboard and common interaction mappings such as the Rotate-Pan-Dolly paradigm. This direct mapping offers a simple way of combining both paradigms.

Evaluating their immersive NeuroCave application, Keiriz and colleagues allowed users to enter and leave the VR mode as desired and observed that they were indeed able to readily move between the desktop and VR displays without complaint.[15]

This is the author's version of an article that has been published in this journal. Changes were made to this version by the publisher prior to publication.
The final version of record is available at http://dx.doi.org/10.1109/MCG.2019.2898856

VirtualDesk in Collaborative Data Exploration

A key aspect in data analysis is collaborative discussion and exploration for the formulation and validation of hypotheses. Even though current prototypes for VirtualDesk target only individual exploration, we are confident that this metaphor is also suitable for different modes of collaboration. Using avatars such as provided by the Oculus Integration Package for Unity, it is possible to extend this environment to accommodate both collocated and remote collaboration between two or more analysts seated at their own desks. In both situations, our idea is that all desks would be unified as a single virtual desk. A question to be investigated is their optimal position relatively to the desk: they could be side-by-side, in a 90º angle or face-to-face. It is reasonable to hypothesize that each of these modes would have advantages under some circumstances, for example for sharing points of view or for discussing the data, respectively, and this is an important perspective for future research.

Besides these typical immersive collaboration scenarios, another possibility is to support asymmetric collaboration, between users who are immersed in VirtualDesk and others who are working in typical Desktop views. These two groups can focus on different tasks benefiting of their own advantages. For example, the Desktop users may have easier access to text input or precise selections, or to external resources, while VirtualDesk users have a better spatial understanding of the data and an easier way of interacting to investigate different points of view.

Different Levels of Immersion: Combination with Complementary Immersive Metaphors

Contrarily to other popular immersive exploration approaches, VirtualDesk inherently affords an exocentric viewpoint in relation to the data. Although the analyst can scale the data representation to a larger size, or move his/her head inside it, he/she is still offered mostly an external view of the data – somewhat like in a desktop application, but with 3D direct interaction, stereopsis and other advantages as we have discussed.

Arguably, however, a potentially different perspective offered by immersive environments would be exactly to place the analyst inside the data representation. In this context, we believe a potentially positive approach would be to support transition to alternative exploration modes on demand. The desk view should always be the standard but could offer mechanisms to transform the data view into an infinite virtual scene, navigated by virtual flying, or into a room-scale environment to be physically walked. The choice to activate such approaches would depend on the analytical task in hand and on individual characteristics of the analyst, such as availability of free space, susceptibility to simulator sickness or interest in obtaining an egocentric view of the data.

Long-term Evaluations

Current results for the evaluation of VirtualDesk, in the same way as most other immersive approaches, are based on small sessions focusing specific tasks. Although we have already expanded immersion exposure times in our second case study, it is important to continue pushing towards longer term, integrated evaluations, aiming to understand how comfort results vary with longer exposures, the effect of consistent training and familiarization on interaction capabilities, and the actual adoptability of such approach in a real-world setting. Three perspectives can be seen in this direction. The first is to conduct repeated testing with a small group of participants during several days or weeks, such as attempted by Bach and colleagues in a study for the evaluation of AR applications.[16] The second is to conduct longer evaluation sessions with repeated blocks of tasks interleaved with tutorials and clarifications, for the evaluation of learning effects – our observations indicate that misunderstandings relative to the interaction or to the interpretation of the data representation, and excessive concern of participants to avoid mistakes under observation negatively affect performance and confound measured values. The third but also more difficult and expensive direction is to conduct in-the-wild testing with the data owners. This is in line with our initial informal study with Geovisualization experts, but will require a more systematic approach, including the recording of different metrics during long periods of usage and the scheduling of repeated interviews.

CONCLUSION

The VirtualDesk metaphor illustrates how previous knowledge from VR and 3D User Interfaces (3DUI) research can be successfully combined to compose more comfortable and efficient data exploration approaches, potentially generating novel design guidelines and increasing the adoptability of Immersive Analytics applications in real-world settings.

So far, two different data domains with widely different characteristics have been targeted, with consistent observed benefits in terms of user preferences, comfort and engagement, and occasional benefits in quantitative task performance. A series of interviews with Geovisualization data experts also indicated clear potential and interest in the development of new features.

This is an ongoing research with multiple possible directions. We believe the design space and perspectives delineated in this article will shed light into some of these, contributing to the definition of future works.

ACKNOWLEDGMENTS

We are grateful to all volunteer participants in our user studies for their availability and feedback. We also thank the reviewers for their insightful comments that allowed us to improve the paper. We acknowledge the financial support from CNPq - Brazil. This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001.

REFERENCES

1. Chandler, T., Cordeil, M., Czauderna, T., Dwyer, T., Glowacki, J., Goncu, C., ... & Wilson, E. (2015, September). Immersive analytics. In Big Data Visual Analytics (BDVA), 2015 (pp. 1-8). IEEE.
2. Roberts, J. C., Ritsos, P. D., Badam, S. K., Brodbeck, D., Kennedy, J., & Elmqvist, N. (2014). Visualization beyond the desktop–the next big thing. IEEE Computer Graphics and Applications, 34(6), 26-34.
3. Wagner Filho, J. A., Freitas, C. M., & Nedel, L. (2018, June). VirtualDesk: A Comfortable and Efficient Immersive Information Visualization Approach. In Computer Graphics Forum (Vol. 37, No. 3, pp. 415-426).
4. Wagner Filho, J. A., & Nedel, L. An Immersive Space-Time Cube Geovisualization for Intuitive Trajectory Data Exploration. Under review.
5. Cordeil, M., Bach, B., Li, Y., Wilson, E., & Dwyer, T. (2017, April). Design space for spatio-data coordination: Tangible interaction devices for immersive information visualisation. In Pacific Visualization Symposium (PacificVis), 2017 IEEE (pp. 46-50). IEEE.
6. Mine, M. R., Brooks Jr, F. P., & Sequin, C. H. (1997, August). Moving objects in space: exploiting proprioception in virtual-environment interaction. In Proceedings of the 24th annual conference on Computer graphics and interactive techniques (pp. 19-26). ACM Press/Addison-Wesley Publishing Co..
7. Wagner Filho, J. A., Rey, M. F., Freitas, C. M., & Nedel, L. (2018, March). Immersive Visualization of Abstract Information: An Evaluation on Dimensionally-Reduced Data Scatterplots. In Proceedings of the 25th IEEE Conference on Virtual Reality and 3D User Interfaces (March 2018) (pp. 483-490).
8. Sousa, M., Mendes, D., Paulo, S., Matela, N., Jorge, J., & Lopes, D. S. (2017, May). VRRRRoom: Virtual Reality for Radiologists in the Reading Room. In Proceedings of

the 2017 CHI Conference on Human Factors in Computing Systems (pp. 4057-4062). ACM.

9. Zielasko, D., Weyers, B., Bellgardt, M., Pick, S., Meibner, A., Vierjahn, T., & Kuhlen, T. W. (2017, March). Remain seated: towards fully-immersive desktop VR. In 2017 IEEE 3rd Workshop on Everyday Virtual Reality (WEVR) (pp. 1-6). IEEE.
10. Caggianese, G., Gallo, L., & Neroni, P. (2018, June). The Vive Controllers vs. Leap Motion for Interactions in Virtual Environments: A Comparative Evaluation. In International Conference on Intelligent Interactive Multimedia Systems and Services (pp. 24-33). Springer, Cham.
11. Kveladze, I., Kraak, M. J., & Van Elzakker, C. P. (2015). The space-time cube as part of a GeoVisual analytics environment to support the understanding of movement data. International journal of geographical information science, 29(11), 2001-2016.
12. Brooke, J. (1996). SUS-A quick and dirty usability scale. Usability evaluation in industry, 189(194), 4-7.
13. Hart, S. G. (2006, October). NASA-task load index (NASA-TLX); 20 years later. In Proceedings of the human factors and ergonomics society annual meeting (Vol. 50, No. 9, pp. 904-908). Sage CA: Los Angeles, CA: Sage Publications.
14. Schubert, T., Friedmann, F., & Regenbrecht, H. (2001). The experience of presence: Factor analytic insights. Presence: Teleoperators & Virtual Environments, 10(3), 266-281.
15. Keiriz, J. J., Zhan, L., Ajilore, O., Leow, A. D., & Forbes, A. G. (2018). NeuroCave: A web-based immersive visualization platform for exploring connectome datasets. Network Neuroscience, 1-18.
16. Bach, B., Sicat, R., Beyer, J., Cordeil, M., & Pfister, H. (2018). The Hologram in My Hand: How Effective is Interactive Exploration of 3D Visualizations in Immersive Tangible Augmented Reality?. IEEE Transactions on Visualization & Computer Graphics, (1), 1-1.

ABOUT THE AUTHORS

Jorge A. Wagner Filho is a PhD student in Computer Science at the Federal University of Rio Grande do Sul, Brazil. His research interests include the application of novel immersive data exploration approaches to abstract information visualization and spatio-temporal data visualization. He is a student member of IEEE. Contact him at jawfilho@inf.ufrgs.br

Carla M.D.S. Freitas is a full professor at the Institute of Informatics, UFRGS. Her main research interest is interactive data visualization, which includes both conventional and non-conventional interaction techniques, 2D and 3D data representations as well as immersive approaches. She has a PhD in Computer Science from UFRGS. Contact her at carla@inf.ufrgs.br.

Luciana Nedel is a full professor at the Institute of Informatics, UFRGS. Her research interests include VR, interactive and immersive visualization, and non-conventional interaction. Nedel has a PhD in Computer Science from the Swiss Federal Institute of Technology (EFPL). Contact her at nedel@inf.ufrgs.br.