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The Data Visualisation and Immersive Analytics Research Lab at Monash University

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A B S T R A C T

This article reviews two decades of research in topics in Information Visualisation emerging from the Data Visualisation and Immersive Analytics Lab at Monash University Australia (*Monash IA Lab*). The lab has been influential with contributions in algorithms, interaction techniques and experimental results in Network Visualisation, Interactive Optimisation and Geographic and Cartographic visualisation. It has also been a leader in the emerging topic of Immersive Analytics, which explores natural interactions and immersive display technologies in support of data analytics. We reflect on advances in these areas but also sketch our vision for future research and developments in data visualisation more broadly.

1. Introduction

The Data Visualisation and Immersive Analytics Laboratory at Monash University, Australia (*Monash IA Lab*) has grown and evolved over a period of more than 20 years and while it retains its earliest strengths and interest in human-centred algorithm design for visual data representations, it has also become a truly multidisciplinary centre with a number of key research topic strengths spanning the field of Visualisation. We take this opportunity to reflect on two decades of work emerging from this lab as well as signalling our current and potential future directions.

The *Monash IA Lab* traces its origins in visual interfaces, to early work investigating the use of optimisation techniques for diagram and document layout, e.g. He and Marriott (1998), Borning et al. (2000), Badros et al. (2001), Wybrow et al. (2008), Braganza et al. (2009). Some of this work later became the foundations of constraint-based GUI layout tools used by Google in Android (ConstraintLayout) and Apple in iOS and macOS (Auto Layout). As the group expanded, these techniques were adapted to information visualisation topics, in particular to algorithms for network layout with applications in visualisation of biological pathways and software architecture, see Section 2. In parallel, the *Monash IA Lab* has continued to build on its own expertise as well as close collaboration with world-leading experts at Monash University in the area of Optimisation, with a focus on the usability of sophisticated optimisation techniques, and interaction with these from a human perspective, see Section 3.

The group developed a new focus on techniques for immersive data visualisation around 2014, spurred by rapid developments in natural user interface and virtual and augmented reality (VR and AR) technologies at the time. It became clear that these technological developments, particularly the reduced cost of VR and AR, coupled with increasing effectiveness of technologies like head and hand tracking, were approaching a critical threshold for widespread adoption, which caused us to revisit some long-held assumptions by Information Visualisation researchers on the practicality of immersion. We led an international effort to establish a new sub-field of Information Visualisation research, which we dubbed *Immersive Analytics*, see Section 4.

As the group has expanded further in the last five years, it has developed innovative user-centred design methodologies (e.g. Kerzner et al. (2019)) and gained expertise in Geovisualisation and Cartography, see Section 5. Most recently, the group has begun to explore how to make data visualisation more inclusive, see Section 6.

2. Network visualisation

As a way to model relational data, networks offer a higher-order representation of information than merely quantitative or categorical data (Dwyer, 2016). Thus, network visualisation cuts across many different application areas, from science and engineering, to law enforcement and the arts.

2.1. Adaptive network layout

The group's work in network visualisation in the 2000s brought together ideas from the graph-drawing and constraint-

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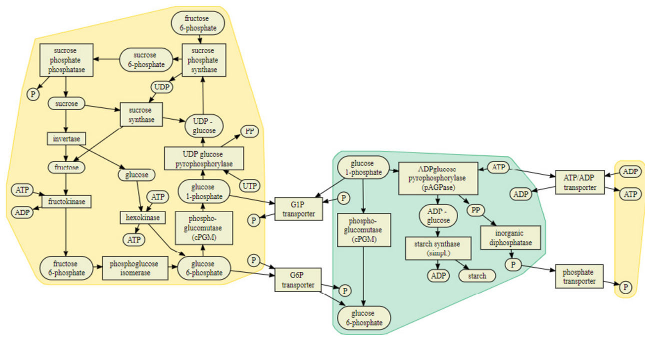

Fig. 1. An automatically drawn layout of a metabolic pathway (Glycolysis and Gluconeogenesis pathway) showing chemical reactions occurring within a cell. Alignment constraints, non-overlap constraints, and handling of convex and rectangular clusters allow the pathways and network hierarchy to be emphasised (Schreiber et al., 2009).

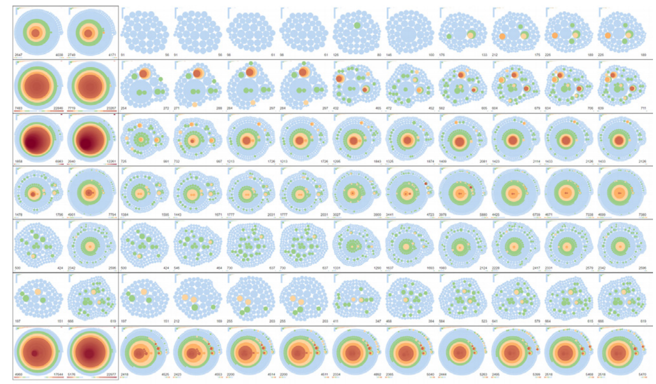

Fig. 2. Graph Thumbnails can be generated in $O(n \log n)$ time for huge networks, with strong readability guarantees. They are particularly suited to browsing and comparison of sets of graphs. Here we compare the evolution of protein–protein interaction across seven organisms (Yoghourdjian et al., 2018b).

programming communities. We explored how algorithms for automatically arranging networks could be extended to operate subject to various constraints, both generated (e.g., non-overlap) and user-defined (e.g., alignment). Layout algorithms that optimise layout subject to user-defined constraints can be flexibly reused to capture many different drawing conventions without the need for specialised programming or algorithm re-engineering.

This work can be seen through a series of papers and software, collectively referred to as *CoLa* (Constrained Layout), gradually becoming more sophisticated with respect to their algorithmics and the classes of constraints that they are able to solve. The first of this series was *DiG-CoLa*, an algorithm able to strictly enforce layering constraints to achieve flow-layout for directed networks (Dwyer and Koren, 2005). Next came *IP-Sep CoLa* which extended the idea to work with *separation constraints* (Dwyer et al., 2006) and which became the interactive layout engine at the heart of the Dunnart interactive diagramming editor (Dwyer et al., 2009b) (see Fig. 1). As part of this work, we also explored algorithms for high-quality, incremental polyline and orthogonal edge routing (Wybrow et al., 2005, 2009). We further extended the constraint-based layout and edge routing approaches to provide *topology preserving layout* (Dwyer et al., 2009c) which was demonstrated to provide stable layout in incremental, interactive exploration of large networks (Dwyer et al., 2008). We have released source code for these algorithms in the widely used *Adaptagrams*[1] C++ and *Web-CoLa*[2] JavaScript libraries, as well as contributing the algorithms to layout libraries such as Microsoft's C# MSAGL library[3] and AT&T GraphViz.[4]

Another important layout constraint is hierarchical or overlapping groupings over sets of nodes in networks, which we have explored in relation to Euler diagrams (Riche and Dwyer, 2010), and as a way to simplify drawings of complex highly-connected networks through power-graph decompositions (Dwyer et al., 2013; Dwyer et al., 2014). More recently we have explored state-of-the-art optimisation techniques to provide more flexible constraints for such nested diagrams (Yoghourdjian et al., 2015), and large-neighbourhood search techniques to make this computationally intensive approach scale (see Fig. 2).

2.2. Human-centred network visualisation

The *Monash IA Lab* takes a human-centred approach to visualisation research involving controlled experimentation with human subjects to understand the requirements for different techniques. In the past, network layout algorithms tended to be developed by algorithms experts, working on some tacit assumptions about the aesthetic requirements for layout. The lab has done fundamental work on human understanding of network diagrams to gain a more nuanced understanding of these requirements. For example, comparing how humans arrange diagrams themselves to the way that algorithms work (Dwyer et al., 2009a) and trying to understand what features of diagrams make them memorable (Marriott et al., 2012).

We take an holistic approach to the user-centred design of visualisation algorithms. An example is the Human-centred Orthogonal Layout (*HoLA*) algorithm. This was developed through a series of studies, beginning with requirements elicitation through to analysis of human-drawn diagrams, followed by incremental development and evaluation of an algorithm to achieve automatic layout with similar qualities (Kieffer et al., 2015).

An ongoing area of study is the scalability of network visualisation techniques. In a survey of 152 studies reported across 124 papers, we found that most studies do not test the question of scale (Yoghourdjian et al., 2018a). That is, they typically focus on evaluating a specific technique or feature of a layout or visualisation and tend to choose only one or two sizes of graphs in their stimuli, chosen specifically to allow for completion of tasks. That is, they rarely push the limits of human understandability. This finding led us to run a study recording physiological and subjective measures of participants to understand the cognitive load induced by path-following tasks in complex networks (Yoghourdjian et al., 2020). We were able to demonstrate limits in terms of size and density on the cognitive scalability of node-link visualisation techniques.

Inspired to find an alternative to node-link visualisations for very large graph representation, we developed a technique called *Graph Thumbnails* (Yoghourdjian et al., 2018b) which efficiently generates space-filling visuals with deterministic readability (see Fig. 2). Most recently we have been exploring layout on a Torus topology (Chen et al., 2020), to create network visualisations which wrap-around both horizontally and vertically to further untangle dense graphs.

1 https://www.adaptagrams.org/.
2 https://ialab.it.monash.edu/webcola/.
3 https://github.com/microsoft/automatic-graph-layout.
4 https://graphviz.org/.

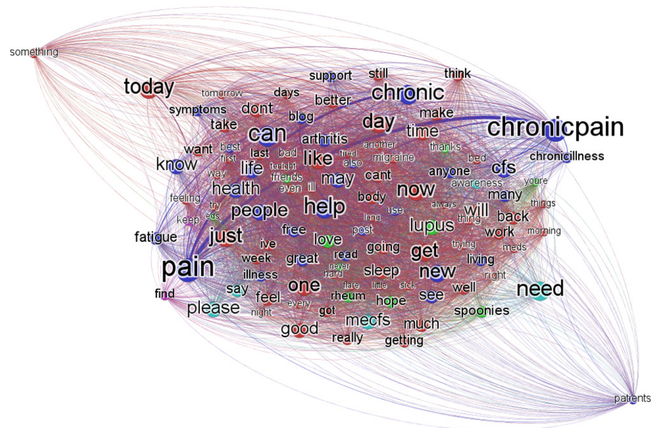

Fig. 3. The term-term graph built based on betweenness centrality of terms posted in Twitter about Fibromyalgia (Haghighi et al., 2017).

2.3. Applications of network visualisation

The adaptive network layout methods and software implementations developed by the group have been used in applications in the life sciences. Constraint-based layout and edge routing methods provided by the *Adaptagrams* libraries have been applied during layout preserving conversion of biological pathways into standardised Systems Biology Graphical Notation (SBGN) representations (Czauderna et al., 2013), for automatic generation of thousands of biological network diagrams built from a range of data sources (Büchel et al., 2013), and for automatic generation of protein topology cartoons from online databases showing secondary structure of proteins (Stivala et al., 2011).

The group has also explored the application of hierarchical network layout for the visualisation of argument maps as part of a commercial reasoning tool (Dwyer et al., 2010; Marriott et al., 2011), for interactive exploration of large ontologies in the biomedical sciences (Yang et al., 2020b), and more recently for the visualisation of Bayesian networks in a decision making tool for intelligence analysts funded by IARPA (Nicholson et al., 2020).

Our research also focuses on visualisation of social networks, particularly concerning health related data using graph analysis. Community detection can be used to identify communities (clusters) of terms commonly associated with one another in a large network. The term-term graph can be built based on betweenness centrality as shown in Fig. 3 for the Twitter data about Fibromyalgia. Such visualisation techniques provide a powerful approach to exploring and understanding of the communities and the relationships between the terms (Haghighi et al., 2017; Pokharel et al., 2019; Jayaraman et al., 2020).

3. Interactive optimisation

Another interest of the lab has been applications as well as fundamental techniques for interactive optimisation. We worked with medical professionals to evaluate novel interactive approaches to prostate cancer treatment planning (Liu et al., 2017). We found many similarities between the workflow of interactive optimisation which we call the "problem-solving loop", and the "sense-making loop" of visual analytics. As such, we further explored the visual design of interactive optimisation interfaces for problems such as delivery scheduling (Liu et al., 2020a), proposing a set of design guidelines.

While the work above focused on end-users of optimisation technologies, another study was aimed at the needs of optimisation experts developing models and solvers. Again using user-centred design approaches we explored the requirements for visual search space profiling (Goodwin et al., 2017).

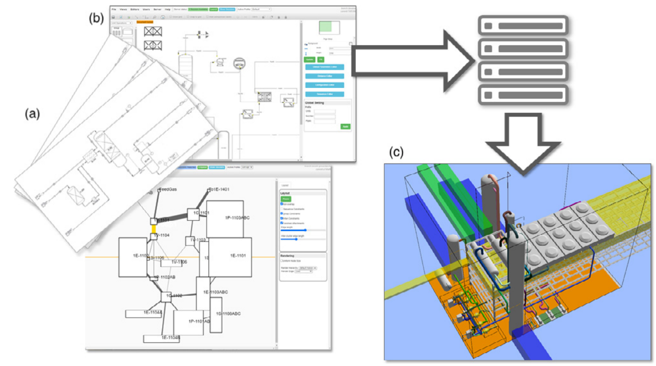

Fig. 4. The semi-automatic process of producing a 3D plant layout from Process Flow Diagrams using our optimisation system.

3.1. Plant layout optimisation

Designing the arrangement of equipment and pipes for a chemical plant is a complex and important task which is typically solved manually, often taking a team of engineers months or even years to complete. Our research collaboration with Woodside Energy has created an interactive workflow for engineers to generate semi-automatic layouts of liquefied natural gas (LNG) plants. The plant layout is optimised with respect to (1) footprint for process equipment, (2) overall length of pipes connecting the equipment, and (3) structure supporting the equipment to minimise costs, while satisfying construction, operation, maintenance, and safety constraints (Belov et al., 2017, 2018). The workflow (see Fig. 4) supports the generation of an optimisation model based on process flow diagrams (Fig. 4a), allows configuration of the optimisation process (Fig. 4b), generates 3D models from optimisation results (Fig. 4c), and provides methods for the interactive exploration and evaluation of the models. Our current workflow employs conventional display technology, i.e., 2D screens or display walls (Fig. 5), but the ultimate goal is to extend this towards immersive environments. One of the aims of the project is to provide layout solutions which challenge traditional engineering thinking with unconventional designs. Since these designs are used for decision-making, people need to be confident in the results and understand the quality. Therefore, our research focuses on how to make generated solutions understandable and explorable, and explains the optimisation process that generated them. Another focus lies on the explanation and correction of unsatisfiable models caused by conflicting constraints. As the number of constraints and thus possible conflicts increase with the size and complexity of the model it can be overwhelming to manually find and resolve those conflicts. Therefore, we are currently exploring methods and visualisations to guide the user through the recovery process.

4. Immersive analytics

The term *Immersive Analytics* was first coined at Monash around 2014 (Chandler et al., 2015). At the time we were considering how the Monash CAVE2 facility – more typically a visualisation facility for scientific and engineering visualisation applications – could be used for information visualisation.

We organised the first workshop to involve data visualisation and VR/AR research at Shonan in 2016.[5] A series of followup

[5] https://shonan.nii.ac.jp/seminars/074/.

Fig. 5. *Monash IA Lab* researchers explore a generated plant layout solution in the Monash CAVE2 facility.

workshops were conducted, hosted in major Visualisation and HCI outlets (ACM ISS 2016 (Bach et al., 2016), IEEE VIS 2017 (Bach et al., 2017), CHI 2019 (Bach et al., 2019) and CHI 2020 (Ens et al., 2020). These events focused on various topics such as 3D visualisations, perception, interaction, collaboration and evaluation. 2016 saw a Dagstuhl Seminar (Dwyer et al., 2016) involving around 40 researchers and practitioners from data visualisation, VR, and HCI. The main outcome was the publication of the book *Immersive Analytics* (Marriott et al., 2018). The book contains chapters on collaboration, 3D perception, storytelling, multi-modality, and applications in different areas (Czauderna et al., 2018).

4.1. Immersive environments

The groups' research in *Immersive Analytics* has led to an early exploration of different immersive environments and the development of various software and tools to be used in these environments.

ContextuWall is a system for interactive local and remote collaboration using touch devices and displays of various sizes (Klapperstueck et al., 2016, 2018). It provides groups of users located at different sites with a jointly used virtual desktop for content sharing which can be shown on different displays, display walls, or visualisation facilities such as the Monash CAVE2 simultaneously, taking advantage of their high resolution. A touch-based client software has been developed enabling users to share, arrange, and annotate image content across locations.

4.2. Immersive collaborative analytics

Collaboration is a central topic in sense-making with data visualisations (Isenberg et al., 2011; Billinghurst et al., 2018). Monash University acquired the CAVE2 in 2013 system that was a promising environment to support collaborative, immersive data visualisation. At the same time, HMDs presented a cheaper alternatives to support collaborative visualisation in 3D immersion. We conducted a study (Cordeil et al., 2016) that compared pairs of users who performed 3D network immersive collaborative tasks in the two environments. We found that performances were comparable in the two environments, hence demonstrating that collaborative data visualisation was suitable with VR HMDs. Later we designed the FIESTA system (Lee et al., 2019), a VR backpack-based visual analytics system that allows multiple users to perform collaborative visualisation in a virtual room. In particular we studied (Lee et al., 2020c) how participants used the 3D space and surfaces around them to make sense of their data and share insights.

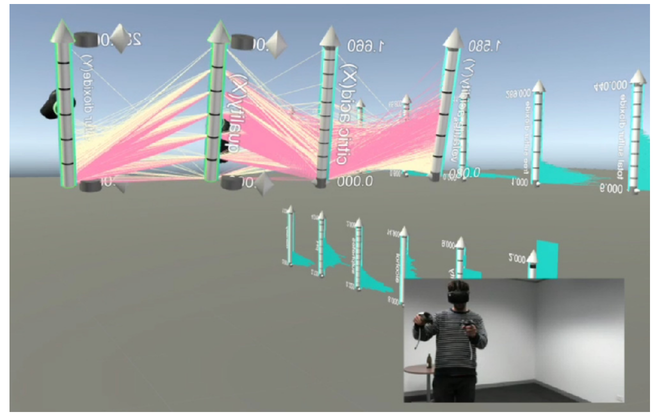

Fig. 6. ImAxes is an immersive multi-variate visualisation tool which uses an *embodied axis* metaphor to allow users to quickly and intuitively construct complex visualisations.

4.3. Tangible and embodied interaction

One fundamental research driver for Immersive Analytics is the use of *Embodied Interaction* (Dourish, 2004). Embodiment enables compelling interactions, where users interact more directly with systems and data in their own 3D space. In our work we have explored several aspects of embodiment for interacting with data visualisations. Our first attempt was the *ImAxes* (Cordeil et al., 2017b) authoring tool; in *ImAxes* the data dimensions are embodied in 3D axes objects that the use can grab and assemble into data visualisations (e.g. 2D, 3D scatterplots, scatterlpot matrices, and so on — see Fig. 6). We studied ImAxes with over 30 data scientists (Batch et al., 2019) and found that in such an embodied interface, users adopt different layouts according to the task (e.g. they created and placed visualisations around them when exploring freely the data but organised their visualisation in more gallery-style layouts when presenting their findings).

Our work has also investigated how tangible interaction in mixed reality, as another embodied interaction approach, could enhance perception of 3D data visualisations (Cordeil et al., 2017a). We provided a design space of tangible interaction devices to support navigation and interaction with 3D visualisations, and built two exemplar devices – a tracked *TouchCube* and the *Embodied Axes* (Fig. 8). In a later study Cordeil et al. (2020) found that *Embodied Axes* were better suited than mid-air interaction for precise interaction with 3D visualisations.

In *UpLift*, a table-top tangible campus energy-use visualisation system, we demonstrate how tangible interaction affordances such as 3D printed building models, and Lego sliders, enable a form of *casual collaborative analytics* to engage stakeholders in data analysis.

4.4. Immersive analytics toolkits

At the time we started investigating data visualisation in immersive environments very few tools existed to support our research. As a result we contributed a series of toolkits (Cordeil et al., 2019; Sicat et al., 2019) and new interaction paradigms (Cordeil et al., 2017b) to support research in immersive multidimensional data visualisation. Those tools helped building new visualisation platforms such as the FIESTA tool (Lee et al., 2019) but also were used to investigate the work of data analysts in VR and AR (Lee et al., 2019; Batch et al., 2019; Liu et al., 2020b).

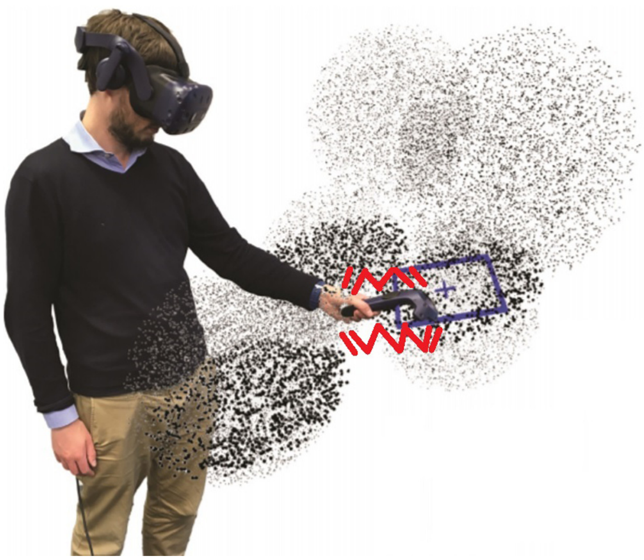

Fig. 7. The *Scaptics* technique leverages vibrotactile feedback on the controller to convey information on occluded features of 3D scatterplots to users in VR.

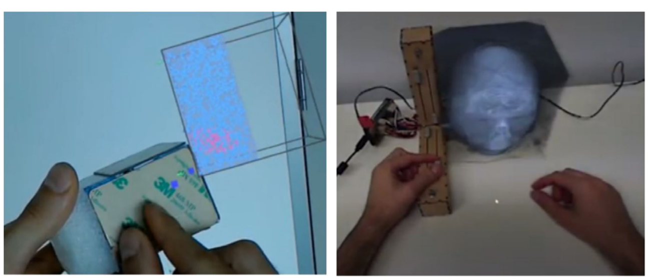

Fig. 8. Exemplar spatio-data coordinated devices: a tracked touchcube (left) and the *Embodied Axes* (right) support tangible and interactive immersive visualisation of 3D data.

4.5. Experimental results in immersive analytics

While early work under the banner of Immersive Analytics tended to focus on novel techniques and systems, more recent work has found concrete benefits to data visualisation in immersive environments through controlled experiments and is beginning to elicit design guidelines.

In a study of how to represent world maps (Yang et al., 2018) we found 3D globes more effective than 2D projections for conveying distance and direction on world maps. Comparing 2D choropleth and 3D prism maps in immersive environments we found that each had benefits to different tasks and are thus complementary (Yang et al., 2020).

Exploring collaborative immersive analytics (Lee et al., 2019) we found that users were able to share the space around them to perform sophisticated analysis in the environment, were comfortable collaborating via 3D visualisations, and were able to structure their virtual workspace to support collaboration. Space use is also key for small-multiples visualisation. For example, we found trade-offs between the real estate offered by full wrap-around displays and the problem caused by some information being behind and out of view of the user (Liu et al., 2020b).

Immersive Analytics research both exploits and tests the boundaries of state-of-the-art interaction and visualisation technologies in way that require careful study to tease-apart human factors from technical limitations. For example, in 2017 we found limitations in the contemporary AR technology (Microsoft Hololens V1) highlighting issues in the field of view, resolution, stabilisation, and training requirements (Bach et al., 2017). Sometimes new technology leap-frogs old in capability, as demonstrated by our comparison of CAVE2 versus low-cost VR headsets for collaborative analytics (Cordeil et al., 2016). Sometimes it is necessary to adapt or reinvent standard desktop visualisation interaction techniques for immersive environments and evaluate how they perform. For example, in adapting overview+detail navigation for immersion we recently found that world-in-miniature and 3D zooming are complementary to physical navigation, but that they introduce overhead in the form of requiring context switching between views (Yang et al., 2020). Sometimes advances in technology offer completely new capabilities with no existing empirical usability data guiding their application to data analysis. We designed and studied embodied haptic feedback on VR controller (Prouzeau et al., 2019) to enhance the perception of 3D dense clusters (Fig. 7), and found that vibrotactile feedback helped perceiving holes and dense zones in immersive scatterplots.

Some experimental results are promising but remain difficult to quantify, establishing the need for future research. For example, a recent qualitative study (Lee et al., 2020a) found that immersive visualisations provide a *visceral* experience with which to engage users in data stories.

5. Geovisualisation and cartography

The *Monash IA Lab* has a range of research activities focusing on geographic information visualisation (geovisualisation) and cartography, including map projections, terrain visualisation, immersive geospatial visualisation and innovative applications for a diversity of sectors including energy networks, virtual ecology and health models.

5.1. Cartographic and visualisation

A mathematically defined map projection is the basis of any computer-generated map. The *Monash IA Lab* recently co-developed the *Equal Earth* map projection, a new map projection for world maps that has been widely adopted by the geoscientific community within an amazingly short period of time due to its visually pleasing and balanced representation of continental outlines, and the fact that areas are not distorted (Šavrič et al., 2019).

The representation of the third dimension of terrain on a flat display is another fundamental cartographic task and an area of active research at the *Monash IA Lab*. Apprehending the third dimension of Earth's surface is essential for understanding many geospatial phenomena. However, reading contour lines (Samsonov et al., 2019) is difficult for many map users and requires considerable training. We are exploring more intuitive and immediate illustrative methods for communicating the three-dimensional shape of Earth's surface (Jenny et al., 2020b; Jenny, 2020), including lightweight interactive camera control techniques for 3D terrain maps on interactive surfaces (Danyluk et al., 2019) or cartographic relief shading (Jenny and Patterson, 2020). We are inspired by masters of the manual cartographic art, and replicate Swiss-style relief shading using neural networks that we train with manually drawn shaded relief masterpieces (Jenny et al., 2020a) (Fig. 9).

Geographical data visualisation research at the *Monash IA Lab* explores novel techniques to unravel the complexities of understanding complex geographical data; including multivariate data across geography and scale (Goodwin et al., 2016), visualising overlapping categorical sets on maps (Meulemans et al., 2013), an innovative method for morphing maps to retain topology yet

Fig. 9. Shaded relief created with a neural network trained with manually drawn shading (Tutuila, American Samoa) (Jenny et al., 2020a).

Fig. 10. Immersive multiview maps in a spherical cap layout surrounding a large central overview. Visual links and colour hues indicate hierarchical groupings (Satriadi et al., 2020).

preserve data similarity (Bouts et al., 2015), and MapTrix a hybrid between a map and a matrix to present flow data (Yang et al., 2017). This geovisualisation work spans many domains from cultural landscapes (McConachie et al., 2020), energy consumption (Goodwin et al., 2016; Ens et al., 2020), disease modelling mapping[6] and a series of urban visualisation workshops.[7]

5.2. Immersive geovisualisation

Bringing maps, globes, and other types of geovisualisations to virtual and augmented reality opens up many exciting new opportunities for a more engaging exploration and deeper understanding of geospatial information (Yang et al., 2018). However, it is not clear how to most effectively interact with immersive geovisualisations. For example, there are no established standards to efficiently zoom and pan, select map features, or place markers on an immersive map. The *Monash IA Lab* has therefore made interactive geovisualisation and interactive immersive maps a research focus and has recently made substantial contributions in this area. We explored how body gestures can control basic AR and VR map operations. We use motion-tracking controllers (e.g., Leap Motion) to capture and interpret gestures and have conducted a set of user studies to identify, explore and compare various gestures for controlling map-related operations. This includes, for example, mid-air hand gestures for zooming and panning (Satriadi et al., 2019) and selecting points of interest, adjusting the orientation of maps, or placing markers on maps (Austin et al., 2020).

How should multiple maps be arranged in immersive space? Our immersive layout interface allows users to create large hierarchies of multiple maps at different scales and arrange them in 3D space (Fig. 10).

Building on these basic map interaction techniques, the *Monash IA Lab* has made major contributions for the visualisation

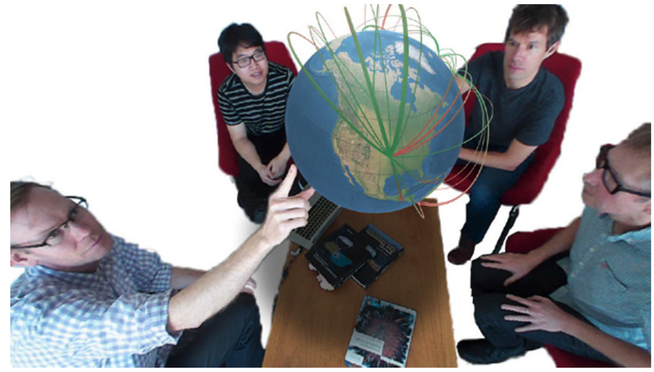

Fig. 11. Future mixed-reality collaboration with flows on a globe (Yang et al., 2019).

Fig. 12. *Tilt Map*: Adjusting map inclination for transitioning between choropleth map, prism map and bar chart (Yang et al., 2020).

of geospatial data in immersive space. For example, we developed innovative ways to visualise origin–destination flows (Fig. 11). Traditional flow maps on desktop displays quickly become excessively cluttered and difficult to read even with a modest number of flows (Jenny et al., 2018). However, with immersive visualisation, we found that careful use of the third spatial dimension can resolve visual clutter in complex flow maps (Yang et al., 2019).

TiltMap is another successful example of how proven cartographic techniques can be enhanced and made more useful with immersive visualisation (Fig. 12). This design concept intuitively transitions from 2D choropleth maps to 3D prism maps to 2D bar charts to overcome the limitations of each (Yang et al., 2020) by simply tilting the VR controller.

Situated geovisualisation using augmented reality is another promising avenue for combining established visualisations with new types of interactions (e.g. Quach and Jenny (2020).)

6. Conclusion and future directions

Most recently the *Monash IA Lab* has realised that traditional data visualisation research has focused on the needs of a relatively small group of users: able-bodied people with strong graphics and numerical literacy skills. However, this is actually a small segment of the world's population and so we are investigating how to make data visualisation more inclusive (Lee et al., 2020b). In particular, there are millions of emerging ICT users in developing countries such as India who have access to computer-mediated data visualisation for the first time as the result of increasing smart phone usage (Jena et al., 2021). The lab is now investigating the use of multi-modal graphics (Goncu and Marriott, 2011), tangible graphics (Holloway et al., 2018; Yang et al., 2020a; Reinders et al., 2020) and sonification for blind people, and the design of more easily understandable visualisations for emerging users of computer-mediated data visualisation (Jena et al., 2021).

6 https://atlas.cancer.org.au/.

7 https://cityvis.io/workshop.php.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

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