

On the Utility of Large High-Resolution Displays for Comparative Scientific Visualisation

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ABSTRACT

In many disciplines, such as computer aided drug design, multiple simulation runs are performed with varying parameters, yielding ensembles of data sets. Comparative visualisation of these simulation results can help understanding the influence of different parameters. However, researchers might need to compare large numbers of variants. Single desktop monitors often do not have the resolution and screen size required for showing a whole ensemble at once with sufficient detail. Wall-sized high-resolution displays can be a solution for this problem. Although a number of studies has been conducted on how large high-resolution displays affect the speed and accuracy of certain tasks, only few of them are related to actual scientific visualisation tasks. We built a system for comparative visualisation of simulation results that can be used with conventional desktop monitors and with large high-resolution displays. We conducted a study using biochemical simulation data to evaluate the impact of screen size and 3D stereo display on a comparison task.

CCS Concepts

•Human-centered computing → User studies; Usability testing; Visualization systems and tools;

Keywords

Large High-Resolution Display, Usability, Visualisation

1. INTRODUCTION

A common scenario in computational drug design is to analyse similar molecules to assess their differences in function or structure. The function is often investigated by conducting simulations under different conditions or with selec-

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tive mutations of amino acids, resulting in so-called ensembles. Grouping of the simulation results is usually based on the principle of molecular similarity: molecules with similar geometry and biochemical properties are likely to exhibit similar functions [11]. Comparisons are based on a variant about which some knowledge is available, and the task is to find the best possible alternatives in terms of similar properties. Consequently, every visualisation actually depicts the differences between a variant and the selected baseline.

Since small multiples are recognised as a sensible choice for multi-way comparison [25], we consider it a reasonable approach to allocate the whole screen space to a grid of identically-sized renderings of pairwise comparisons. The details that can be gleaned from each variant are directly related to the available resolution of the display. Thus, one major challenge of comparative visualisation for large data is scalability. Regular desktop monitors usually lack the resolution for large ensembles. Large high-resolution displays (LHRD) might be an alternative. However, while allowing for improved insight, they require specialised interaction concepts, since mouse and keyboard are impractical when a user should be able to move freely in front of the screen.

We performed an experiment to investigate how the display size and resolution impact participants finding very similar and very different members of an ensemble of molecules. In the experiment, we used a layman task comparable to the one of the application domain scientists from the field of biochemistry. Other than broadening the audience significantly, the task offers the additional benefit that we know the ground truth, which allows for a quantitative evaluation. These conditions do not pertain to the fully-fledged application case. We thus only present the results of an informal evaluation with our collaboration partners that provided this data since the analysis cannot be performed by non-experts.

2. RELATED WORK

Comparative visualisation facilitates finding similarities or dissimilarities between data sets. Thus, it has been applied to gain insight into large data sets, e.g. from CFD simulations [9]. In structural biology and drug design, similarity-based methods using geometrical properties of the respective molecules are used to examine chemical databases [4]. There

are a number of comparison algorithms that perform either shape-based comparisons [8] or focus on physical properties like the electrostatic potential [1]. Scharnowski et al. [21] combined these approaches.

Large displays or powerwalls emerged more than two decades ago and were built using projectors [7]. Recent installations often use LCDs and achieve up to 1.5 billion pixels [18] at a comparatively low price [14]. Applications for such LHRDs range from control rooms over geo-spatial visualisations to scientific ones. Ni et al. [17] provide a comprehensive overview of system designs and applications.

The general benefits and drawbacks of LHRDs have been previously studied using navigation, comparison, and search tasks mostly using satellite imagery [2, 23] or maps [10, 20]. Ball et al. [2] reported improved performance of users for finding and comparison tasks when using LHRDs. They also found benefits from physical navigation in front of the display compared to panning virtually. Shupp et al. [23] obtained similar results for searching or navigational tasks. However, some studies suggest that user performance does not generally improve with resolution or wider views: Jakobsen et al. [10] explained this discrepancy with the fact that certain methods, like focus and context techniques, do not work well with LHRDs. They conclude that, in order to be useful on LHRDs, visualisation techniques need to be carefully chosen and adapted. Similarly, Yost et al. [28] showed that displays beyond human visual acuity make sense only if the employed visualisation method is designed appropriately. Ruddle et al. [20] emphasised that the advantages of physical navigation compared to virtual navigation only emerge if the entire data set is visible on the LHRD and there is, thus, no need for panning and zooming, as is the case with our approach.

Although Moreland [14] states that research on LHRDs should focus on “how to use displays” and that this research should be application-driven, only few specific application areas have been tested. Gjerlufsen et al. [5] identified a biological comparison task as application case for LHRDs, but did not conduct a user study. A study comparing the display of long documents on a large screen with a desktop monitor and printed paper yielded mixed results [27]; the LHRD only showed significant benefits for searching differences.

The need for interaction techniques beyond keyboard and mouse for wall-sized displays is widely known [13]. We emulate a pointing device using ray-casting [3]. Although it has been shown that 3D navigation tasks can generally benefit from physically large screens [24], the performance of LHRDs for scientific visualisation applications has not yet been investigated sufficiently. For example, Nam et al. [16] mainly discuss frame rates and delays, while Scheidegger et al. [22] already hint at a small multiples scenario, but do not offer any details or evaluation. Most importantly, none of the aforementioned studies specifically addressed 3D visualisation, which is the focus of our experiment.

3. APPLICATION SCENARIO

3.1 Comparative Visualisation

We used a modified version of the MegaMol system [6] to implement a tile-based comparison of the techniques described below. These two comparative visualisation methods address analysis tasks from the domain of structural biology:

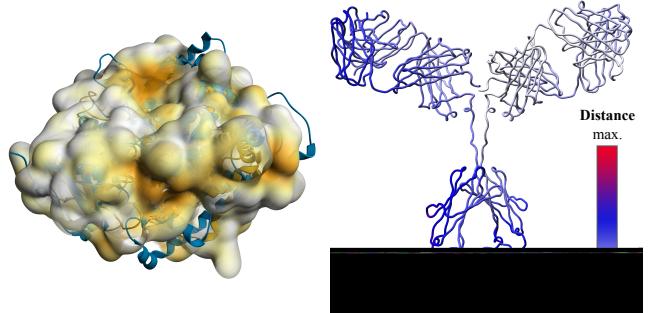


Figure 1: Examples of the two visualizations used in our comparison. Left: The pairwise surface-based comparative visualisation [21]. Right: The structure-based comparative visualisation applied to two conformations of an antibody (data set D1). The colour gradient to the right was used to illustrate the structural deviation.

Surface-based Comparison. A biomolecule’s function is heavily influenced by both shape and physico-chemical properties of its surface. For example, many enzymatic reactions are triggered by smaller molecules docking to the surface. Not only the geometric surface shape has to fit, but also the electrostatic potential. Hence, one of the approaches used in our setup is the surface-based comparative visualisation presented by Scharnowski et al. [21]. Here, a point-to-point-mapping between two given input surfaces is defined by using a deformable model approach. This mapping is then used to compute local difference measurements for both the local surface geometry and the electrostatic potential at the surface. Figure 1 shows a resulting rendering. The potential difference is encoded as colour saturation of the surface. Geometrical differences are mapped to transparency to provide a measurement for the uncertainty of the comparison as comparisons between geometrically very different surface parts are less meaningful. The rendering consequently focuses on geometrically similar regions and highlights regions of high potential differences, and hence allows to draw conclusions about functional regions of the surface.

Structure-based Comparison. Not only the surface structure, but also the underlying internal structure of a protein is essential for its function. Proteins are linear chains of amino acids. These chains fold into a specific, three-dimensional structure. This so-called tertiary structure is often visualised using a spline that closely follows the amino acid chain [19]. The spline is usually decorated with 3D geometry to enhance perceptibility, e.g. using a tube that surrounds the spine. As proteins are flexible, there can be differences in the structures. These differences are of interest since misfolded proteins can cause illnesses like Alzheimer’s disease. Hence, the second application we use in our setup is a comparison of the tertiary structure. Here, two proteins with equal chain length are superimposed as good as possible using the established RMSD alignment algorithm [12]. The Euclidean distance of two splines that represent the proteins is computed. These distances are then colour-coded onto the tertiary structure as shown in Figure 1. This visualisation allows biologists to analyse structural differences and to assess their impact on the protein function.

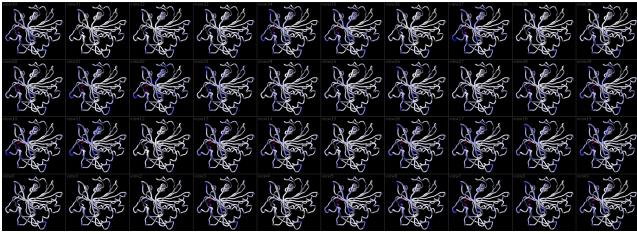


Figure 2: Layout of the application on the tiled display: all 40 variants of data set D2 are visible. Each of the views covers approximately 1000×1000 px.

3.2 Large High-Resolution Display

Our powerwall is a tiled LHRD made of five portrait-oriented strips [15]. Two 4K LCoS projectors are projecting the images for the left and the right eye on each strip. The setup yields a total net resolution of $10,800 \times 4,096$ pixels for each eye, which are projected onto a physical screen size of about 6×2.2 metres. A pixel is about 0.5 millimetre in size, which corresponds to about 50 ppi. Stereo separation is done using interference filters (Infitec). The lack of colour fidelity is the main disadvantage of this technique as it filters the colour spectrum to achieve the channel separation. As our comparative visualisation makes use of colour coding, we expect this to be disadvantageous, although we chose the colour table such that it also works in stereo mode. The users interacted with the system using a 6DOF mid-air pointing device with two buttons (wand), which was tracked using an optical tracking system from NaturalPoint.

4. USER STUDY

4.1 Test Scenarios

The goal of our user study was to test whether an LHRD is applicable for comparative scientific visualisation. Although combining the comparison of different display scenarios and interaction techniques into one experiment makes it difficult to isolate the effects of either factor, we opted for a setup that is as close to a real application scenario as possible. We tested three data sets under the following display conditions.

Large High-Resolution Display. Two of the three display conditions that we tested have been performed on the LHRD described above. One was performed in stereo mode (Infitec filters active), while the other was done without colour filters. In both cases, the user was presented a grid of 10×4 visualisations using the same baseline molecule (Figure 2). Although the grid is freely configurable, the views could not be resized by the user. However, their order in the grid could be changed using the wand. For doing so, the user had to point the wand at one of the views, which indicated the selection by a brighter border line. By pressing both buttons of the wand at the same time, this view then could be dragged to a different location. Pressing the buttons separately allowed for rotating and zooming according to the indirect HOMER technique [3]. All transformations were synchronised over all views. While performing the task, the participants were free to move anywhere inside the tracking volume, which covered the whole area in front of the screen up to four metres distance from the wall.

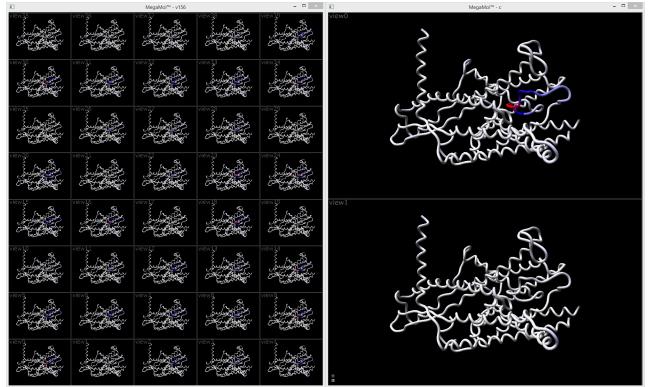


Figure 3: Layout of the application on the desktop monitor: the left view shows an overview of all variants while the right view enables side-by-side comparison of two user-selected variants (data set D0).

Desktop Monitor. In the single monitor case using a 24 inch WUXGA display, we split the screen into two views (Figure 3), similarly to what van den Elzen and van Wijk [26] used for visual data exploration via information visualisation techniques. Our first view showed the same grid of 40 visualisations that is used on the LHRD, only at a much smaller scale. The second one allowed the user to compare two of these visualisations side-by-side to overcome the limited resolution available for each member of the ensemble view. As in the LHRD case, the user had the option to rotate the data set and to zoom into the views, in this case using two different mouse buttons. Again, all views were synchronised. The desktop application provided two additional modes of mouse interaction: one that allowed reordering the small multiples by exchanging two variants with mouse clicks and another for selecting the content of the two detail views.

4.2 Experiment

Task. We used the simplified structure-based comparison for two reasons: First, a user who is no expert in structural biology must be able to complete the task. Second, the task should not be exploratory, but rather yield a quantitative result so we can compute its distance to the ground truth.

The structure-based comparison can be used without prior knowledge in structural biology, since it only requires assessing distances which are colour-coded on the geometry. The reduced colour spectrum for red tones due to Infitec stereo separation poses a difficulty for colour coding. The selected colour gradient shown in Figure 1 is not optimal, but still retains the saliency of red for emphasising important parts.

For each test, we showed 40 views each displaying a comparison with a different point in time of the simulation. The geometry of the baseline variant was used in all views, i.e. participants did not have to compare different structures. They had to identify the view that showed the protein with the smallest deviation from the baseline and the one with the largest deviation. As there can be multiple similar variants, we told the participants that they did not have to find the absolute minimum and maximum, but a view that was as close as possible. For the evaluation, we computed how far the chosen solution was from the correct one.

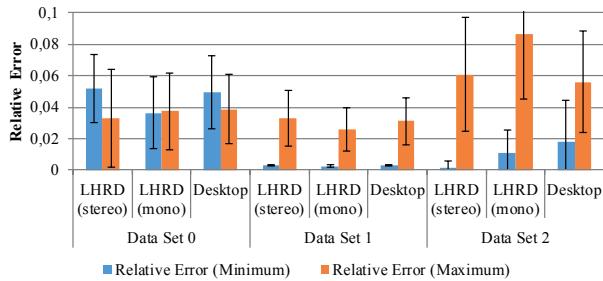


Figure 4: Averaged relative error that participants made when searching the variant with the minimum deviation and the maximum one from the baseline variant. Error bars indicate standard deviation.

The three data sets we used were a transmembrane protein (D0, Figure 3), an antibody (D1, Figure 1), and a globular protein (D2, Figure 2). D0 is difficult, because it has a relatively high number of candidates for both minimum and maximum deviation. The antibody (D1) is geometrically most complex, but has three quite obvious candidates for the minimum deviation. D2 has many good candidates for the smallest deviation having almost equally good scores. Finding the maximum deviation is difficult, because medium deviations, which are hard to assess, occur in several regions.

Participants. The study was performed by 18 volunteers including one of the application domain experts (two females and 16 males) aged between 24 and 41 (avg. 31, $\sigma = 4.06$). We recruited participants that rated themselves either expert on the field of 3D visualisation (avg. 4 on a five-level Likert scale, $\sigma = 1.25$) or on the field of structural biology (avg. 1.5, $\sigma = 0.83$). The average experience with 3D stereo output devices was 3.28 ($\sigma = 1.28$), with 3D input devices like the wand used in our setup it was only 2.61 ($\sigma = 1.01$).

Procedure. Each participant first performed the experiment with an easy test data set in each of the abovementioned scenarios to familiarise themselves with the task and the respective interaction methods. Then, all data sets were tested in all scenarios. The order of the scenarios and of the data sets was different for each participant to account for learning effects. Also, the variants displayed in each view have been assigned randomly for every single test.

The participants could freely choose how they performed the task, i.e. no specific strategy was prescribed. They could also decide for each test in which order they searched for the view with the minimal and maximal deviation. The time was stopped once both views had been named. After the user completed a single task, we asked them to rate on an unlabelled five-level Likert scale how confident they are that they found the correct answers and how easy it was finding them. The participants had no time limit for completing the task, but were told that they should stop once they felt that they could not find any better candidate.

4.3 Hypotheses

Based on the outcome of previous studies, it was difficult to predict which setup would perform best. On the one hand, it has been shown that physical navigation in front

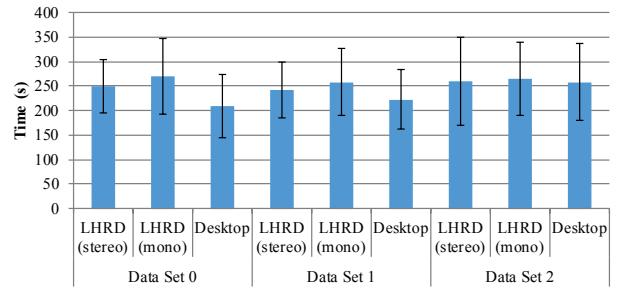


Figure 5: Performance averages for all data sets in all display configurations. As the participants could search the least and most deviation in an arbitrary order, only the overall time for finding both is given.

of large displays has advantages over virtual navigation on small displays. On the other hand, users could try to solve the task without any or with very little (virtual) navigation, have more experience using the mouse, and the mouse is also more accurate than the wand. Nevertheless, we hypothesised that the large display has slight advantages.

However, as we required colour coding, we believed that the stereo setup would be less advantageous for three reasons: the stereo technology used for our tiled display relies on Infitec, which has less colour fidelity than other technologies like polarisation or active shutter glasses. The glasses themselves also limit the field of view. Furthermore, due to the simplification of the task for average users, no comparison of the spatial structure is necessary for solving the task. Thus, we did not expect significant advantages from the improved depth cues when using stereo; in contrast, the negative effects should predominate, particularly as the need for interaction remains: occlusion, which is inherent to 3D visualisation, is not neutralised by stereo projection. The interesting question was whether the colour distortion would stay in an acceptable range for the actual application.

4.4 Results

Accuracy and Speed. The RMSD value [12] is commonly used in structural biology as a ground truth for the structural difference of two proteins. However, this single value has no spatial interpretation in relation to the tertiary structure of the molecule. Therefore, we computed a piecewise distance for every pair of protein variants and mapped it to the tertiary structure. The sum δ of these distances serves as a localised variant of the RMSD. The error of the participants' answer was calculated as the difference between the correct variant's δ_c and the chosen variant's δ_u . It was normalised to the global difference range of the respective data set to make the results comparable. Two outliers – one for the LHRD (mono) and one for the desktop – have been excluded from the evaluation, because the error was an order of magnitude larger than for the rest of the participants.

We evaluated whether the display scenario is relevant for the relative error, which is depicted in Figure 4. Normal distribution of the data was rejected by the Shapiro-Wilk test. We therefore performed a Kruskal-Wallis test, which did not reveal significance ($H = 0.87$, 2 d.f., $p = 0.65$). Although participants were on average slightly faster on the desktop (see Figure 5), the difference is not significant ($H =$

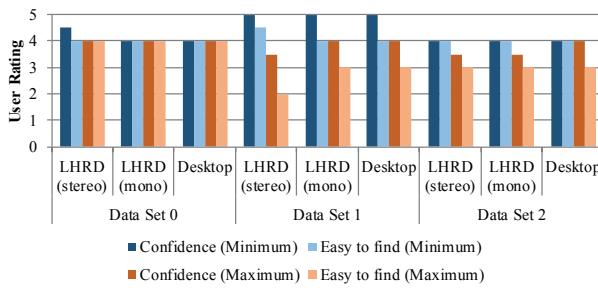


Figure 6: Medians of the confidence ratings by the users for finding the minimum and maximum deviation on a five-level Likert scale.

1.76, 2 d.f., $p = 0.41$). Performing the tests for the data sets individually led to analogous results. We only found statistically significant differences for the correctness of answers between the three data sets ($H = 14.29$, 2 d.f., $p = 0.00079$). This is in accordance with our estimation of the respective difficulty. The timings, however, did not differ significantly between the data sets ($H = 0.38$, 2 d.f., $p = 0.83$).

Participants were generally very confident that they chose the correct variants (see Figure 6). In almost all cases, they found it easier finding the view with the minimum deviation and in turn also were more confident about this task. However, we found that there is a tendency towards anti-correlation (-0.0968) between measured error and confidence rating as well as between error and perceived easiness (-0.0973). That is, participants slightly underestimated the problem independently from the three display scenarios.

The results of our user study back our hypothesis regarding pros and cons of the desktop and the LHRD. As mentioned above, there is no significant difference in accuracy and time. This is in line with previous findings [20] as our tasks did not require virtual navigation in either setup and the whole data set could be visualised on all screens. Surprisingly, the participants did not perform significantly worse using the stereo display, despite the colour distortion.

User Feedback and General Observations. We asked participants to order the three test scenarios according to their preference for solving the task. The desktop and the large display without stereo glasses clearly performed best with each of them being seven times nominated for the first place. The LHRD in stereo mode was ten times on the last place. One of the most frequent complaints was the lack of colour fidelity. Although three participants explicitly liked stereo and preferred the better spatial impression, there have also been complaints about the glasses being annoying by one subject and four participants said the stereo display was stressful and useless for the task. We believe that this led to a higher rating (median 2.5 on a five-level Likert scale) in user fatigue for the stereo scenario. The difference between the other setups was smaller: median 1.5 for LHRD (mono) and median 1 for the desktop monitor. Interestingly, eye-strain was a frequent reason for people disliking the desktop application. The size of the comparison matrix as well as the pixel density was oftentimes considered too low, thus requiring the user to concentrate more on the task, which in turn was perceived as exhausting. A quarter of the partici-



Figure 7: A selection of 10×4 views of the surface-based comparison visualized on our LHRD.

pants chose the desktop as favourite scenario mainly due to familiarity. Users also felt being faster, mostly because they did not have to move physically and could move the mouse very quickly from one view to the next.

Although some participants compared the variants in an almost chaotic pattern, eight of them sorted potential answers, mostly on a line in the middle of the screen. In the LHRD cases, seven participants immediately started wandering around as the test started, while three participants did not move at all. Users generally did well with the wand, although they had little experience in using it. Only two participants disliked the *object in your hand* metaphor and one suggested that the rotation angle should be exaggerated in order to enable faster rotations.

5. EXPERT FEEDBACK

We showed the application used for the user study and the actual surface-based comparison application (similar to Figure 7) to three researchers working in the field of technical biochemistry. They often work with large sets of simulated molecular structures. One task is to find differences or similarities in the molecular structure that indicate whether the function of the proteins is similar or not. They are confident that their exploratory data analysis tasks would benefit from LHRDs. They also believe that the possibility to see many different data comparisons at once in full detail facilitates making unexpected scientific discoveries and observing correlations between multiple data sets. Especially for tasks that require more complex visualisations like the surface-based comparison explained above, they found that stereo output makes it easier to discern structural differences.

6. CONCLUSIONS & FUTURE WORK

Comparative visualisation of ensembles can consume a lot of screen space for displaying all variants, making LHRDs an obvious choice. Using a sample application from structural biology, we investigated the feasibility and potential benefits and drawbacks of such an approach in a user study. As this scientific visualisation application uses inherently spatial data, which suggest a 3D representation, we specifically included 3D stereo visualisation in our experiment.

We found that accuracy and timings do not significantly differ between our scenarios. Users had no clear preference towards LHRD or desktop monitor, making the latter the economical choice. We believe that our findings can be transferred to ensembles of 3D objects that differ in colour,

but not in geometry. In contrast to our expectations, we did not see significant negative effects of the stereo glasses. If geometrical differences are compared, the increased layers of depth in stereo LHRDs [15] might be beneficial. Investigations whether a stereo LHRD has significant benefits for spatial comparison remain for future work.

Expert feedback was very positive concerning the LHRD. One reason for that is that an actual scientific question can require comparison of more than 100 variants. However, for our user study, we restricted the number of variants to a number that allowed our participants to complete the task in a reasonable amount of time. A user study with expert users performing actual exploratory analysis tasks could furthermore identify the benefits for the application domain.

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7. REFERENCES

- [1] S. Anzali, G. Barnickel, M. Krug, J. Sadowski, M. Wagener, J. Gasteiger, and J. Polanski. The comparison of geometric and electronic properties of molecular surfaces by neural networks. *J. Comput. Mol. Des.*, 10(6):521–534, 1996.
- [2] R. Ball, C. North, and D. Bowman. Move to improve: Promoting physical navigation to increase user performance with large displays. *Proc. CHI*, pages 191–200, 2007.
- [3] D. A. Bowman and L. F. Hodges. An evaluation of techniques for grabbing and manipulating remote objects in immersive virtual environments. In *Proc. I3D*, pages 35–ff., 1997.
- [4] P. W. Finn and G. M. Morris. Shape-based similarity searching in chemical databases. *Wiley Interdiscip. Rev. Comput. Mol. Sci.*, 3(3):226–241, 2013.
- [5] T. Gjerlufsen, C. N. Klokmose, J. Eagan, C. Pillias, and M. Beaudouin-Lafon. Shared Substance: Developing Flexible Multi-surface Applications. In *Proc. CHI*, pages 3383–3392, 2011.
- [6] S. Grottel, M. Krone, C. Müller, G. Reina, and T. Ertl. Megamol – a prototyping framework for particle-based visualization. *IEEE Trans. Vis. Comput. Graphics*, 21(2):201–214, 2015.
- [7] M. Hereld, I. R. Judson, J. Paris, and R. L. Stevens. Developing tiled projection display systems. In *Proc. Immersive Projection Technology Workshop*, 2000.
- [8] C. Hofbauer, H. Lohninger, and A. Aszódi. SURFCOMP: A novel graph-based approach to molecular surface comparison. *J. Chem. Inf. Comput. Sci.*, 44:837–847, 2004.
- [9] M. Hummel, H. Obermaier, C. Garth, and K. Joy. Comparative visual analysis of lagrangian transport in cfd ensembles. *IEEE Trans. Vis. Comput. Graphics*, 19(12):2743–2752, 2013.
- [10] M. R. Jakobsen and K. Hornbæk. Sizing up visualizations: Effects of display size in focus+context, overview+detail, and zooming interfaces. In *Proc. CHI*, pages 1451–1460, 2011.
- [11] M. A. Johnson and G. M. Maggiora. *Concepts and applications of molecular similarity*. Wiley, 1990.
- [12] W. Kabsch. A discussion of the solution for the best rotation to relate two sets of vectors. *Acta Crystallogr. Sect. A*, 34(5):922–923, 1976.
- [13] B. Lee, P. Isenberg, N. Riche, and S. Carpendale. Beyond Mouse and Keyboard: Expanding Design Considerations for Information Visualization Interactions. *IEEE Trans. Vis. Comput. Graphics*, 18(12):2689–2698, 2012.
- [14] K. Moreland. Redirecting research in large-format displays for visualization. In *Proc. LDAV*, pages 91–95, 2012.
- [15] C. Müller, G. Reina, and T. Ertl. The VVand: A two-tier system design for high-resolution stereo rendering. In *CHI POWERWALL Workshop*, 2013.
- [16] S. Nam, B. Jeong, L. Renambot, A. Johnson, K. Gaither, and J. Leigh. Remote visualization of large scale data for ultra-high resolution display environments. In *Proc. UltraVis*, pages 42–44, 2009.
- [17] T. Ni, G. S. Schmidt, O. G. Staadt, M. A. Livingston, R. Ball, and R. May. A survey of large high-resolution display technologies, techniques, and applications. In *IEEE Virtual Reality 2006*, pages 223–236, 2006.
- [18] C. Papadopoulos, K. Petkov, and A. Kaufman. Building the Reality Deck. In *CHI POWERWALL Workshop*, 2013.
- [19] J. S. Richardson. The anatomy and taxonomy of protein structure. *Advances in Protein Chemistry*, 34:167–339, 1981.
- [20] R. A. Ruddle, R. G. Thomas, R. S. Randell, P. Quirke, and D. Treanor. Performance and interaction behaviour during visual search on large, high-resolution displays. *Inf. Vis.*, 2013.
- [21] K. Scharnowski, M. Krone, G. Reina, T. Kulschewski, J. Pleiss, and T. Ertl. Comparative visualization of molecular surfaces using deformable models. *Comput. Graph. Forum*, 33(3):191–200, 2014.
- [22] L. Scheidegger, H. T. Vo, J. Kräger, C. T. Silva, and J. L. D. Comba. Parallel large data visualization with display walls, 2012.
- [23] L. Shupp, C. Andrews, M. Dickey-Kurdziolek, B. Yost, and C. North. Shaping the display of the future: The effects of display size and curvature on user performance and insights. *Human-Computer Interaction*, 24(1-2):230–272, 2009.
- [24] D. S. Tan, D. Gergle, P. G. Scupelli, and R. Pausch. Physically large displays improve path integration in 3D virtual navigation tasks. pages 439–446, 2004.
- [25] E. Tufte. *Envisioning Information*. Graphics Press, Cheshire, CT, USA, 1990.
- [26] S. van den Elzen and J. J. van Wijk. Small multiples, large singles: A new approach for visual data exploration. *Comput. Graph. Forum*, 32(3pt2):191–200, 2013.
- [27] S. Yang, H. Chung, C. North, and E. A. Fox. The effect of presenting long documents with large high-resolution displays on comprehension of content and user experience. In *Proc. Intl. Symposium on Electronic Theses and Dissertations*, 2010.
- [28] B. Yost and C. North. The perceptual scalability of visualization. *IEEE Trans. Vis. Comput. Graphics*, 12(5):837–844, 2006.