Information visualization and the arts-science-social science interface

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ABSTRACT
In a world of ever-increasing and newly discovered complexities, and rapidly expanding data sets describing man-made and natural phenomena, information visualization offers a means of structuring and enabling interpretation of these data in the context of that complexity. Advances in graphics hardware, art asset pipelines and parallelized computational platforms offer unprecedented potential. However, harnessing this potential to good effect is challenging and requires the integration of skills from the arts and social sciences to support scientific endeavor in the physical and life sciences. Here, we consider those skills and describe four case studies that highlight interoperation among disciplines at this arts-science-social science interface.

Categories and Subject Descriptors
H.5.1 [**Information Interfaces and Presentation**]: Multimedia Information Systems – *animations, artificial, augmented and virtual realities, evaluation/methodology*

General Terms
Measurement, Performance, Design, Human Factors

Keywords
Computer arts, graphics, visual analytics, immersion, serious games, complex systems

1. INTRODUCTION
The ‘data explosion’, highlighted for over a decade, is being continuously driven by technology. Biology, for example, has become “a data-rich and information-hungry science” [22] as a consequence of high-throughput data generation techniques: in a single experiment terabytes of data may be generated [11]. This data explosion occurs within the context of an increasingly connected world of socio-technical systems, where science impacts on society through policy, and where policy decisions relating to at least the essential socio-technical infrastructures must account for the interconnections and interdependencies in these systems [45]. This growing complexity is difficult to comprehend and information visualization has been proposed as a possible approach to analyzing and interpreting such data [18]. In principle, information visualization has never been better placed to cope with the technical demands of managing these large data sets, with advances in graphics hardware outstripping Moore’s law [19]. However, challenges including the volume of data needing visualized in relation to any single problem and the need to involve a wide range of stakeholders in the decision making [52] introduce demands on the information visualization process.

Here, we consider the creation of interactive digital media for information visualization. We highlight technical developments, including frameworks and interaction approaches, and the importance of artistic input to visualizations (§2.1). We also consider the role of new and emerging computational platforms in relation to information visualization (§2.2). However, while these platforms offer remarkable levels of detail visually and can be interactive in real-time, for information visualization to be effective, content creation needs to take account of human factors (§3.1) and be evaluated quantitatively in the domain of application (§3.2). We demonstrate interdisciplinary applications of information visualization, focusing on decision-making (§4.1) and understanding complex systems (§4.2), drawing on current practice arising from the interdisciplinary interaction among four of Abertay’s largest research groups, which together combine expertise from arts, psychology, and the physical and life sciences. These case studies present information visualization as a medium for interdisciplinary communication and as a platform for stakeholder engagement.

2. CONTENT CREATION
2.1 State-of-the-art Technologies
2.1.1 Graphics and interaction
Interactive 3D content has in recent years become more accessible and can now be created by users with limited programming experience. There has been an explosion in scientific visualization

IITM’10, December 28–30, 2010, Allahabad, India.

packages, games engines and virtual reality (VR) platforms. This sudden growth in 3D content software is due to the rate of technological progress in the field of 3D graphics that far outstrips that of other, more firmly established areas. For approximately the past ten years, graphics hardware has improved at a rate nearly three times faster than Moore's Law predicts, effectively doubling in processing power every six months [19]. 3D games engines, scientific visualization packages and VR platforms are built upon a Graphics Application Programming Interface such as Direct3D or OpenGL that provide a software abstraction of the GPU or video card. A core objective of Virtual Reality engines, such as Vizard, is flexibility in the number and modes of interaction e.g. haptic devices such as head mounted displays and data gloves. Games engines, such as Blender, OGRE and Second Life are aimed at optimizing the rendering pipeline to achieve maximum visual impact and generally offer traditional modes of interaction i.e. keyboard and mouse. However the distinction between Virtual Reality platforms and games engines is diminishing due to technological advances in 3D stereoscopic displays and 'wand' controllers in games.

Scientific visualization packages are aimed at generating realistic rendering of 3D datasets with a temporal aspect such as climate change data superimposed over geographical data, visualization of interior of 3D opaque objects such as human body and soil. There are many scientific visualization packages available both commercially and open source including the Visualization Toolkit (VTK) and the ParaView visualization library. Additionally content creation using VR platforms, scientific packages or games engines is achieved using high level programming or scripting languages which are easier to implement eliminating the need to learn 3D graphics APIs such as OpenGL or DirectX. As game and VR technologies have matured and become easier to learn and use their application areas have widened. Game and VR technologies are now exploited in serious games such as, landscape visualization, medical and military training.

Multi touch interfaces appear to be growing in popularity due to the iPhone and Microsoft's surface technology. Multi-touch devices provide a shift in information navigation offering a pragmatic solution to address the limitations of single touch interfaces that require complex and unintuitive gestures to discriminate actions. With multi touch interfaces the gestures can be simpler and intuitive and a direct way to interact with software. Multi-touch interactive displays have the potential to create a subjective feeling of genuine engagement with the subject matter at hand, and are ideally suited to any engagement activity. With intuitive gestures it is possible for users to interact with digital artifacts in a much more direct way [20]. The theoretical notion of embodied cognition or grounded cognition [1, 23] suggests that the modality in which information is presented can influence the user's perception of it. Multi touch interfaces facilitate more expressive gestural control and we will most likely see the leading game engines and VR platforms releasing updates to support touch screen interfaces.

2.1.2 Art and animation

Similarly, current technologies, processes and pipelines for art and animation have become so advanced in terms of scope and accessibility that while the opportunity for outstanding visualizations has never been higher. However, issues have arisen concerning the appropriate skill sets and methods required to take advantage of these newly available toolsets. While it is technically easier than ever before to create potentially beautiful visualizations, this should never be perceived as a diminishment of the need for artistic ability on the part of the content creator. In modeling, texturing, animation and rendering technologies such as Maya and Max have ensured that the technology for visualization continues to evolve at an incredible pace. For example, models for movies and games now easily portray millions of polygons, and cinema and home entertainment systems are becoming capable of ever more immersive viewer experiences. However, the role that these toolsets and pipelines actually take in the creation of effective visualizations is at risk of being misinterpreted, with technology somehow being perceived as a replacement for skill and artistic sensibility.

For example, while subdivision modeling packages such as Zbrush and Mudbox allow for the creation of digital portrayals of musculature and anatomical form speed and ease, they require specialist knowledge on the part of the artist. If an artist does not know for example the structure of a bird's wing that allows for flight, or the way lights should best be placed in a scene to capture mood and ambient tone, then the technology pipeline's capability to display millions of polygons instead of hundreds will result in highlighting the artist's failings rather than accomplishments. Previous advances in virtual lighting and camera work within digital art have led to the necessity to involve traditional 'real world' practitioners in the creation of virtual environments. Likewise motion capture for animation now increasingly calls upon effective performances from an actor or professional performer in order to avoid issues such as Masahiro Moriri's concept of the uncanny valley [13]. Recent motion pictures such as the Lord of the Rings Trilogy demonstrated this, with all the advancements in modeling, mapping, lighting and virtual cameras ultimately still requiring a particularly skilled actor (in this case, Andy Serkis), to breathe life into the ultimate visualization. Thus technologies provide ever-increasing opportunities for artists to take advantage of innate talent and acquired knowledge; these pipelines do not in themselves teach color theory or effective visual composition, and they cannot inject the spark of life into a soulless collection of texture maps and polygons.

2.2 Computational Platforms

Likewise, the past ten years have seen a dramatic change in the nature of commodity computing: parallel hardware has become commonplace. Hyperthreaded, multicore, and now "manycore" processors allow work to be divided between multiple processing units. At the same time, graphics processing units have moved towards becoming general-purpose parallel computing devices. With growing integration between CPU and GPU hardware, especially at the low-power end of the market, these two trends are likely to converge: the future of programming – or, at least, the future of program execution – will be parallel. Parallel computing for scientific applications has a long history. Traditional approaches to parallelism focus upon "data-parallel" techniques, where regularly-structured, independent operations are performed across large sets of data. Where the operations to be performed cannot be determined ahead of time, or the components of the problem have complex interactions, data-parallel approaches are insufficient. We must instead turn to concurrent programming techniques, where a problem is decomposed into many concurrent, interacting behaviors, with the efficient execution of those behaviors across the available computing resources managed at runtime by a software scheduler.

Agent-based simulations of complex systems are particularly amenable to concurrent programming, since they have a high degree of natural concurrency, consisting of sets of concurrently interacting agents. Such simulations can exploit recent developments in concurrent runtime systems to achieve good scalability on parallel hardware [29]. Furthermore, structuring a simulation in terms of concurrent interactions allows it to execute efficiently upon distributed systems such as clusters. These techniques can be used to allow simulations to operate at realistic scales – necessary to reproduce real-world emergent behaviors.

The complexity of the interactions rises when the requirements of visualization and user interaction are taken into account: agents must not only interact with the world and each other, but also with the user – a fundamentally unpredictable entity! Managing the latency of interaction is important both for visualization – maintaining the illusion of immersion within the simulated world – and simulation – efficiently transferring data between simulated entities. Maintaining simulation consistency (and scientific validity) in the face of high communication latency presents interesting challenges, requiring a balance to be struck between simulation accuracy and performance [14]. The CoSMoS project [4] has developed techniques for complex systems modeling, concurrent simulation and validation that are now being applied to a number of real-world scientific problems. CoSMoS work on the Display Wall at the University of Tromsø, a 22-megapixel, gesture-driven display system backed by a cluster, has demonstrated effective interaction between a distributed simulation and a distributed visualization using a reusable simulation infrastructure [33]. Ongoing research within the University of Abertay Dundee's HIVE facility explores how CoSMoS techniques can be applied to achieve live, immersive interaction with large-scale scientific simulations.

3. INTERACTION EVALUATION

The animation, interaction and graphical capabilities afforded by contemporary technologies offer visually rich, highly interactive real-time dynamic visualizations. For interactive visualizations to be effective they need to be more than content rich; they need to be designed to accord with human perceptual and cognitive processes and be evaluated objectively in terms of domain-relevant tasks.

3.1 Visual Analytics

The key issue for modern visualization is the need to generate analytic tools that rapidly convey the information required. The exponential increase in the volume and complexity of digital information available means that less time is available for scrutiny of information. More importantly, as the public increasingly become stakeholders in science, and receive their information about science through more open and unrestricted channels (including open access journals), it becomes imperative that the communication of scientific ideas and data analysis becomes transparent and inclusive to the non-specialist. Using the approaches described above, it is possible to create visually appealing charts and interactive media that conveys information in ways that static printed media cannot easily display and that statistical tests cannot show. However there are constraints on the efficacy of such tools, and there is a trend to use new techniques simply because they are new and are available rather than because they have any proven utility [48].

We have sought not only to develop new interactive research media but also to evaluate them [39, 40]. Surveys of needs and current uses of analysts and researchers confirmed previous assertions in the literature that outlier detection [46] and trend detection [49] are the most frequent uses of chart techniques. By assessing human performance in terms of speed and accuracy of identification of outliers, with artificial data sets designed to include particular trends, anomalies and a varied degree of randomness, the general principles of data comprehension can be explored. For interactive scatter plots, we have shown that in outlier detection tasks the use of the extra dimensions does not significantly improve search times. In addition to using a standard mouse, we have assessed the utility of interaction devices with six degrees of freedom and a high level of spatial precision (Intersense IS900 data wand), allowing for real time gestural control. In the case of trend detection, we have shown that it is possible to seek out complex nonlinear trends in data and the ability to rotate and manipulate the data does in this case help the user. Results thus indicate that 3D scatter plots can be efficient in detecting nonlinear trends but not for revealing singular anomalies [38, 40]. We found that allowing full 3D view control is actually counterproductive in simple visual analytical tasks, leading to a longer learning curve and slower performance.

The ability to render multiple detailed objects in real-time based on complex dynamic models presents new opportunities, where emergent properties of underlying data could, in principle, be detected in real time. This detection can only take place if data are presented in an appropriate manner, and recognition of motion perception skills is important here [27]. The phenomenon of 'change blindness' [29, 41] has shown that in complex arrays, the salience of items changing over time can become reduced to the point that large changes in a visual array can become undetectable with the introduction of a time delay or blank between updates. Subsequently this 'blindness' has also been demonstrated for comparisons of arrays presented at the same time but across space [34]. Together they pose a significant problem for the efficient integration of visual information in complex displays. Part of the solution proposed is to find ways to establish the differences across the visual array that maximize the salience of the emerging pattern of change distribution. This is best achieved with animation, provided the stimulus array transforms at an appropriate speed and that the array itself comprises appropriately arranged features. It is an awareness of the biological constraints on effective perception that underpins efficient and effective visual object recognition in conditions that would otherwise be visually overwhelming [35].

3.2 Immersion Measurement

The usability of digital technologies can be measured in a multitude of ways. The more traditional methods comprise questionnaires, which may tap into subjective user ratings on aspects of the used technology, but also behavioral data, such as time to task completion, errors made while a user is interacting with the technology etc. One drawback of questionnaires is that the data are based on users' introspection and subjective judgments, which may be subjected to such factors as memory, but also social desirability of responses as perceived on part of the user. Furthermore, questionnaire data are usually gathered at the end of an interaction sequence and capture the user experience in its entirety, rather than allowing an observation of point-to-point changes in the level of user experience, such as immersion in the case of interactive media.

With the rapid advancement of technologies in everyday use, usability challenges arise due to the variety of technology, the diversity of the user and gaps in user knowledge [36]. The last decade has seen a development towards assessing the user experience, that is, their emotions and physiological responses, as usability or immersion indicators. Immersion is a key feature especially for games technology-based interactions. Players often show immersion in their games for example, to the extent that they forget time and place, such that they feel to be in the game or 'just in the computer' [4]. Measurements of physiological responses can provide a fine-grained objective monitoring of the user experience, such as immersion. The recording of quantitative, objective data therefore may be a more reliable measure in assessing the experience of engagement that a particular technology, including but not limited to gaming, creates 'in' the user over time.

Quantitative Measurement of Immersion: Measuring a variety of indicators, such as people's eye-movements as well as their physiological responses, when they engage with a digital product can provide objective data. For example, the measurement of game players' eye movements can be indicative of different types of interactions within a game. Immersed players exhibit fewer eye movements compared to non-immersed players [17]. In addition, players adopting a first person perspective have a different eye movement pattern compared to players who adopt a third person perspective, suggesting different levels of immersion [7]. Furthermore, psycho-physiological indices such as heart rate and its variability, skin conductance level, pupil dilation, and EEG [26] etc., indicate different levels of physiological arousal that may be associated with emotional states of the individual engaging with a game and may be indicative of immersion [e.g., 47]. Thus, game immersion and other critical 'emotional' indices associated with the 'quality' of a interactive digital media can be measured objectively, in addition to traditional subjective, questionnaire-based measures.

Measurement of immersion is of clear relevance to the design of technologies in an iterative manner, and could be used to assess what makes environments 'immersive' or at least impacting on a human user. Equally, immersion measurement can contribute to further knowledge in human cognition, experience and behavior, i.e., which features of an experimental setup impacts on users in which way. Interdisciplinary research at the biological/ psychological and technological/ computational interface can result in knowledge generation for such measurement of user engagement with interactive digital technologies.

4. APPLICATIONS

We highlight four applications where we exploit information visualization in the area of public well-being. The first two application examples are in the area of decision-support using serious games: urban planning and police firearms training. While the time-scales and nature of decisions are very different, the underlying use of computer arts, games technology and evaluation are crosscutting. The second pair of examples relate to complex systems modeling where we employ visualization techniques to support interpretation of in-silico experimentation. The first, in the field of soil science, explores technical challenges relating to efficient visualization of very large and detailed data sets. The second, located in healthcare, considers information visualization as a cross-disciplinary bridging tool that aids knowledge transfer in both directions between theoretical and experimental scientists.

4.1 Serious Games

4.1.1 Sustainable urban planning

The development of urban environments that are sustainable is of increasing importance as urban populations continue to grow [50] and impacts on the environment and society in a multitude of ways, including loss of green spaces [53], traffic congestion [42] and pollution [24]. Effective decision-making requires both integration among disciplines including ecology, economics and sociology and interaction between planners and users [52], i.e. the public. Tools and models exist to promote integration among disciplines. For example Stevens et al. detail a computational model to explore the impact of urban growth on land planning decisions under different scenarios of residential, commercial and recreational land usage. de Groot [6] describes a framework that considers land use options that synthesizes discipline-specific views. de Groot [6] highlights the importance of collaboration with landscape stakeholders, in their case through interviews.

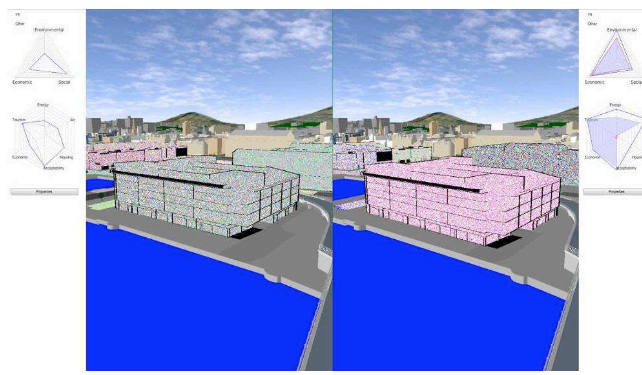

Fig. 1 Sustainable urban planning tool highlighting split pane for different scenarios and radar plots showing computational model data, reproduced from [15]

In Isaacs et al. [15] an innovative interactive visualization and modeling tool to support stakeholder engagement in sustainable urban planning decision-making is presented. The visualization itself is linked to an established computational model of social, economic and environmental indicators of sustainability over time. The framework provides, through a bespoke 3D visualization engine, dynamic visualization of those indicators, flexible user navigation around the virtual city, representation of traffic congestion and noise levels, and comparison through a split-pane view of sustainability indicators for different scenarios (Figure 1 above). Important features include the ability to import architects' models of the buildings, the capacity to modify the layout and properties of buildings in real-time, and the ability to wind time forwards and backwards across different seasons over many years. The approach represents the nature of the decision in terms familiar to the non-expert stakeholder to increase transparency of decisions and their impact and to best utilize stakeholder knowledge, and stakeholder evaluation is an essential part of this project.

4.1.2 *Police firearms training*

The definition provided by Zyda [55], "Serious game: a mental contest, played with a computer in accordance with specific rules, that uses entertainment to further government or corporate training, education, health, public policy, and strategic communication objectives", demonstrates the breadth of applicability of serious games. While there have been demonstrable successes, e.g. in the military (see [32] for review) and in healthcare (see [44] for review), and empirical research on the contribution of serious games to learning is lacking [30][54]. To support the development of serious games, Yusoff et al. [54] outline a framework that includes: cognitive and psychomotor skills, instructional content, learning outcomes, learning activities and reflection based on game feedback.

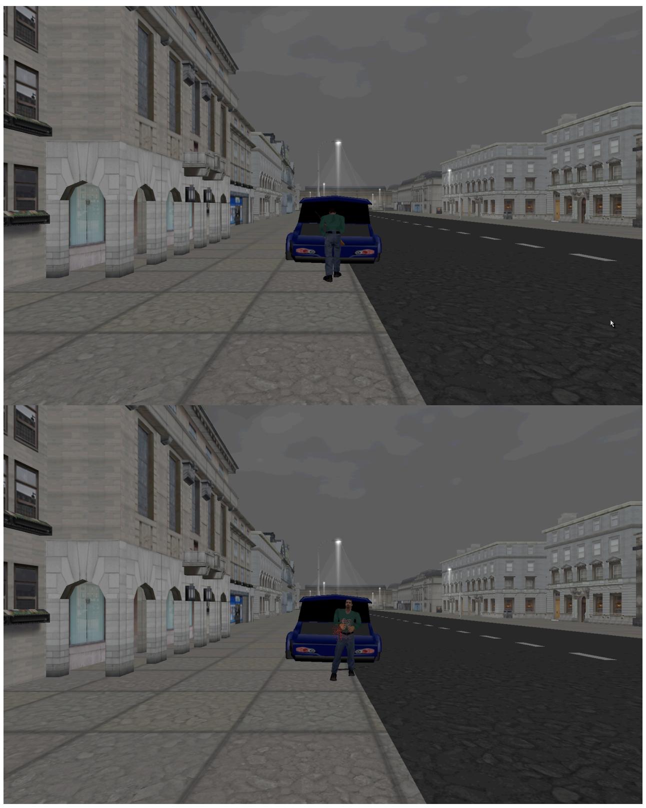

Fig. 2 A suspect searching for an object in a car (top) from the participant's perspective, suspect turns in a carefully animated sequence holding an object that may or may not be a threat (not shown), the participant has to decide on the level of threat and then the action taken. In this case the participant shoots (bottom).

In Robertson et al. [31] we describe a serious games framework that focuses on the 'shoot – no shoot' decision [51], where police firearms officers must decide in a fraction of a second whether to use deadly force in a given situation (Fig. 2 above). Video-based trainers have been used in the UK to explore conditions under which this decision is made (e.g. [25]), but this technology lack the immediacy of feedback and flexibility in training material provision offered by games. The simulator in [31] provides configurable decision-making scenarios with interactive artificially intelligent agents, and provides dynamic feedback to the user based on multi-modal input. In line with the framework in [51], the essential art animations, including artist-defined timings of movement and the range of objects held, were carefully designed and assessed with respect limits on psychomotor and perceptual skills prior to task performance evaluation, the instructional content and learning outcomes were designed in collaboration with professional trainers, participants were briefed on the learning activities in the simulator and feedback given to participants through the game mechanics.

Importantly here, through structured task-based performance testing we were able to both refine and assess the simulator. For example, where the level of certainty in threat-level and level of accountability for the decision [5] were varied, we have demonstrated that manipulation of accountability has a significant impact on performance in conditions of uncertainty in threat level. This finding has implications for the development of both instructional content, i.e. scenarios, and learning outcomes in such training simulators.

4.2 Complex Systems Modeling

4.2.1 *Soil science*

Soil respiration represents the second largest Carbon flux between ecosystems and the atmosphere that is more than 10 times the current rate of carbon release from fossil-fuel combustion [2]. Despite soil's global significance, understanding the effect of environmental factors on the dynamics of soil Carbon is limited, and this may be attributed to existing models not taking into account the spatially complex physical and bio-chemical micro-environments in which microorganisms proliferate. A step towards understanding the Carbon dynamics of soil is to integrate the physical environment of soil, quantified using Computer Aided Tomography (CT), with descriptive models of fluid flow and microbial dynamics as affected by Carbon distribution. The generation of large 3D time series data from simulations of water and microbial distributions at the pore scale may be integrated with the soil structural properties and analysed. Coupling visualization techniques to quantitative measures and simulation output can provide an insightful and intuitive technique to understanding soil processes such as the effect of pore scale structure on dynamics of water flow and microbial species and more importantly how these are interrelated.

Soil visualizations can be broken down into two categories: volume visualization and isosurface rendering. Volume visualization now uses as standard the GPU (hardware acceleration) and provides a mechanism for viewing the interior of the object, which is useful for following connected pore volumes that enable movement of water and microbial species. Volume data are 3D entities, possibly time varying, that may not possess tangible surfaces or edges and may be too voluminous to be represented geometrically. 3D contours, isosurfaces, are approximated by many polygonal primitives and from the CT data it is possible to extract a mesh representing the particular phase based on its isovalue. Although mesh representation loses the internal structure and information it may be readily processed in many artistic 3D modeling packages such as Maya and 3D Max. This allows scientific data to be presented in a more natural way by applying textures and lighting models to the mesh to add realism. The appearance of many POV exporters in scientific visualization packages, which allow lighting models to be applied to meshes, demonstrates the demand for more realistic representation of scientific data, enhancing communication of science to non-experts.

As an example of the challenges in this area, Fig 3 (below) shows a volume visualization of distribution of water droplets in 3D pore space as predicted by the Single Component Multi Phase (SCMP) Lattice Boltzmann (LB) model [43]. The presence of water droplets alters the connectivity of the pore space, and this may have implications for microbial dynamics and interactions. What is more interesting is to superimpose the pore space, predicted water distribution and modeled microbial response [9, 21] onto a single visualization. One technique is to show the dominant phase (water, solid, air, microbial species) at each voxel using glyphs or a color map where each phase will have its own unique glyph or color map. This would illustrate large contiguous voxel regions of dominating phases and phase interfaces. Alternatively color (including transparency) coding and/or scaling (size) of glyphs can be used to provide an indication of quantitative distribution of each phase. An alternative is to blend together color maps or glyphs weighted by the associated ratios of the phases, similar to [16] where blending and weaving techniques were used to display multivariate data overlain on a 3D virtual environment. Finally an isosurface can be displayed for each phase. Great flexibility in the display of multivariate soil information is afforded by these technologies, and there is real potential in conveying scientific information to stakeholders if designed and used correctly.

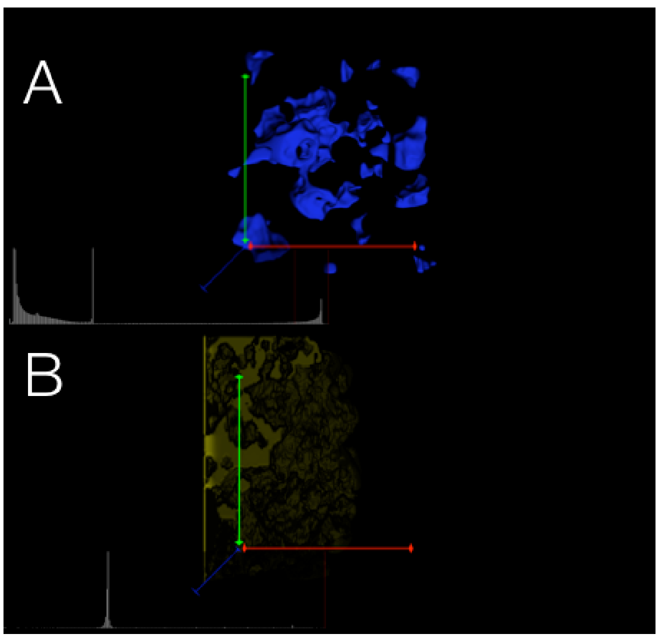

Fig. 3 A) Water distribution predicted by SCMP LB model [43]; B) Fungal biomass distribution, t=450 as constrained by soil structure and water distribution and predicted by Fungal growth model [9]

4.2.2 Cancer systems biology

Cancer is one of the major health concerns facing society today. To maintain our bodies, normal cells undergo a well-defined lifecycle of growth, reproduction (cell division) and death, regulated by a complex network of pathways exists along which biological species circulate. Cancerous cells do not follow that lifecycle, and may grow and reproduce much faster and live much longer than normal cells. Drugs designed to treat cancer cells seek to disrupt the behavior of those cells by changing the flow of biochemical compounds around that network. However, these drugs have a limited impact on patients [10]. A large proportion of patients therefore unnecessarily receive ineffective and expensive treatments with toxic side effects. Computational models of cellular signaling networks offer an excellent platform for exploring the impact of drug interventions on cell functioning, and can provide biomarkers – indicators based on biological measurements – that can help inform assessment of the likelihood of success of treatment for individuals [8].

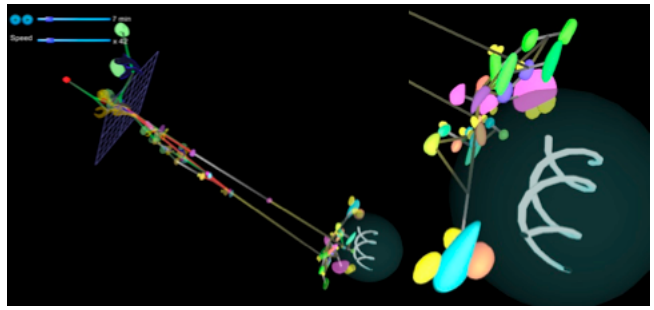

Fig. 4 Dynamic visualisation of the cell signalling network in [12], with cell membrane (blue grid), receptor system located on the membrane, signalling pathways (gray) and nucleus (white); close-up view of the receptor membrane (right).

This is possible because these models represent behavioral mechanisms of the cell that determine cell functioning in response to external input stimuli, including drugs. However, these models are necessarily complex, often comprising a system of tens of coupled differential equations, supported by static network topology diagrams (e.g. [12]) and this means that it is difficult for cancer scientists to interpret model operation and resulting predictions. Again, visualization can offer an invaluable communication tool, depicting model dynamics. Our existing visualization (Fig. 4 above) [37] illustrates rates of movement, locations and concentrations of biological species over time, and interaction provides navigation through the network, designed to avoid change blindness. Importantly, model components have been developed by 3D computer artists and are based on domain knowledge such that the graphics are consistent with domain knowledge. Currently, we are dynamically coupling the visualization to the predictive model and this allows us to rewind and replay the visualization under different configurations (as in [16]. Crucially, because the visualization is directly coupled to the dynamical network simulation it will be possible to design drug interventions via manipulation of the visualized network and observation of the resulting dynamics.

5. SUMMARY

The case studies presented in Section 4 exist at the boundary between society and technology. Consequently, they would not have been possible without input from a mix of disciplines, different in different case studies, from the arts, sciences and social sciences. In each case, information visualization plays a central role: it provides a conduit for cross-disciplinary dialogue amongst researchers and/or opportunities for stakeholder engagement in meaningful representations of the problem domain.

The technologies and computational infrastructures outlined in Section 2 offer remarkable opportunities for development of increasingly interactive, engaging visualizations that can provide compelling views of complex problems to support both decision-making and understanding. Rich animation and detailed artwork may be combined with dynamic interaction, linked in real-time to simulation execution. However, the effectiveness and appropriateness for specific tasks of such visualizations should be designed and evaluated with respect to human factors and task performance.

This is a challenging area, requiring ongoing interoperation across the discipline divide, and we have, in Section 3, highlighted some of the factors to consider, outlining the role of the field of visual analytics and how to measure user actions and engagement with interactive digital media. Our case studies highlight areas where such analysis has been undertaken or where analysis is part of intended developments. It is this linking of theoretical evaluation with artistic and technical practice that offers the opportunity to genuinely change the way that science is communicated among scientists and in dialogue with the general public.

6. ACKNOWLEDGMENTS

We acknowledge support from SICSA, the Scottish Informatics and Computer Science Alliance (Goltsov and Shovman), and SAGES, the Scottish Alliance for Geoscience, Environment and Society (Falconer).

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