Knowledge in (Geo)Visualisation: The relationship between seeing and thinking

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Abstract

Modern research in geovisualisation has framed the discipline as a field more akin to "geovisual analytics" – one that places an emphasis on the human elements of exploration of data through interactive and dynamic geo-interfaces, rather than simple data representation. This rephrasing highlights the importance of cognitive aspects of human interaction with geo-based data and the interfaces designed to present them. In an attempt to provide a psychological background to the benefits of geovisual analytics, this paper will explore the role that perception has in complex problem solving and knowledge discovery, and will demonstrate that, through modern interactive technologies, (geo)visualisations augment and facilitate our natural ability to surface novel, surprising and otherwise invisible relationships between information. It will argue that it is through these novel relationships that we add to our understanding of the original information and simultaneously reveal new knowledge 'between the gaps'.

Keywords: cognitive psychology, visualisation, Web 2.0, social objects, geovisualisation

Introduction

Geovisualisation is a relatively new field of study that draws on expertise from Cartography, Scientific Visualisation and Image Analysis to provide tools and methods through which the display, analysis and synthesis of complex, multivariate and location-based data can take place (Dykes et al., 2005, Fabrikant & Lobben, 2009). Whilst artifacts such as maps have been used for thousands of years as knowledge representation and communication tools (MacEachran, 1995) and for pattern analysis and relationship discovery (Snow, cited in Tufte, 1997), geovisualisation, through the employment of highly interactive interfaces, focuses more on the human elements of interface interaction and exploration (Fabrikant & Lobben, 2009). By taking advantage of our powerful perceptual abilities to help recognise patterns and link existing understanding with new sets of knowledge, geovisualisation provides an important link between interactive interfaces, data, and the human decision making process.

With recent advances in technology, the tools that support the kinds of interactive interfaces seen in geovisualisations have become more widely available. Information itself has also become more accessible, and the range, quality and scope of this information has also increased dramatically (Dykes et al., 2005). Despite this, there is a lack of research that looks specifically at the cognitive aspects of geographic information visualisation – specifically, there is a need for further research into the effectiveness of interactive visual displays in human decision making (Fabrikant & Lobben, 2009; MacEachren & Kraak, 2001).

Whilst there lacks this specific research, there still exists a large body of literature in psychology and cognitive science on the role that perception and visual representation play in human thought. We know that our perceptual abilities can be used to overcome cognitive limitations (Larkin & Simon, 1987), and that spatial representations play an important role in learning, problem solving and memory (Piaget, cited in Ginsburg and Opper, 1987; Baddeley & Hitch, 1974). Similarly, there are bodies of research in sociology that discuss the benefits an increased level of sharing, collaboration and conversation that technology advances enable (Knorr-Cetina & Breufer, 2000).

Whilst not offering a solution to the current need for research into interactive visualisations, this paper will highlight some of the foundational research in cognitive psychology and sociology literature that provides evidence for the value of visualisations in sense-making and knowledge discovery. It will explaining how much of how we learn and think has a strong basis in perception, and will show how diagrams and visualisations exploit our visual system and augment our cognitive ability. From there, we will explore the role that social sharing and discussions have in the discovery of new knowledge, particularly in the context of Web 2.0 and its participatory culture.

By exposing the relationship between internal cognitive processes, visualisations and the social contexts in which they exist, we will argue that geovisualisations greatly improve our ability to process complex problems, and help surface novel, surprising and otherwise invisible inferences. In this regard, this paper will highlight that, despite a lack of research into the specific effectiveness of interactive interfaces, geovisualisation research has a solid foundation on which it can progress.

The Perceptual Basis of Human Thought

Humans are visual creatures - our perceptual and visual processing abilities are extremely powerful and pervasive. When we open our eyes, millions of stimuli in the form of photons of light travel from the rods and cones of our retina, across our optic nerves and through to our visual cortex. Here, the raw perceptual data of light and shades is parsed into edges and objects, and attributes such as shape, size and depth are calculated. Other areas of our brain then interpret, categorise, compare and filter this information into a conscious, vivid image of the world around us. This process happens hundreds of times a second, and is so instantaneous that, to our conscious selves, there is no perceivable effort to look at something and realise we are seeing a pen, the word 'hello' or a smiling face. Compared to the difficulty most of us have solving a complex mathematical problem, the agility with which our mind processes such visual input would lead one to believe that perception and cognition are entirely separate processes (Roam, 2008).

Both philosophers and early psychologists were long of the belief that perception and thought were only superficially related; that the senses mechanically recorded and coded stimuli in the external world for submission to the higher and more dignified processes of cognition (Arnheim, 1980). At the birth of experimental psychology in the late 19th century, due in large part to the work of early physiologists, much attention was paid to the visual sense and it's role in sense-making and problem solving (Thomas, 2009). The concept of mental imagery, otherwise referred to as 'visualising' or 'seeing in the mind's eye', was the cornerstone of this research and laid the foundation for our modern day understanding of internal representations (Piaget, cited in Ginsburg and Opper, 1987) and mental models (Johnson-Laird, 1980).

With an increased understanding of the overlaps between perception and cognition, visual and spatial thinking, employed through the use of external visualisation techniques, have been given more weight in the analytical process (Arnheim, 1980). Perception, in a physiological sense, is still regarded as having a significant and important role in human thought, but it is the degrees to which we form and manipulate internal spatial representations that have taken on a greater significance in the literature on cognition, perception and learning (Thomas, 2009).

Jean Piaget, a widely influential experimental psychologist, contributed a comprehensive body of work on perception and learning through his research into cognitive development in children (Ginsburg & Opper, 1987). Broadly, he theorised that there were two major processes through which humans learn: through operative cognition; where lessons are learned through sensorimotor activity and manipulation of the external world, and through figurative cognition; a purely internal process whose aim is to imitate and store reality, rather that overtly change or manipulate it. For Piaget, mental imagery was the cornerstone of figurative cognition, and hence the majority of internal thought and problem solving (Ginsburg and Opper, 1987).

Building on the work of Piaget, cognitive scientists through the 70s and 80s began to explore further the concept of internal representations. Whilst not strictly giving imagery the same esteem that Piaget and certainly Wundt gave it, the importance of these representations, with their strong basis in perception, remains a consensus amongst psychologists (Thomas, 2009). Johnson-Laird (1980), in a similar vain to Piaget, stated that humans do not understand the world directly, but possess only internal representations of it. Coining the term 'mental model', he argues that these representations, like mental images, have the properties of arbitrariness and subjectivity, but instead of being direct representations of the world, consist of sets of propositions aimed at approximating it. They are consequently more robust than images, which can only take the form of a specific instance.

In addition, modern accounts of the ways in which our short and long-term memory operate also propose an intimate interaction with perception. Baddeley and Hitch (1974) claim that visuospatial reasoning has a significant role to play in the retention of information, and that spatial representations, formed naturally out of a conscious effort to rehearse and retain information, result in significantly better recall.

However, the specific limits of our cognitive ability have been well documented through research into memory, most notably by Miller (1956), where he presents evidence that humans can only work with 7 ± 2 elements at any one time. Similarly, the abstract and dynamic nature of mental models may seem to be all powerful, but Johnson-Laird (1980) is quick to point out that there is a limit to the extent to which they can be manipulated and explored mentally, and the process of validating and evolving models through purely cognitive means can be severely taxing.

Exploiting Perception to Think

Visuospatial thinking, as efficient and effective as it is, still has its limits. We have discussed briefly how our working memories can only process a certain amount of data (Miller, 1956), and despite the significance of visuospatial reasoning to our current understanding of thought and memory (see Baddeley and Hitch, 1974), visual thinking still submits itself to the limits of our cognitive abilities. However, the perceptual roots of cognition are no longer in doubt, and as we better understand the limits of our computational ability to process and manipulate information, we are seeing an increasing amount of research into how our perceptual system can be used to augment and assist our problem solving abilities.

Lowe and Bouchiex (2008) explored the role of diagrams in the formation of mental models, and propose that they can assist in acquiring a better quality understanding of a domain of knowledge. Similarly, Ware et al. (2008) found that interactive diagrams can provide important cues that assist in the long-term recall of information, and Lohse (1993) found that perceptual inferences are made much faster than those using tabular data.

On a similar note, and perhaps the most seminal paper on the value of diagrams in sense-making, Larkin & Simon (1987) present a distinction between sentential representations; representations of a problem presented as a 'list' of sentences, and diagrammatic representations; those presented visually. They found that, despite containing identical data, diagrams provide a significant advantage over sentential representations in our ability to solve problems. Regarded as driver for much of the research into the role of diagrams in thinking (Koedinger, 1995), it is worth summarising their findings.

They highlight three situations that benefit from the use of diagrams: those that aim to replicate real, physical space (a diagram of a pulley-system - see Figure 1, or something else in the real world); those that represent an abstract 'ideal' space, usually dealing with geometrical problems (Figure 2); and those that do not describe an actual spatial arrangement, termed 'artificial diagrams' (Figure 3). These artificial diagrams are perhaps the most interesting application of visual thinking - despite being based on abstract, non-spatial ideas, we still enjoy significant benefits through the use of our spatially oriented visual system.

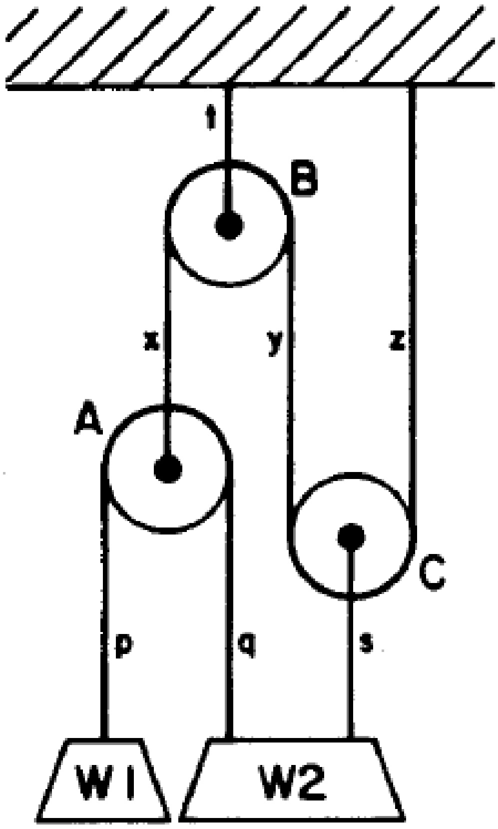

Figure 1. A diagram representing real, physical space – showing the intricacies of a pulley system, and used to calculate the two weights necessary for each to remain level with the other (Larkin & Simon, 1987, p 73).

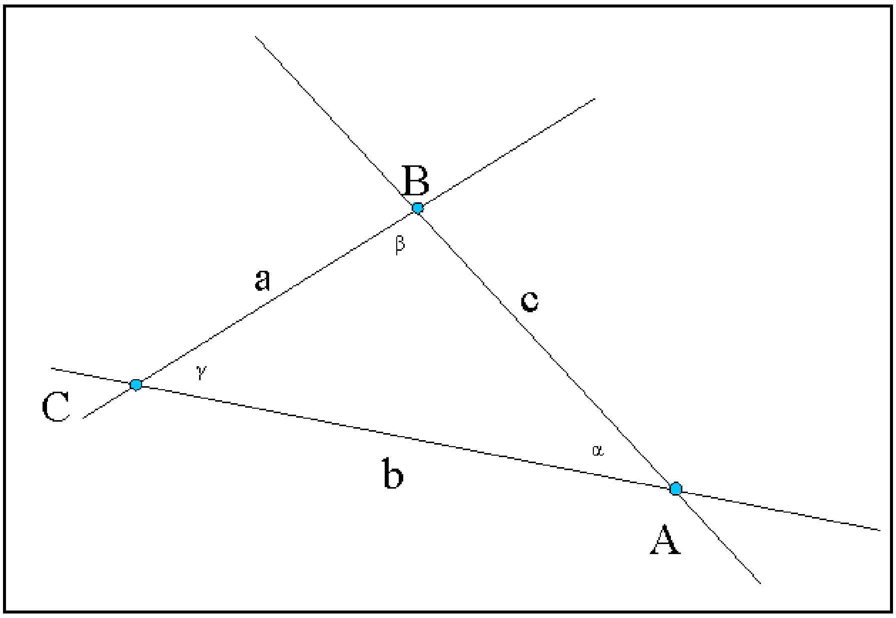

Figure 2. A geometrical diagram representing an abstract, ideal space. Source: *http://www.k12math.com.* Accessed 22nd April, 2010.

They argue that the reasons for this are three fold: in terms of computational costs and savings, we enjoy significant cognitive benefit across the areas of *search*, *recognition* and *inference*.

Search
Firstly, diagrams tend to group together all the information that is used together - that is, things and data of a similar nature are often seen adjacent to other related data. This leads to large savings in the need to search for and associate the various elements required to make an inference, and augments our working memory's ability to process more than 7 ± 2 elements, as described by Miller (1956).

Recognition
Secondly, diagrams use location to group information about an element, and this location itself can be used as the context in which meaning can be derived. This avoids the need for symbolic labels describing every piece of information, and, importantly, decreases our need to match these labels.

Inference
Thirdly, and perhaps most importantly, diagrams automatically support a large number of perceptual inferences, which are much easier for humans than inferences based on numbers or words alone (Larkin and Simon, 1987).

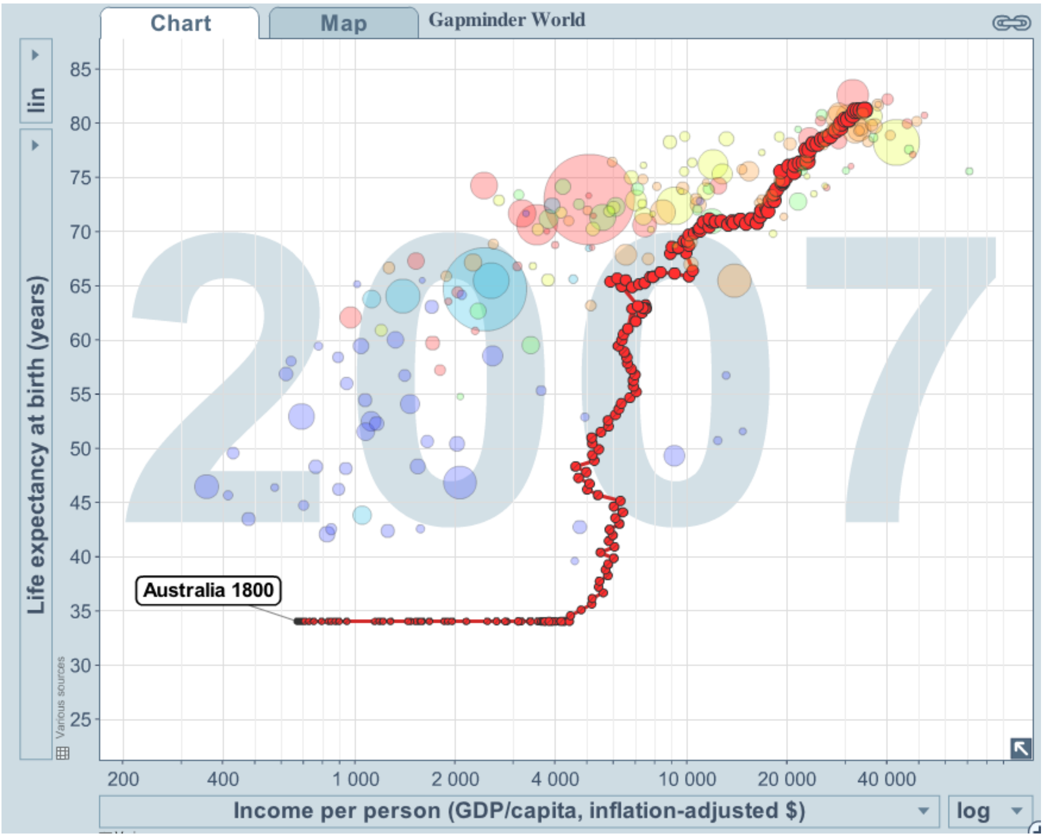

Fig. 3 Gapminder - A chart plotting life expectancy versus income, and tracking Australia's progress. Each dot represents a country, the size of which is representative of its population. Visual inferences are much easier than those using raw numbers Source: *http://www.gapminder.org*. Accessed 20th April, 2010.

The Role of (Geo)Visualization

With the general consensus evolving out of cognitive science literature that much of how humans think and learn is based in perception, we have begun to see research into how we can exploit our visual system to help us process problems and discover new knowledge (Canham & Fabrikant, 2010., Tufte, 1997., Larkin & Simon, 1999). This section will explore how visualisations as objects can lead to the discovery of new and surprising information.

Maps as tools of discovery

Broadly defined as graphical representation of a geographical setting (Robinson et al., 1995), maps have played an important role in knowledge store and transfer over the course of human history. From the clay survey tablets used for tax collec-tion purposes in 2300BC (Brown, 1979) through to the advent and near ubiquity of modern geographical representations (Google Maps, GPS navigation), spatial representations have long been an important tool for humans. Whilst their primary goal has been grounded in communication (Robinson et al., 1995), their use as analytic tools, as ones for the discovery of patterns and new knowledge has long been documented (Tufte, 1997; MacEachren, 1995).

In the area of health geography, advances in remote sensing technology have led to initiatives such as the *Emotion Map* (Nold, 2007), which combines biometric and location data to provide a "psycho-geography" (pp. 67) of cities such as San Francisco, New York and Paris. Zambrano & Engelhardt (2008) point out that geographers, through thematic visualizations, have contributed to the understanding of the transmission of HIV/AIDS (Wilton, 1996), and through a combination of freely available mobile and mapping technology, platforms such as *Ushahidi* (*www.ushahidi.com*) and *FrontlineSMS* (*www.frontlinesms.com*) are enabling real-time spatial representation of aggregated user data for everything from urgent crisis information (as in Haiti; *haiti.ushahidi.com*) and election monitoring (in the Kenyan elections of 2007) to the tracking of ivory poachers (in East Africa; *wildlifetrackers.wildlifedirect.org*).

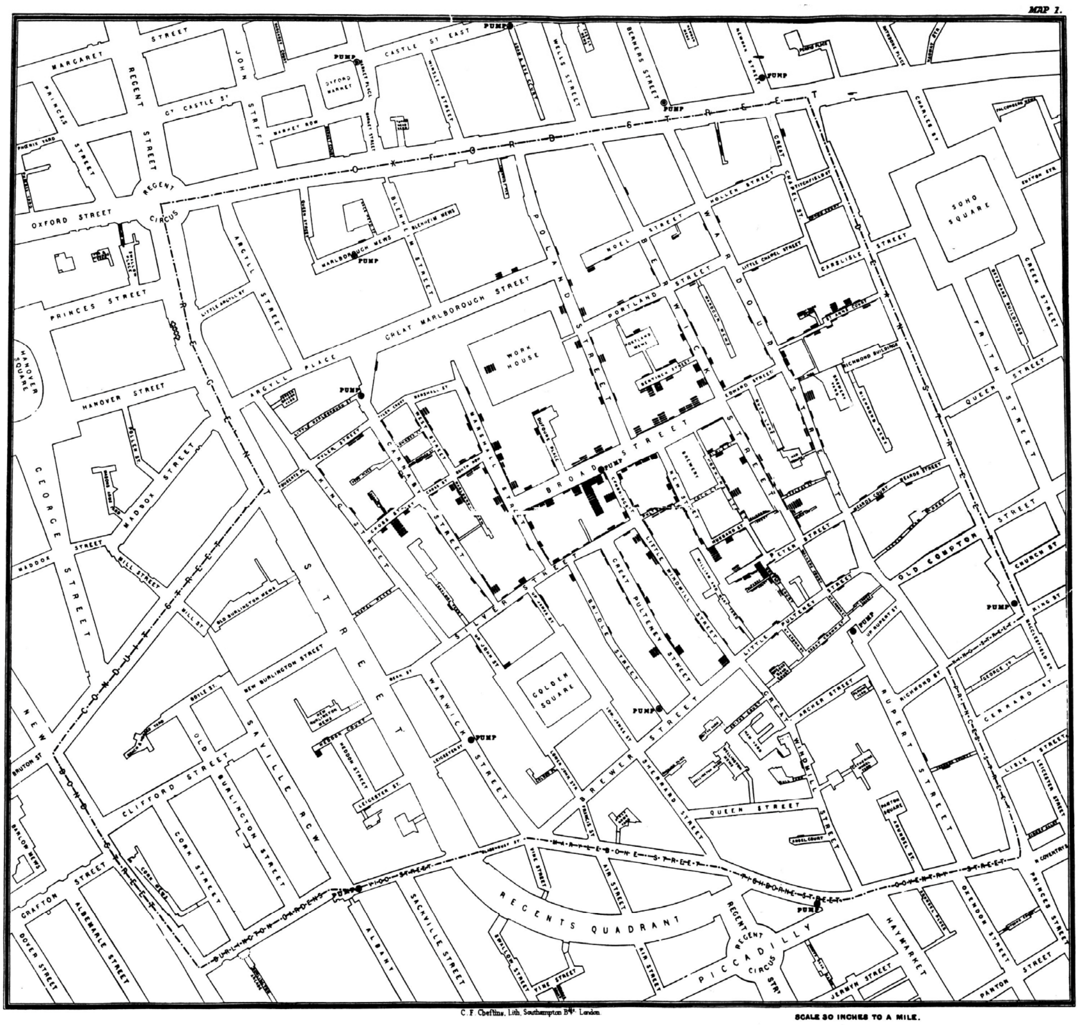

Figure 4. Dr. John Snow's map of Soho, London depicted cholera deaths. Source: *http://upload.wikimedia.org/wikipedia/commons/2/27/Snow-cholera-map-1.jpg.* Accessed 20th April, 2010.

One of the most widely cited examples of visualisation in analysis and discovery in that of John Snow (figure 4), when in 1853 he used the location of cholera deaths to detect the source of an epidemic (a water pump on Broad Street). In a time when the theory of bacteria was not yet widely accepted, Snow's visualisation allowed such strong inferences to be made that authorities ignored common consensus that the cause of the outbreak was 'bad air', and removed the handle from the pump accessing the infected water supply.

This example is one that highlights the three benefits of visualisation discussed by Larkin and Simon (1999) – Snow, through the use of a visualisation, not only deduced the root cause of the outbreak, but managed to persuade sceptical authorities of its likely cause. It assisted its viewers to search for, recognise and infer meaning in ways that simple raw data may not have been able to reveal. As Tufte (1997. Pp. 24) alludes to, as a communication and sense-making tool, this visualisation 'testified about the data far more efficiently than calculation', and the overwhelming strength of the visual inferences afforded by his creation led to the end of an outbreak that cost more than 500 lives (Tufte, 1997).
It is here that the lack of empirical evidence around inference from graphics is evident. Whilst Snow's example is a powerful one, the majority of scientific studies of inference from graphics have been limited to tasks that simply require people to recognise patterns from information shown in visualisations (Hegarty et al., 2010). The acquisition of new knowledge through the examination of graphics alone has not been fully explored, and those that have attempted such studies have found that knowledge already held by users is a far more important indicator of their ability to discover new knowledge than the graphical or interactive displays used in experiments (Lowe & Boucheix, 2008; Ware et al., 2008; Khooshabeh & Hegarty, 2010).

Still, the ability to recognise patterns in data is a powerful one, and in the previous section we have discussed the cognitive foundations of the benefits of perception in this regard. Like Larkin and Simon's artificial diagrams, Snow's diagram combines data about an area and a geographical display, and the location of this data provides a powerful visual context from which meaning can be derived (Larkin & Simon, 1987).

With the joint benefit of free mapping technologies (see Google and Yahoo Maps) and new ways of capturing and disseminating data, thematic visualisations are becoming an increasingly important means of displaying, exploring and understanding exponentially increasing sets of data. Coupled with a rise of openness in government and organisational statistics (Macdonald et al., 2009) and the wide availability of user-generated data with an element of location (see Twitter and Flickr, which allow geotagging), the need for tools that make sense of this data has never been greater (Shirky, 2007). The widespread use of these simple, open platforms is also paralleled with more technically savvy uses of other web technologies, such as Flash and Javascript, which are allowing more specialised, interactive and exploratory visualisation techniques (Dykes et al., 2005). Further, the common platform in which these tools reside, the Internet, is allowing a greater level of conversation and co-exploration to occur around these visualisations.

It is through the creation of these artefacts, and their values as objects in a social network, that further knowledge and understanding is being reached. Where empirical evidence of the value of *only* visualisations to uncover new knowledge is lacking (Hegarty & Canham, 2010), there are theories from sociology that can inform investigations into the value of visualisations in the context of a social network, enhanced by technological advancements and wide-spread adoption of the internet. The next section will discuss the benefits of visualizations as artefacts that can be shared and discussed.

Web 2.0 and social objects

'Web 2.0' is a term widely used to describe the evolution of the Internet from a one-way information-communication medium to one in which it's consumers are also participants. It is categorised by its open and accessible 'network as a service' approach to information, and encourages users to create and contribute their own data to the applications and services in which they participate (O'Reilly, 2005).

With this new openness, we are seeing vast amounts of information being made available to users, and the tools with which they filter and make sense of this in-formation have similarly become more complex and sophisticated. Sites such as Gapminder.org make public data available for exploration through it's robust and adaptable visualisation interface, and others such as IBM's *Many Eyes* and Swivel.com allow users to upload and explore their own data through similar interfaces (Macdonald et al., 2009).

At the same time, the web in enabling an unprecedented level of communication between people from vastly different backgrounds and geographical areas, and the efficiency with which existing day-to-day communications are taking place has also been greatly increased (Shirky, 2007). In other words, the barriers with which we can share and communicate information with each other have never been lower, and the ways in which we do this are more sophisticated and efficient than ever before (Weinberger, 2008).

With this efficiency and ease of sharing, visualisations now have a dual role: The first is that of a sense-making object; one that exploits our visual perceptual system, offers a subjective view and allows us to search for, recognise and infer meaningful conclusions with much greater ease than non-visual means. This is the role we explored in the first half of this paper. The second role is that of a social object, defined by sociologists Knorr Cetina & Breugger (2000) as the core around which social interactions take place - affording discussions and focusing and initi-ating conversations between and amongst people. The Internet allows (geo)visualisations to become embedded and integrated within a network of people much more easily, and it is through this 'embeddedness' that a shared under-standing can be reached (Knorr Cetina & Bruegger, 2000).

In their paper, 'The Social life of Visualisation', Macdonald et al. (2009) discuss the concept of visualisations as social objects, and go as far as to propose a set of design patterns, or a generic interface framework, in which the interpretation and creation of visualisations becomes a social activity. Their paper highlights the benefits of having such an object embedded within a framework of interactivity, enabled through technology and interface design, and a social context, enabled through the web's heightened sense of social connectivity. They describe a set of stages and attributes a visualisation might have in order for it to be useful in both a sense-making and communication context (Figure 5).

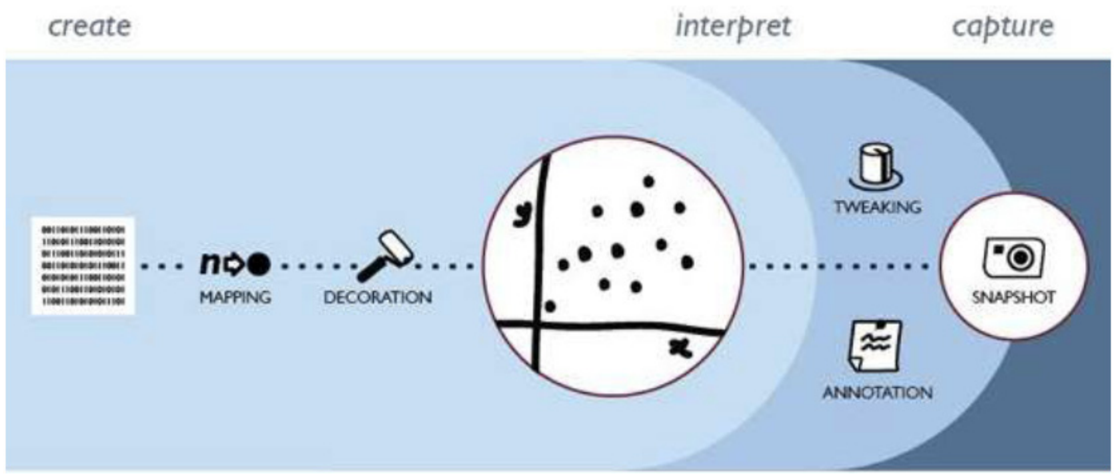

Figure 5. Macdonald et al (2009, p. 2) framework for social visualization.

Their three stages – *create*, *interpret* and *capture* – each describe steps in a lifecycle of story-telling and sense-making in a social context. The first two stages serve as a sense-making mechanism, where the creation of a visualisation begins in *mapping* the problem to be explored to a visualisation type, which is then *decorated* to highlight key the data of interest. Then, through the ability to *tweak* and *annotate*, visualisations are interpreted and discussed, and notes that describe inferences can be recorded. It is in the final stage, *capture*, where the role of the visualisation turns from one of sense-making to that of communication – a visualisation, with its associated annotations and reached inferences and conclusions, is captured and sent to others for discussion.

It is through this cycle that a shared understanding can be reached and new knowledge discovered. The ability for dynamic visualisations to switch between the modes of sense-making and communication relatively simply testifies to their great value as tools of discovery, whilst at the same time highlighting that the Internet and Web 2.0 serves as a robust platform within which knowledge can be created, shared and discussed.

Through a triumvirate of rich data, interactive visualisations and unprecedented levels of sharing and communication, the Web itself has become an invaluable tool for sense making and knowledge discovery.

Conclusion

Despite a lack of investigation into the effectiveness of interactive interfaces, we have seen much research into how the raw processing power of our visual system can be used to augment and improve our problem solving abilities. We now understand that perception plays a large role in our ability to process information – we find it much easier to reason spatially and in imagery than we do to process data in a flat list (Larkin & Simon, 1987), and significant parts of our memory are reliant on perceptual manipulation (Baddeley & Hitch, 1974). However, despite our natural perceptual agility, the manipulation of such internal representations can be extremely taxing. The relatively little effort it takes to externalise a problem visually, on a cognitive and computational level, is repaid exponentially – we enjoy significant gains in our ability to search for, recognise and infer from visual elements.

The advent of Web 2.0 and the subsequent availability of rich data and visualisation tools, particular those with a geo focus, are similarly allowing the visualisations to be created around larger, more complicated sets of data. Whilst the perceptual benefits we enjoy are still present, the web, its interactive technologies and participatory culture allow greater ability explore problems, both individually and, importantly, with others.

Through a combined understanding of how we process visual information and of the ubiquity of tools that are allowing greater levels of interaction, we are seeing how visualisations as exploratory devices and social objects can facilitate the discovery of new knowledge. It is through this dual role of visualisations as both sense-making and social objects that research into the effectiveness of geovisualisations can be progressed. Whilst cognitive-based research into the particulars of visual displays and our ability to process them is necessary, research into the role of visualisations as social objects in knowledge discovery and sense-making would be an interesting thread to pursue. Increasingly, it is through shared understandings new knowledge 'between the gaps' of data and people is being uncovered.

Acknowledgements

The authors of this paper would like to acknowledge the support of the Australian Research Council through a Linkage Grant that is supporting this research. The research is being undertaken in collaboration and with the support of Parks Victoria. This paper reports on part of broader research effort being undertaken under the umbrella of the RMIT University Design Research Institute's Geo-placed Knowledge research node. It is part of the Affective Atlas project. We also recognize the valued input of two anonymous reviewers whose comments and suggestions have been used to guide improvements of this paper.

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