Interactive Animated Mobile Information Visualisation

Paul Craig*
Xi'an Jiaotong-Liverpool University, Suzhou, China

Abstract

While the potential of mobile information visualisation is widely recognized, there is still relatively little research in this area and few practical guidelines for the design of mobile information visualisation interfaces. Indeed, it would appear that there is still a general feeling in the interface design community that mobile visualisation should be limited to simple operations and small scale data. Information visualisation research has concentrated thus far on desktop PCs and larger displays while interfaces for more compact mobile device have been neglected. This is in spite of the increasing popularity and widespread use of smart-phones and other new mobile technologies. In this paper we address this issue by developing a set of low-level interface design guidelines for mobile information visualisation development. This is done by considering a basic set of interactions and relating these to mobile device limitations. Our results suggest that the mindful application of existing information visualisation techniques can overcome many mobile device limitations and that proper implementation of interaction mechanisms and animated view transitions are key to effective mobile information visualisation. This is illustrated with case studies looking at a coordinated map and timeline interface for geo-temporal data, a distorted scatter-plot, and a space filling hierarchy view.

CR Categories: H.5.2 [INFORMATION INTERFACES AND PRESENTATION]: User Interfaces—Graphical user interfaces (GUI)

Keywords: information visualisation, mobile visualisation, animation

1 Introduction

The beginning of the 21st century has been marked by the proliferation of increasingly powerful mobile computing devices. Following on from the laptops, palm-pcs and mobile phones of the 80s and 90s, we now have smartphones, tablets, notebook computers and, more recently, smartwatches and augmented reality glasses. There are currently over 2.23 billion mobile phone users and over 1.75 billion smartphone users worldwide meaning that a remarkable 31% of the global population now own a mobile phone and around 25% already have a smartphone [Lee and Lee 2014]. These numbers are expected to rise in the near future and mobile devices are set to play an even bigger role in our daily lives with the advent of the *internet-of-things* [Weber and Weber 2010; Sun et al. 2014] which looks to connect a growing number of electronic devices via the internet.

A parallel trend has been the rise of *big data* [Chen et al. 2014] where we are now able to record and collate massive amounts of information related to things like personal activity, biology, social trends, the economy, environmental conditions and the weather. This explosion in the quantity and availability of data has massive potential to enhance our lives by helping us improve things like our fitness, health, personal interactions, management of resources and business activities. We do however need to consider that the utility of the data only goes as far as our ability to use it properly [Chen and Zhang 2014]. This depends on how well interface designers cater for human factors and make use of information from field such as human-computer interaction, interaction design and information visualisation [Card et al. 1991; Card et al. 1999] that work to reinforce our natural cognitive processes in order to make data accessible and comprehensible. The big data is useless unless we actually have some way to work with it, understand it and, most importantly, *think* with it.

Information visualisations are interactive representations of abstract data (i.e. data without an intrinsic spatial quality) that can be used to amplify cognition by allowing users to browse, explore or otherwise interact with that data [Card et al. 1999]. In other words, information visualisations help us to *think* using data. Classic examples are an interactive map used to help find a property [Shneiderman 1994] or an interactive scatterplot used to explore film releases [Ahlberg and Shneiderman 1994]. And information visualisation techniques have been found to be particularly useful for the analysis of large-scale data and complex data in areas such as gene expression analysis and financial data analysis. Indeed, this push towards larger scale data and more complex data analysis is a possible reason why information visualisation research has focused on larger displays, since larger displays are inherently more suitable for larger datasets.

Despite the recognized importance of interaction to information visualisation and the opportunity of more natural interaction offered by mobile devices [Lee et al. 2012], relatively little work has been done to develop information visualisation interfaces for mobile devices or indeed understand how we can better design information visualisation for mobile devices. This lack of active research in this area can no-doubt be attributed, at least in-part, to the attitude that displays for information visualisation should be as large as possible [Harrison 2010] and the perception that there is essentially a proportional relationship between the amount of information that can be displayed in an interface, or at least an interface that is comfortable to use, and the dimensions of the display space. This leads some authors to conclude that a smaller display can only be used effectively for aggregates and overviews of the data [Chittaro 2006]. Still other authors cite input peripherals and device limitations as a reason why mobile visualisation is less feasible for more challenging data-sets [Salim et al. 2015].

While there is certainly a strong case for limiting our expectations of what can be achieved on mobile devices, we feel that this needs to be balanced by a realistic evaluation of the potential benefits of mobile device information visualisation and the opportunities to improve mobile interfaces through inventive and thoughtful design. While mobile devices, by their very nature, will continue to have limited display space (although in recent years there has been a trend toward slightly larger displays) other device limitations such as limited processing and graphics capabilities are rapidly disappearing. And other useful features such as global positioning, tactile feedback and voice recognition are being added. Moreover, the natural application domain of mobile devices has expanded from

*e-mail:p.craig@xjtlu.edu.cn

activities that *need* to be performed on a mobile device, such as replying to important messages or checking a map, to include things that can in any way benefit from being done on the move, even if this means just making slightly better use of our time or occupying ourselves in what would otherwise be a dull moment. This now includes things like posting images to social media and even making purchases online. People are now using increasingly sophisticated applications on mobile devices and application developers need to either cater to this trend or find themselves left behind. This undoubtedly includes information visualisation developers who need to leverage new and improved device capabilities to support mobile visualisation.

There are indeed a number of researchers who recognize the potential of mobile visualisation and have proposed some useful general guidelines for their design. These tell us that the interface should be simple and user should be able to interact more directly with the data rather than have to operate menus and controls [Lee et al. 2012]. Others suggest that interaction should be fluid and flow seamlessly between different functions [Roberts et al. 2014]. In this paper we build on these guidelines by taking a lower-level approach to consider how specific aspects of information visualisation design should be implemented on mobile devices. This allows us to draft a set of guidelines that can be used to either adapt existing information visualisation applications for mobile use or begin considering which techniques to employ in the design of new applications.

2 Design Considerations

We begin our development of a set of draft guidelines for mobile visualisation interface design by considering issues related to how some basic interactions can be implemented on mobile devices and how these influence the display and overall design of the application. These are as follows:

1. **Inspection:** This can be considered as one of the most basic actions a user can perform on a desktop PC application environment. It's equivalent to hovering the mouse-cursor over an object or objects with the result of being able to momentarily reveal some relevant details such as the location of a file or the name of a person tagged in an image. This is a fundamental action for most information visualisation applications and is sometimes known as a hover or a type of data brush [Hochheiser and Shneiderman 1999].

   The closest equivalent to this action on a touch-screen device is for the user to make contact and move their finger across the screen. This can, however, be problematic for information visualisation as whatever is under the user's finger will be hidden. Naturally, this likely to be whatever is being selected since a natural direct-manipulation approach advises that we make the user press directly onto the object they want to interact with. Moreover, pressing and moving your finger is more equivalent to a drag action where, on a desktop computer, a mouse button is pressed while the mouse is moved. If a movement is made without pressing on the touch-screen it will not be detected.

2. **Selecting an object:** This is another fundamental action for most information visualisation applications [Martin and Ward 1995; Becker and Cleveland 1987]. On a desktop pc this action is normally realized by pressing the left mouse button while the mouse cursor is positioned over the object.

   The equivalent action on a touch-screen device is to simply press on the object. This is however a lot less accurate because touch-screen devices have no way of sensing the position of your hand before it presses on the screen, and there is no way to line-up the cursor to make sure you are pressing in the right place before making your selection. This problem is exacerbated by the small amount of screen space on mobile devices and the fact that contact is made with the blunt point of our finger which covers a relatively large area rather than anything that could be reasonably considered as an actual point.

   Another possible equivalent for this type of selection is for users to move a cursor by pressing and moving their finger, until they are sure the object they want is selected, then wait until a timer elapses to confirm the selection. While this allows the user to be more accurate and has the advantage of allowing selection and inspection type interaction to be realized together on the same interface, it adds an extra step to each interaction and is unlikely to be conducive to what we might think of as the fluid style of interaction necessary for a satisfactory user experience. Another option is to highlight the selected object and wait for the user to remove their finger before the selection is confirmed (as is the case with most virtual keyboards on mobile devices). The problem with this option is that selecting by releasing your finger is counter-intuitive. If we really think about it, moving your finger away from the screen is more like the action to cancel an operation.

3. **Selecting an area:** This action is realized using a click-and-drag action on a desktop PC. The equivalent action on a touch-screen device is to press and drag your finger. This is a relatively simple operation on smaller mobile devices but it can cause a degree of fatigue if the action is sustained on a larger device.

4. **Moving an object:** Moving an object has the same click-and-drag action on a desktop pc as selecting an area. This also has a similar action to selecting an area on touch-screen devices and suffers from the aforementioned problems of fatigue and inaccuracy.

5. **Scrolling:** This has the same click-and-drag action as moving an object. The main difference is that with scrolling the user moves a background onto which objects, such as list items, are fixed and movement is normally restricted to being along either the vertical or horizontal axis. On touchscreens this action can be made easier by programming the surface to have a sort of virtual momentum. That is, if the user presses and drags to start the surface moving then it continues moving even after the user has released their finger. Without contact, the surface gradually slows down until its initial momentum is depleted. This *kinetic* effect can reduce the fatigue and monotony a user would otherwise experience by scrolling through a long list. Other advantages of scrolling on mobile devices are that the user doesn't have to press on the item of interest to select it, and accuracy is dependent on the timing of user actions rather than the positioning of their finger.

   This is a good example of a direct manipulation technique that doesn't suffer from being implemented on a mobile device. Indeed, we can even consider that scrolling is more natural on a mobile device than a PC since a press and drag on the actual screen, and the object to be moved, is closer to the emulated physical action of scrolling than holding down a button and dragging a mouse or winding a mouse wheel. This is most likely the reason why many of the more popular mobile applications make use of scrolling or scrolling lists.

6. **Entering text:** On a desktop PC, text is entered via the keyboard. Most touch-screen device operating systems have a virtual keyboard but these are less efficient than actual physical keyboards due to the lack of tactile feedback. We can envision that future devices may use some sort of tactical feed-

back through the touch-screen or speech recognition for textual input but, as for now, text entry is clumsy and impractical. Likewise, the use of shortcut-keys or keyboard modifiers (like shift-select or control-select), which would also rely on keyboard input, is impractical on mobile devices.

This list is useful but it is far from exhaustive. It accounts for only the most basic user interactions and omits any proper consideration of the new interaction modalities becoming available on mobile devices. These would include things like interaction with vibrational tactic feedback, device orientation and other types of sensor input. The list does however give us a useful insight into the limitations of mobile touch-screen interaction from which we can begin to formulate a draft set of guidelines for mobile visualisation design.

Perhaps the most significant problem encountered is the inability of touch screens to easily differentiate between inspection and selection type actions. Here dragging (with the mouse button pressed) is normally distinguishable from hovering (without holding the mouse button) on a desktop PC but there is no equivalent distinction between these actions for touch-screen devices. Since both these actions are normally important for information visualisation interfaces it's important for this study to consider another way to implement these types of selection.

One possible solution is to use a toolbox metaphor where the user can press buttons in the interface to select different tools that operate in either inspect or selection mode. The toolbox metaphor has the additional benefit of being able to include virtual buttons to realize functionality normally associated with keyboard shortcuts and keyboard modifiers.

Other problems highlighted by our analysis are information being hidden by the user's finger and the inaccuracy of selection type actions. The problem of the user's finger hiding data can be solved easily enough by labelling that shows selection details away from the finger. Inspection details can also persist for a time after the user lifts their finger. The problem of reduced accuracy on a mobile device can be resolved by making the targets for selection actions larger or using selection techniques that do not rely on accuracy and select multiple objects around the point of selection. Given these criteria, excentric labelling [Fekete and Plaisant 1999] would appear to be an ideal technique for mobile visualisation since it allows users to select a group of objects in a larger area and can be easily modified to shift labels away from the area hidden by the user's finger. Space filling layout techniques [Stasko et al. 1999; Craig and Kennedy 2008] might also be appropriate for mobile devices as they make optimal use of limited screen space and can offer larger targets for less accurate user selections.

Other aspects of a mobile visualisation depend on how it can best convey information across a small display space. The basic trade-off already established is that the quantity of information displayed is proportional to the amount of available screen-space [Roberts et al. 2014]. We would argue that one should also factor in the time we have to interact with and look at the data. Hence, to convey the same amount of information in a smaller interface we need a more interactive interface and the user has to spend more time interacting with the visualisation. If we think of an information visualisation as consisting of different levels starting with the overview and being filtered down successive levels to the final detail view, a mobile visualisation simply has more layers than its large screen counterpart.

This makes the need for fluid interaction even more pressing on mobile displays. If we have additional interaction steps on a mobile device and these steps are not natural, then by the time a user navigates from one view to another they may lose something of the sense of the initial view in the process of the interaction. For example, in the process of navigating from an overview to a detail view the user may lose their comprehension of the overview. This could also be problematic when comparing elements in different views or relating between different views that contain the same element. Both of these operations are relatively simple using juxtaposed coordinated views [Roberts 2007; Craig and Kennedy 2003] but these have the disadvantage of reducing the screen-space for individual views and so are largely impractical for smaller mobile displays. A strategy to partially resolve this problem is to use animation to smooth the transition between views and carefully plan how users can navigate between views with the minimum disruption to their natural interaction with the data.

Configuring the layout of individual views is also important. If we consider how HTML renderers scale web-pages by keeping certain elements such as the size of the text fixed and scaling all other elements to fit these restrictions within the limited display space, we can apply a similar logic to the scaling of information visualisation interfaces. Items with a fixed minimum size for any given device are text (which has to be readable) and the target area for selections. Other variables that need to fit around these are the number of elements or aggregates displayed on the screen and the amount of detail. If the information the user wants cannot be displayed on a given screen they need to be able click on an aggregate to zoom-in to the visualisation. So, a mobile view will typically have a greater degree of data aggregation in order to display more elements effectively on a smaller screen, it will also include less detail, and it will rely more on user interaction with more active exploration of the data.

Another important consideration for the design of mobile interfaces should be the physical context in which an interface is likely to be used. When designing desktop PC interfaces we can presume that the user is able to operate the mouse and keyboard comfortably with both hands throughout the duration of their interaction. This isn't the case for mobile device usage, where users can be on-board public transport, driving, cycling or using their hands for other things like carrying bags or holding children. This means that users often have to operate their devices with one hand and interaction can be sporadic or distracted. The implication for interface design is that we need to carefully consider the physical context of use and adapt interfaces appropriately to fit the way a user is likely to use them. This would mean that certain applications should be designed to minimize essential interaction or be operable with one hand and others should be able to communicate information at a glance. Observing one handed smartphone use showed us that in order to account for one-handed mobile use we need to cater for users who tend to operate their phone oriented lengthwise by cradling it in the palm of their writing hand while tapping the screen or dragging with their thumb.

3 Mobile Information Design Guidelines

The design considerations relating to the limitations of mobile devices and how we tend to use mobile devices, as described in the previous section, can be digested and summarized as a draft set of guidelines for mobile information visualisation interface design as follows:

1. **Be aware of the situations in which the application is likely to be used and adapt the interface accordingly for sporadic, hands-free or one handed use.** Sporadic use means that the screen should efficiently communicate essential information and interaction should be short. Hands-free means that the user cannot directly interact with the device and one-handed interaction has the phone cradled in the palm with tapping and dragging across a smaller area of the screen using the thumb.

2. **Use techniques that make more efficient use of available screen space or do not require accurate selections.** Techniques such as excentric labelling [Fekete and Plaisant 1999] and space filling layouts [Stasko et al. 1999; Craig and Kennedy 2008] fulfil this criteria. Interaction is less accurate on a mobile display so we shouldn't rely on any degree of accuracy for the user to select objects.

3. **Keep text and selection targets above a constant device-specific minimum size and scale other elements to fit these constraints.** Text should be readable and the user should be able to make selections using appropriately sized selection targets.

4. **Don't display too much information on the screen at the same time.** Data should be aggregated or split over multiple screens to avoid saturation of the limited screen space. The user can interact with the interface to view more data over time with animation used to smooth the transition between views.

5. **Use virtual buttons to switch between different types of selection.** There is no natural equivalent to the differentiation between an mouse drag and a mouse hover on a touch screen so it is better to use virtual buttons and the toolbox metaphor to allow the user to user to choose between different types of selection. Virtual buttons can also be used as an equivalent for keyboard shortcuts.

6. **Don't allow important information to be hidden by the user's finger during interaction.** Information that is revealed by brushing should be positioned away from the point of contact or remain visible after the user releases their finger.

4 Case Studies

In order to test our guidelines for mobile information visualisation we developed three prototype applications as case studies. These were a coordinated map and timeline view for geo-temporal data, a distorted scatterplot, and a space filling hierarchy view for exploring hierarchical data. Each of these represents a reasonably challenging data-set from a visualisation perspective with over three hundred events in the first data set, just under two-hundred points in the second, and around a hundred nodes in the third. User objectives are to browse the data, explore, gain an overview, find patterns, look at outliers and detect correlations between variables.

Our coordinated map and timeline view for geo-temporal data (see figure 1) is adapted from an original desktop application [Craig et al. 2014]. This clusters events across time and space and allows users to select cluster outlines to drill down into the data. The mobile version of the application has a reduced number of clusters and visible labels, and moves the animated map and timeline onto different screens to save space. The cluster outlines in the map and timeline are enlarged to provide enough space for inaccurate touch-screen selections. Selecting clusters to filter and drill-down into the data allows the user to view more of the data over time. When clusters are selected in either the map or timeline, the transition to a new re-clustered view is animated by sliding elements gradually into their new position as the geographical or temporal focus of the visualisation is shifted.

Our second case study is a scatterplot for exploring multi-dimensional or bi-variate data (see figure 2). Here buttons on the left-hand-side can be used to switch between excentric labelling [Fekete and Plaisant 1999] and box selection modes or move to the details view on another screen. Excentric labelling can be used to label all the elements in a given area with the labels moved away

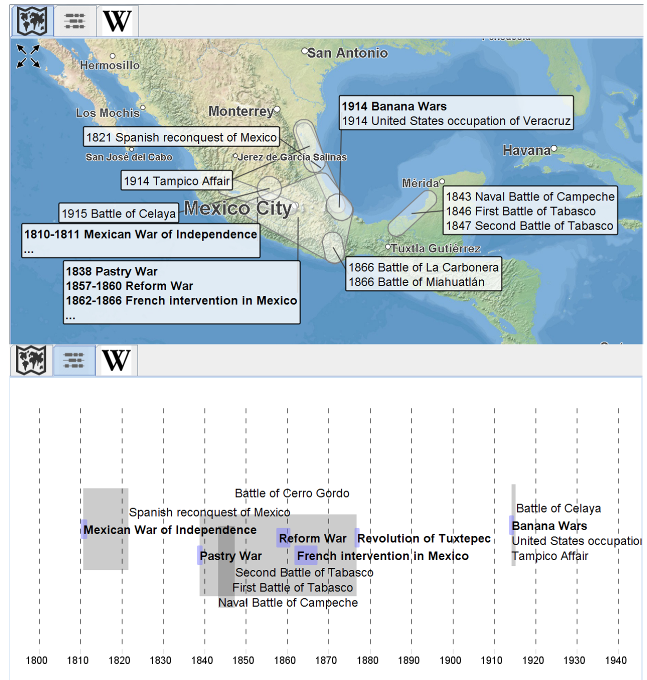

Figure 1: *History-explorer coordinated animated map and timeline views for geo-temporal event data.*

from under the user's finger. Distortion is based on the distribution of data about the x and y axes. This can be applied using the slider on the right-hand-side and makes it easier to view patterns of correlation and select smaller groups of items when outliers would normally push the body of the data into a small area of the plot. Distortion is variable so the user can move between undistorted and distorted views. While undistorted views are better for viewing outliers, distorted views improve our view of data with similar values. As the slider is moved, and the level of distortion changes, the points gradually move to their new positions so as not to disorientate the user.

The third case study application allows users to navigate file folders containing music using an animated space filling hierarchy view [Craig and Kennedy 2008] (see figure 3). This visualisation prioritizes the display of nodes that are considered important for navigation (i.e. the selected node or nodes, selected node children and

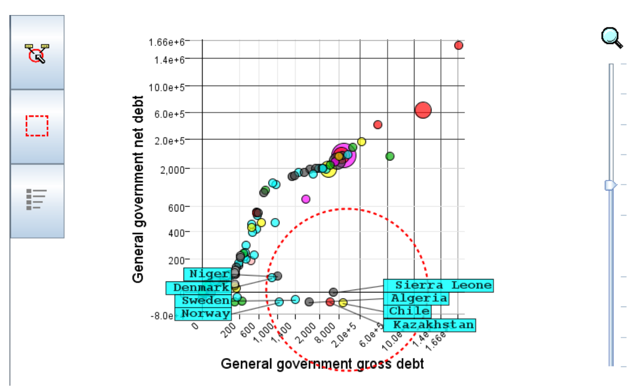

Figure 2: *Scatter-plot with variable distortion and excentric labelling.*

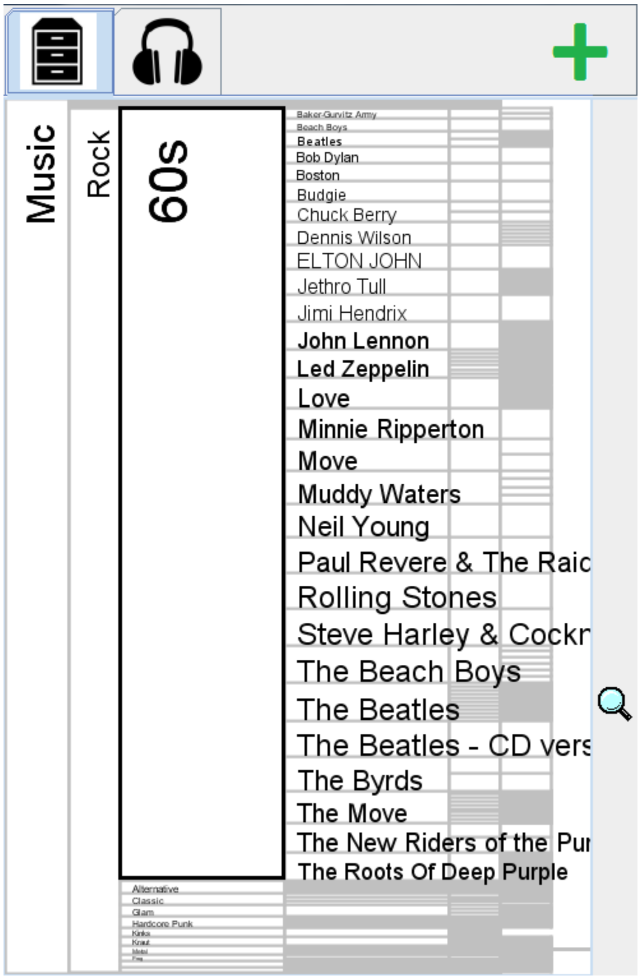

Figure 3: *Space filling hierarchy view.*

selected node ancestors) and uses animation to smooth the transition between views when the user presses on a node to change their selection. Unlike a standard tree view, all nodes are visible on the screen at the same time or at the very least have screen space assigned to them so they have a visible ancestor node. If there is not enough space to provide adequate height to all the nodes under the selected focus node(s), for either reading or selection, a fisheye distortion effect is used to magnify the labels closest to a movable magnifying glass icon. This icon is aligned at the right hand side of the screen so that the glass can be moved while the mobile device is held in the user's hand without obscuring important information in the display.

The advantages of this display over a standard Microsoft windows file-explorer style tree view are that more space is given to ancestor nodes making it easier to navigate up the hierarchy and it is possible to have two nodes from different parts of the hierarchy selected and on-screen at the same time to, for example, alternate between music from different artists or move files between folders.

5 Discussion

Each of our different mobile visualisation interfaces was developed by accounting for a different subset of the interface design guidelines stated in section three. For example, the last application can be used with a lengthwise layout suitable for one handed use while the first two applications have a sideways layout. In this case the benefits of having more horizontal space for text are judged outweigh any potential advantage of supporting one-handed use with a lengthwise layout. As part of a portable music player, the third application is more likely to be used on the move in situations where one hand is busy, so it's more important to account for one handed usage.

We can also reflect that, at least in some cases, individual design guidelines would appear to be in some conflict with each other. For example, the third interface could possibly be considered to break our rule of having too much information on the screen at the same time by showing all the nodes deemed important for navigation. In this case it is considered that interface will be used sporadically and that efficient navigation is more important than any reduction in display saturation that might be achieved by moving the information onto different screens.

This tailoring of design decisions and balancing of design guidelines reflects the essential nature of interface design as something of an art as well as a science. This is guided in equal part by theory, experience and user feedback. Nonetheless design guidelines form an important part in this equation and the guidelines developed in this paper were found to be a useful tool in the formulation of interface design, serving as both inspiration for and validation of design decisions. None of the rules set out were, or should be, broken or bent, without carefully consideration and the application of solid reasoning.

6 Conclusion

We have drafted a set of guidelines for the design of mobile information visualisation applications through an analysis of different forms of interaction and device limitations. We applied these guidelines to the design of three case study applications. These applications use visualisation techniques that can be applied with inaccurate touch-screen selection and, crucially, make the display more interactive to allow the user to view more of the data over time without saturating the limited display space. The additional cognitive load of having to interact more with the data and having less of the data shown at any one time is reduced by using animation to smooth the transition between successive views. These early results suggest that information visualisation on mobile devices can be more capable than we previously imagined and that interaction and animation will be a key part of the implementation of effective information visualisation interfaces for more challenging data-sets and more demanding user requirements.

References

AHLBERG, C., AND SHNEIDERMAN, B. 1994. Visual information seeking using the filmfinder. In *Conference companion on Human factors in computing systems*, ACM, 433–434.

BECKER, R. A., AND CLEVELAND, W. S. 1987. Brushing scatterplots. *Technometrics 29*, 2, 127–142.

CARD, S. K., ROBERTSON, G. G., AND MACKINLAY, J. D. 1991. The information visualizer, an information workspace. In *Proceedings of the SIGCHI Conference on Human factors in computing systems*, ACM, 181–186.

CARD, S. K., MACKINLAY, J. D., AND SHNEIDERMAN, B. 1999. *Readings in information visualization: using vision to think*. Morgan Kaufmann.

CHEN, C. P., AND ZHANG, C.-Y. 2014. Data-intensive applications, challenges, techniques and technologies: A survey on big data. *Information Sciences 275*, 314–347.

CHEN, M., MAO, S., AND LIU, Y. 2014. Big data: A survey. *Mobile Networks and Applications 19*, 2, 171–209.

CHITTARO, L. 2006. Visualizing information on mobile devices. *Computer 39*, 3, 40–45.

CRAIG, P., AND KENNEDY, J. 2003. Coordinated graph and scatter-plot views for the visual exploration of microarray time-series data. In *Information Visualization, 2003. INFOVIS 2003. IEEE Symposium on*, IEEE, 173–180.

CRAIG, P., AND KENNEDY, J. 2008. Concept relationship editor: A visual interface to support the assertion of synonymy relationships between taxonomic classifications. In *Electronic Imaging 2008*, International Society for Optics and Photonics, 680906–680906.

CRAIG, P., ROA SEILER, N., AND OLVERA CERVANTES, A. D. 2014. Animated geo-temporal clusters for exploratory search in event data document collections. In *Information Visualisation (IV), 2014 18th International Conference on*, IEEE, 157–163.

FEKETE, J.-D., AND PLAISANT, C. 1999. Excentric labeling: dynamic neighborhood labeling for data visualization. In *Proceedings of the SIGCHI conference on Human Factors in Computing Systems*, ACM, 512–519.

HARRISON, C. 2010. Appropriated interaction surfaces. *Computer*, 6, 86–89.

HOCHHEISER, H., AND SHNEIDERMAN, B. 1999. Understanding patterns of user visits to web sites: interactive starfield visualizations of www log data.

LEE, S., AND LEE, S. 2014. Early diffusion of smartphones in oecd and brics countries: An examination of the effects of platform competition and indirect network effects. *Telematics and Informatics 31*, 3, 345–355.

LEE, B., ISENBERG, P., RICHE, N. H., AND CARPENDALE, S. 2012. Beyond mouse and keyboard: Expanding design considerations for information visualization interactions. *Visualization and Computer Graphics, IEEE Transactions on 18*, 12, 2689–2698.

MARTIN, A. R., AND WARD, M. O. 1995. High dimensional brushing for interactive exploration of multivariate data. In *Proceedings of the 6th Conference on Visualization'95*, IEEE Computer Society, 271.

ROBERTS, J. C., RITSOS, P. D., BADAM, S. K., BRODBECK, D., KENNEDY, J., AND ELMQVIST, N. 2014. Visualization beyond the desktop–the next big thing. *Computer Graphics and Applications, IEEE 34*, 6, 26–34.

ROBERTS, J. C. 2007. State of the art: Coordinated & multiple views in exploratory visualization. In *Coordinated and Multiple Views in Exploratory Visualization, 2007. CMV'07. Fifth International Conference on*, IEEE, 61–71.

SALIM, S. S., ET AL. 2015. A systematic review of shared visualisation to achieve common ground. *Journal of Visual Languages & Computing 28*, 83–99.

SHNEIDERMAN, B. 1994. Dynamic queries for visual information seeking. *Software, IEEE 11*, 6, 70–77.

STASKO, J., GUZDIAL, M., AND MCDONALD, K. 1999. Evaluating space-filling visualizations for hierarchical structures. In *Proceedings of Late Breaking Hot Topics/IEEE Information Visualization Symposium*, 35–38.

SUN, Y., BIE, R., THOMAS, P., AND CHENG, X. 2014. Advances on data, information, and knowledge in the internet of things. *Personal and Ubiquitous Computing 18*, 8, 1793–1795.

WEBER, R. H., AND WEBER, R. 2010. *Internet of Things*. Springer.