

Developing visualization-based decision support tools for epidemiology

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Abstract

The paper describes the application of user-centred design (UCD) methods to a case study of the development of visual decision support tools to support epidemiological research. Understanding the causes of obesity requires analysis of complex medical surveys and geographic information. Translating research on obesity into effective public health measures requires collaboration between medical researchers and public health analysts. The objective of this research is to develop software tools to support medical researchers and public health analysts in collaborative investigation of obesity in children. The UCD approach consisted of scenario-based design, storyboarding and prototyping to explore design options to meet the needs of public health analysts and academic researchers. An evaluation of the prototype was carried out to assess the extent to which the medical researcher model would support public health professionals in their analysis activities. The design and evaluation of the prototype are discussed. A visualization-based research and decision-support system was implemented leading to positive evaluation results from users.

Keywords

Human factors, visualization, decision support, user-centred design, maps

Introduction

Background

This paper focuses on the experiences of applying user-centred design (UCD) methods to the ADVISES project, which is developing visualization tools to support public health decision-making based on epidemiological data. In order to encourage epidemiologists to make more use of visualization tools, the project focused on understanding how epidemiologists make decisions using maps¹ while exploring the statistical properties underlying the graphical representations.²

Funded by the UK e-Science programme, which aimed to create new and more powerful infrastructure and tools for scientific research and decision support,³ the objective of the ADVISES (ADaptive Visualization for E-Science) project was to develop collaborative systems for health informatics; specifically, to develop visualization tools to support public health

decision-making based on epidemiological data. In this paper, we describe a decision-support tool with a web browser user interface that makes use of web services, that is computational services on a remote host that provide a uniform resource locator (URL)-accessed application programming interface (API) via a protocol such as RESTful.⁴

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Obesity is rapidly becoming a dominant health concern in western countries.^{5–7} Effective intervention to reduce the inexorable rise in obesity requires epidemiological research to understand the causal factors behind the increase in this problem. Modelling epidemiology in the large to understand general causality needs to be coupled with analysis of local conditions, so targeted intervention can be planned by public health analysts and policy makers; consequently, solutions to the obesity problem involve collaborations between academic researchers in epidemiology, local health analysts, policy makers and clinicians.

Improvements in data collection by organizations such as the UK National Health Service (NHS) and open access to government-curated data resources are encouraging the use of ‘data-driven’ approaches in epidemiology; instead of forming hypotheses and then looking for confirmatory evidence, data are ‘mined’ for possible lines of enquiry.⁸ Epidemiologists are tackling ever more complex concepts of causality, often involving diverse sets of factors. Also, the availability of geocoded extracts of health records and health surveys is increasing. As spatial factors are related to many other determinants of health, there is a need for visualizations to help epidemiologists explore concepts and data fully, blending abstract reasoning with systematic statistical processing.

If it were to deliver usable tools, ADVISES had to satisfy the needs of two different user communities: academic epidemiologists interested in causal analysis from epidemiological data and public health analysts whose concern was local policy decisions. Furthermore, as one of the fundamental aims of e-science is to improve research practices, a thorough understanding of users’ requirements and their reaction to potential innovations was necessary. Consequently, we adapted UCD and requirements engineering techniques to investigate the users’ analytical process^{9,10} and to explore how new visualization tools might be used by academic epidemiologists as well as by public health professionals.

The paper addresses two inter-related themes: first, user-centred requirements analysis for distributed Internet-based applications in health informatics, with a design exploration process for functional specification in transformative applications, i.e. where no a priori vision of the desired application exists. The second theme assesses the effectiveness of applying and integrating interactive visualization techniques from the human–computer interface (HCI) literature into a practical application.

Related work

At first sight, geographic information system (GIS) tools may appear suitable for visualizations to support

epidemiological and public health research. There have been reports of the use of GIS tools within public health research and the potential of such visualizations to support epidemiological thinking¹¹; however, several challenges and concerns remain. A review of GIS use by public health practitioners¹² identified problems associated with accessing GIS tools, including expense and complexity, as well as technical problems such as software inaccuracies and difficulties in obtaining precise local geographic data. Other concerns have been data confidentiality and risks of misinterpretation.¹³ A survey of user requirements for geospatial analysis in healthcare demonstrated the need for geographically based analysis, but also that map-based representations needed to be integrated with other statistical analysis tools; furthermore, that commercial GIS applications did not address many requirements.¹⁴ Although GISs have contributed to epidemiology, for instance for the characterization of populations, study of communicable disease and development of models,¹⁵ the focus has been on descriptive rather than causal epidemiology. One of the few reports of developing tools for geospatial analysis is the Pennsylvania Cancer Atlas, which integrated maps with graphs and statistical analysis tools for epidemiological investigations of cancer.¹⁶ This application provided an interesting baseline for ADVISES development. User-centred approaches have been applied for developing multimedia health informatics applications,¹⁷ while websites to encourage weight loss and counteract obesity have used visualizations to persuade users.¹⁸

Interactive visualizations for health and medical applications have been developed over several years by Shneiderman¹⁹ and others²⁰ based on the alpha slider paradigm. This couples iterative querying of variable ranges by sliders with dynamically updated displays, so the effect of iterative, incremental querying is immediately apparent in the visualization. This concept has been applied to a large range of problems involving temporal data analysis in the lifelines visualizations²¹ including patients’ records. Interactive querying was augmented with functions to filter, align and rank displays in the Lifelines-2 visualization,²² which was evaluated with healthcare professionals to demonstrate effective support for discovering temporal patterns across multiple patient records. The Lifelines design has been developed with colour and shape–height coding to display trends in medical data over time.²³ Similar timeline representations have been used to display results from a restricted natural language query system for a patient health records application to enable the effect of updates and different types of information to be inspected,²⁴ although this system did not use the close coupling of dynamic queries and display updates. Visualizations to represent results of

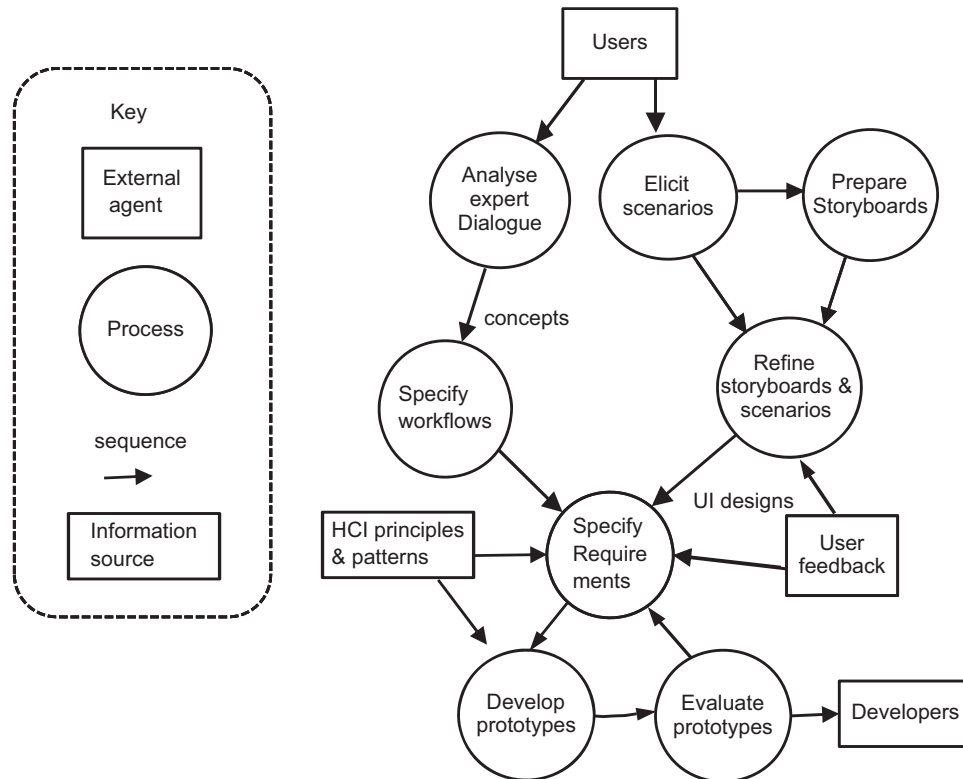


Figure 1. Scenario-based design process, illustrated as a data flow diagram to show the sequence of activities in the design process.

queries over several datasets have combined timeline-style displays with network representations, so relationships over several datasets can be discovered in biomedical databases.²⁵ These networked multiple displays, called semantic substrates by Shneiderman and Aris,²⁶ are based on an entity relationship model and encourage model-based comprehension of the visualization.

Method

User-centred design

We adapted scenario-based design²⁷ and user-centred requirements engineering,²⁸ both of which advocate the use of scenarios, storyboards and prototypes in iterative cycles of requirements elicitation, design exploration and user feedback to create the process. Scenario-based design (SBD) was chosen owing to the often volatile and complex requirements of e-science applications. As research practices often change as an investigation evolves, requirements can become moving targets, which is particularly true in the rapidly developing field of biohealth informatics. SBD is well suited to such circumstances because its iterative approach facilitates collaborative design exploration

between users and developers. The process is summarized in Figure 1.

Twenty-one participants were involved in the requirements exploration and evaluation session (8 male, 13 female); representing two user groups: eight academic epidemiologists and 13 public health analysts who worked for Primary Care Trusts (PCTs; local organizational units in the UK NHS, consisting of one or more hospitals and associated healthcare services including local doctors (general practitioners)). Only one of the epidemiologists had any previous GIS experience. Most of the public health analysts made use of maps produced by colleagues with GIS training but only one analyst regularly made use of GIS tools. A 'snowball' approach to recruitment of academic epidemiologists was used; initial participants were recruited via ADVISES team member contacts and each one was asked if he or she knew of other colleagues who might make use of geographical information in his or her work. Health analysts were contacted via a local public health analysts networking group.

Initial requirements elicitation involved only the academic users. Four unstructured interviews were conducted at the beginning of the project to gain background knowledge on working practices, user

preferences and domain norms. Interviews were conducted on site, allowing the epidemiologists to show us existing software they prefer to use, discuss their data management practices and allow us to view example datasets. Users were encouraged to talk aloud as they worked, prompted by questions from the analyst, to analyse workflows and the decision-making process in epidemiological research. These early interviews provided key insights into epidemiologists' attitudes, which influenced the project direction:

- An early exploratory interview discussed the software tools used to carry out epidemiological research. A question about image and graph creation software led to a discussion about epidemiologists' preference for numbers over images – they feel images can be ambiguous and open to interpretation, and prefer to see numbers in academic publications.
- Routine data collection and warehousing are becoming the norm within the NHS and Department of Health. The academic users had access to these data, and made use of them in hypothesis testing, but they were also interested in the idea of data-driven hypothesis generation and pattern identification.

The academic epidemiologists were observed carrying out their research and in five weekly progress meetings. These observations helped to gather background knowledge, as well as understanding epidemiological language, research questions and workflows. A key orientation to explore requirements as research questions was motivated by the Goals–Questions–Results method.²⁹ Research questions elicited from academic users were used to create scenarios and use cases that envisioned a new system to support analysis, e.g. 'What are the characteristics of the GP (General Practitioners)-registered population in North West England?' This scenario described how a user could explore a map of patients registered with PCTs in the North West, stratifying the population by location, gender and ethnicity. Scenarios were supplemented by analysis of the users' language in interviews and meetings to develop an ontology describing the key components of epidemiological maps. Development of this ontology also informed the design of the query interface.

Subsequently, interviews and workshops were held with both academic and health analyst users. Ten workshops were facilitated by the second author, seven with health analysts and three with academic users. A combination of scenarios, sketching and brainstorming was used in the first workshops to generate design ideas. Scenarios, based on initial interviews, were used

as 'idea seeds'. For example, one scenario contained data that were too sparse to produce a statistically sound map so the data had to be aggregated into larger units. Storyboard sketches were prepared for each scenario; however, these were presented only after users had been given the opportunity to sketch ideas themselves. In subsequent workshops more detailed storyboards and prototypes were presented, and discussed in 'walkthroughs' based on the scenarios. The analyst facilitated the walkthrough by explaining the operational sequence then requesting feedback and suggestions for improvements from the users.

Experience with user-centred design

Preliminary analysis with academic epidemiologists created requirements for a system that supported querying datasets, statistical analyses of differences between populations and trends over time, which produced displays of the retrieved results on maps and graphs with summaries of the statistical analyses. As the application had to serve two user communities, we investigated how the initial expert-orientated system might be used by analysts in the NHS, who had some appreciation of statistics but were not experts. The study aimed to find out how much of the functionality users were prepared to use if they did not have knowledge of the research-orientated workflows, familiar to the academic epidemiologists.

The preliminary design used in paper prototyping is illustrated in Figure 2 (more detail on the prototypes can be viewed at www.youtube.com/watch?v=8EfSM9KG3Dg). This prototype was used in scenario walkthrough sessions observing the users' behaviour while they followed scenarios to answer relatively complex, realistic questions. The users were health analysts with varying degrees of experience. The requirements storyboard walkthrough used several scenarios to assess health analyst users' reactions to the prototype and, inter alia, the academic users' mode of operation. Design of the scenarios was motivated by the need to encourage the users to explore functional requirements as well as investigating their domain-specific practices and workflows. For example, one scenario contained data that were too sparse to produce a statistically sound map so the data had to be aggregated into larger units. Another scenario asked users to interpret population densities in map regions according to the colour coding, in order to test awareness of the danger of drawing inferences from small samples. Areas that showed high levels of diabetes had very small populations, making it impossible to confirm whether or not they were genuine hotspots.

The workshops provided a good opportunity for both groups of users to articulate their processes and

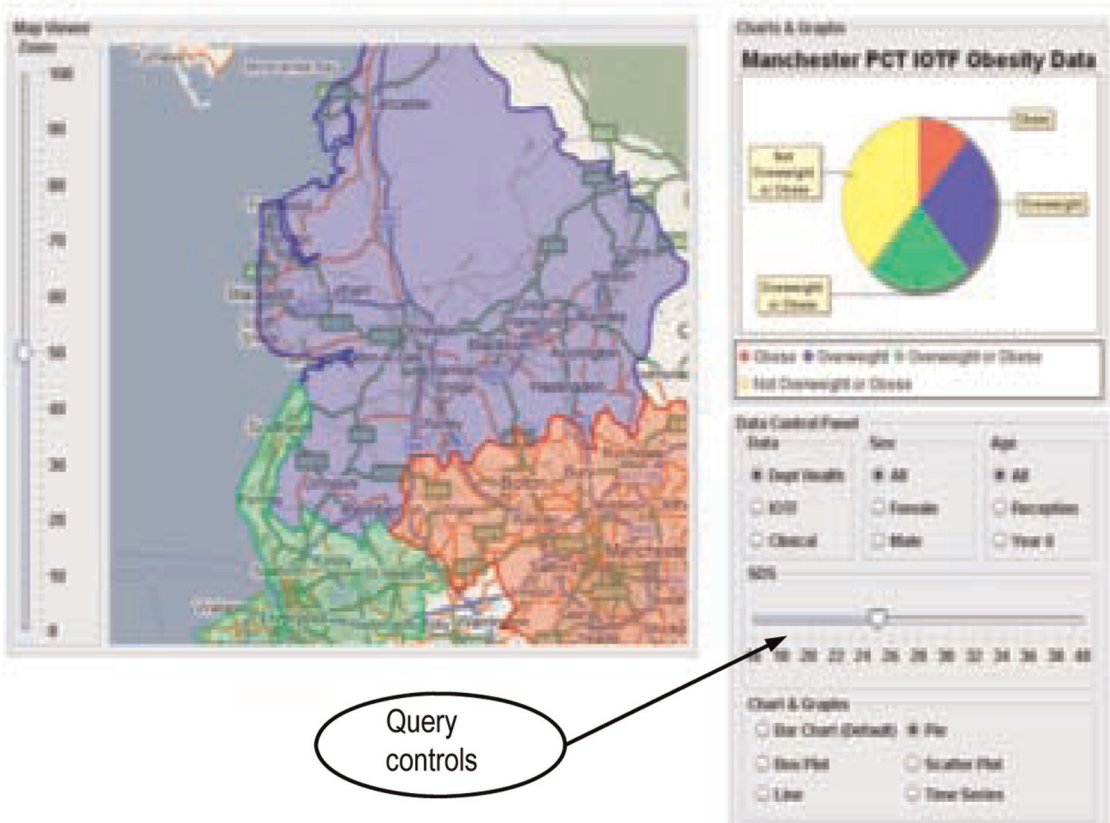
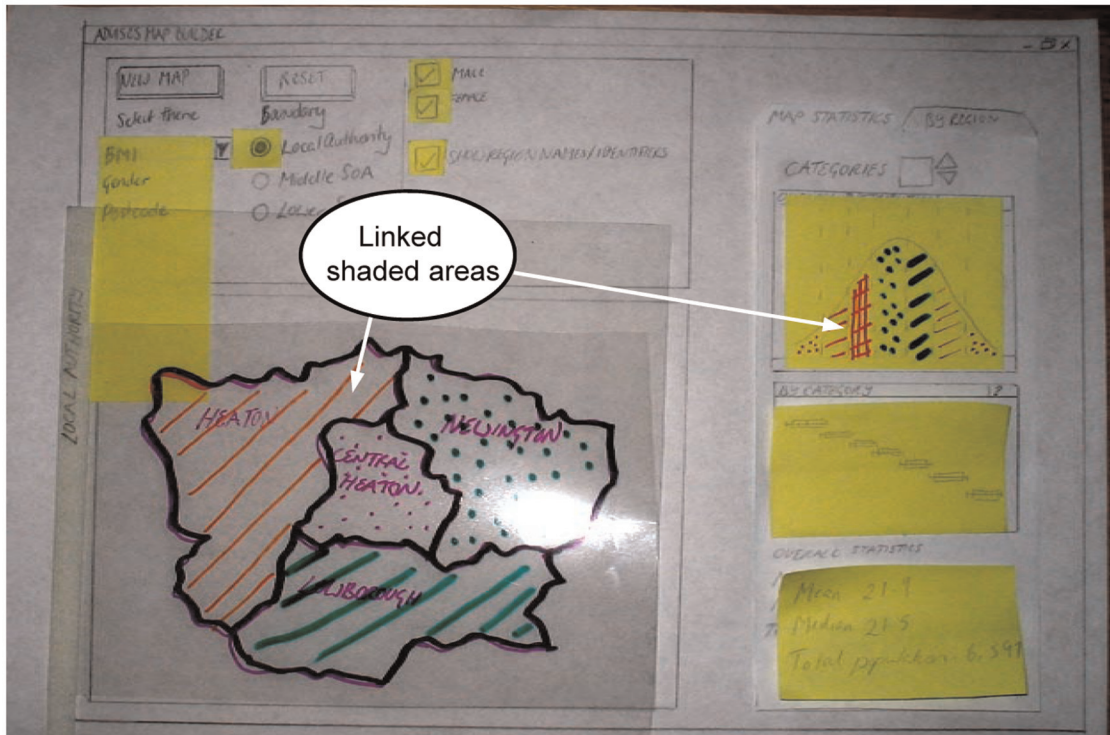


Figure 2. Upper panel: paper prototype illustrating a map of a fictitious city including an apparent hotspot indicated by shading the distribution; lower panel: later concept demonstrator prototype, illustrating scripted query–results display sequences.

abstract concepts, and provided data for both development of an ontology and understanding of tacit workflow processes, such as how the researchers make decisions about the reliability of a particular dataset. Scenarios facilitated exploring possible system designs as well as producing information on the users' tasks and workflow. Several design representations were used, ranging from simple storyboards or paper prototypes, through scripted concept demonstrators to functional prototypes. Scripted concept demonstrators illustrated pre-set operational sequences within the look and feel of the prototype, although they were implemented as PowerPoint animations or in Macromedia Director. Prototypes were implemented in Microsoft Studio with Visual Basic. The various prototypes were used in combination with scenarios in task walkthroughs to explore how the software tool might support the steps in the user's work.

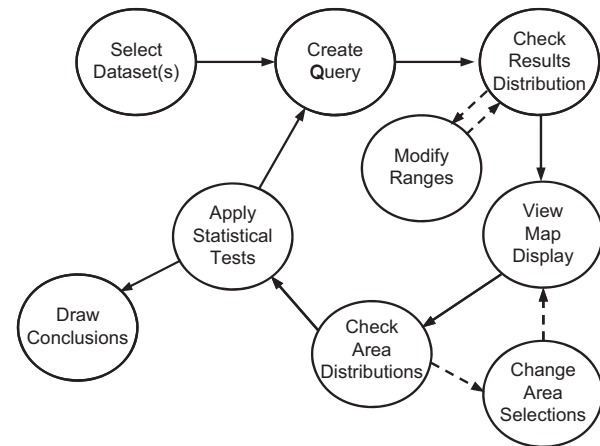
The users approved of the basic design concepts: multi-panel displays, query sliders coupled to dynamically updated displays and a high-level research question interface, rather than SQL-style queries. New requirements emerged for comparison between areas using two maps as well as complex association questions between two or more variables, e.g. 'What is the link between asthma and obesity?' The health analysts used local geographic knowledge when interpreting maps and requested support for understanding the implications of local geography, for example adding overlays of the street network or adding point locations of schools or hospitals. However, these users' actions did show potential errors in walkthroughs with expertise-probing scenarios. For example, the majority of users did not notice the data density problem associated with coloured regions; furthermore, only one user explored different boundary levels in order to examine the hotspot apparent on the map.

The requirements analysis with academic epidemiologists and the investigations with health analysts were summarized in two workflows to reflect their respective practices (see Figure 3).

Academic users progressed through cycles of checking and validation tasks to satisfy themselves that the patterns on map displays and accompanying statistical analysis would support valid conclusions, rather than being misled by hotspots in small areas, or by inappropriate and sparse distributions. In contrast, health analysts had a much simpler workflow focused on inspection of results displayed on maps with limited use of statistical tests. They did not appear to be concerned with such validation steps; instead, they were more interested in exploring the implications of visible patterns on the map display.

In summary, the results of the evaluation study pointed to three main conclusions:

Academic Epidemiologist Workflow



Health Analyst Workflow

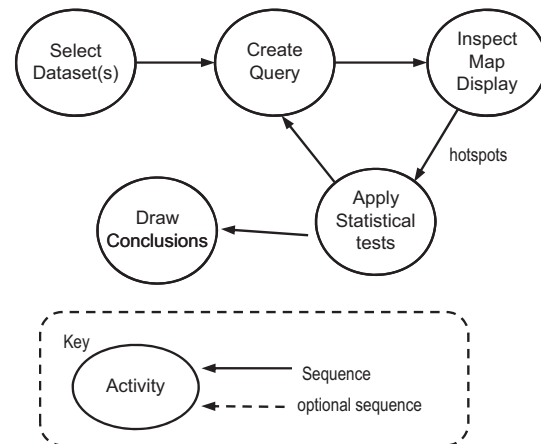


Figure 3. Academic user and health analyst workflows, illustrated as data flow diagrams to show major activities organized in a workflow sequence.

- (i) Health analysts adopted different workflows from the academic epidemiologists. This reflects different research questions; for example, academic epidemiologists are interested in finding general trends and causal influences between several variables, whereas the health analysts requested simpler, location-based questions reflecting their concerns with local health issues.
- (ii) Use of the statistics was often incomplete and sometimes even incorrect, depending on the level of statistical expertise. In particular, some health analyst users exhibited a 'confirmation bias', employing statistics that confirm rather than contradict their hypotheses. Some participants did not engage in data analysis, assuming that the system would 'know best'. As a result they could misinterpret data and draw incorrect conclusions (rationale gap).

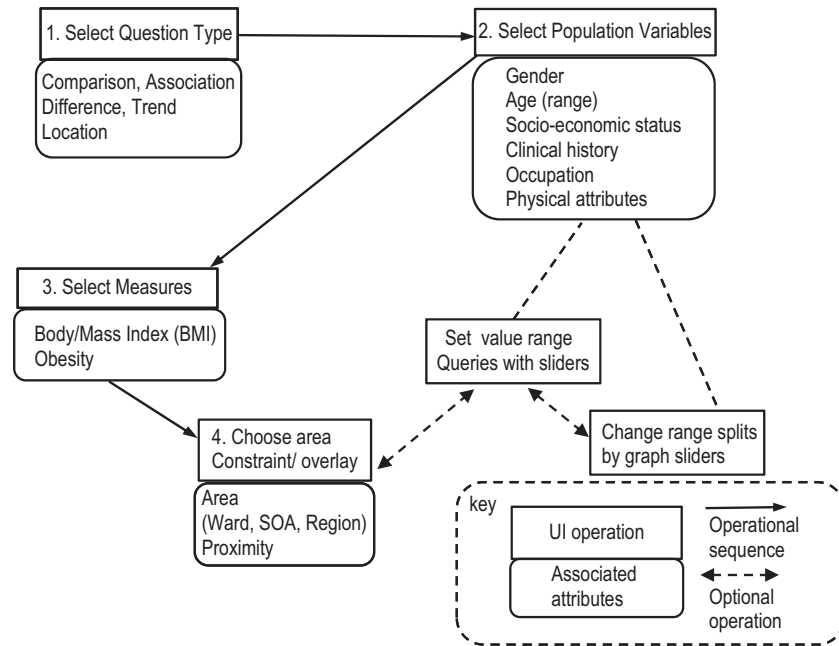


Figure 4. Query interface operational sequence. The sequence of user operations is shown by arrows with dotted arcs representing optional iterations in the sequence.

(iii) There was a need for more local geographical detail so that the health analysts could exploit their detailed local knowledge to interpret patterns apparent on the maps. For example, they were interested in plotting the locations of particular services or amenities to see if these related to the occurrence or outcome of diseases.

A statistics advisor component assisted health analysts to query, evaluate and explore datasets, while a visualization expert component encoded the value ranges on map and graph displays to optimize pattern analysis. These advisors were motivated by the requirement to caution against unsafe inferences being drawn from sparse or awkwardly distributed data in map displays, and to save the users effort in choosing visual display coding. To bridge the rationale gap, we yoked the research questions and workflows to pre-set configurations of displays. This design was also motivated by the display combination pattern, so users could view concurrent juxtaposed visualizations of maps and graphs, to encourage comprehension of the underlying data models.

User interface design and implementation

The workflows from the two user communities posed problems in how to allocate somewhat different sets of the requirements to each user community. Producing

two versions of ADVISES would lead to maintenance concerns and incur the additional expense of duplicating software processes. The solution adopted was to develop a layered architecture with a core functionality targeted at the health analyst users, with an outer layer of functionality for the academic users who required additional statistical analysis. Exposure of the functions was controlled by menu configuration on the user interface.

Users form queries as high-level question types. Then, queries are elaborated by selecting one or more subject populations from the available datasets with variables such as age, gender, socio-demographics, lifestyle and medical history followed by the desired measures, which are usually body mass index (BMI) and other obesity metrics. Queries are organized in menu-picking lists (see Figure 4), which can be combined with query-by-pointing to map areas and use of sliders to set value ranges; hence queries can be composed flexibly and iteratively. The location questions are elaborated with specializations to create display overlays that support the health analysts' desires to investigate local implications of hotspots, such as proximity to doctors' surgeries, hospitals and schools.

All queries can be constrained by map areas, and overlays selected for additional spatial data, e.g. point location of health centres or sports facilities. Query range sliders become active once the population and measures variables are selected (e.g. for age, the BMI

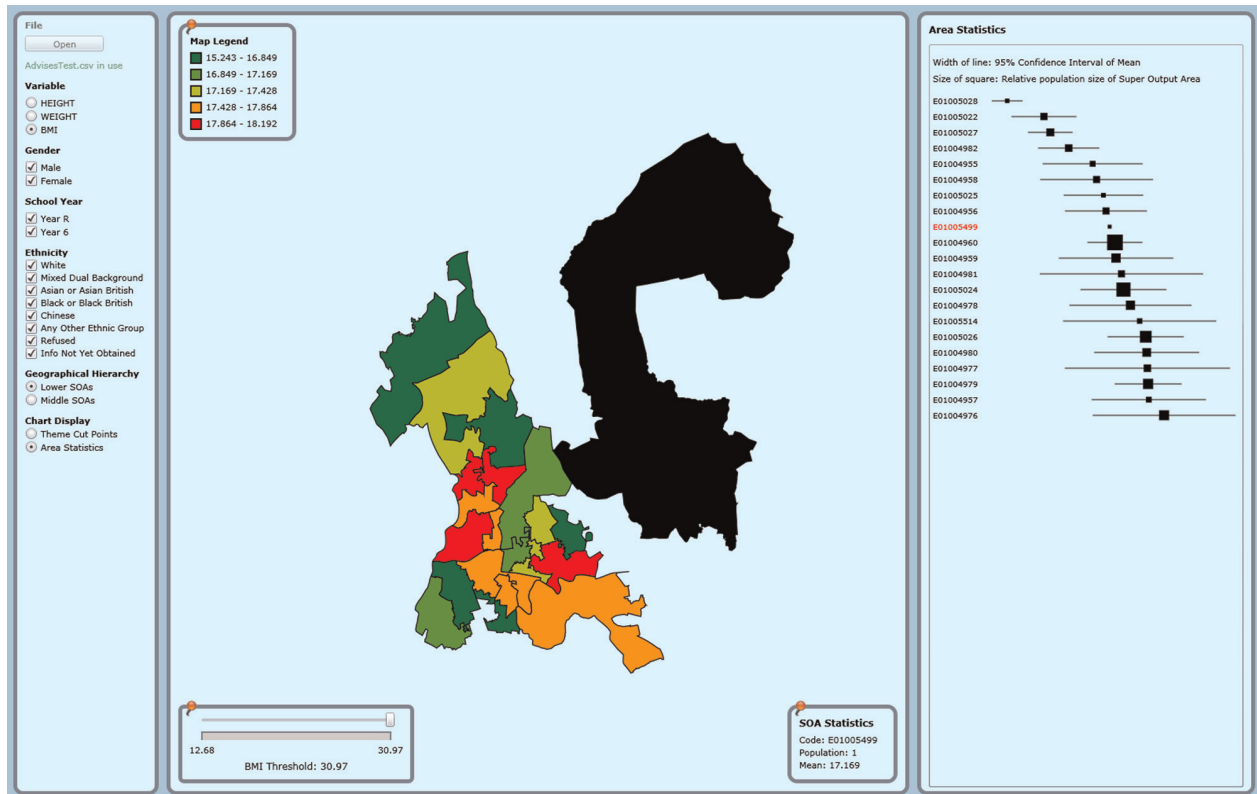


Figure 5. Prototype user interface showing the map–chart display combination for the ‘check area density’ task (For more detail see video demonstration at www.youtube.com/watch?v=RpMLGmQtRs4).

range). The display for the ‘check area density’ task in the current prototype is illustrated in Figure 5.

The multi-panel display affords rapid data inspection and exploration of epidemiology datasets, while colour and patterns in the charts indicate sparse and non-normal distributions when statistics analyses and other inferences may be invalid. Incremental analysis is supported by sliders for value-range queries, so analysts can carry out sensitivity analysis by changing range values, e.g. inspect obesity by area by age.

Range category histograms and descriptive statistics support the ‘check the data distribution’ task. Users can inspect the shape of the distribution and use skew and kurtosis metrics to check symmetry and normality. They can segment a continuous distribution into discrete categories (e.g. extreme, high, medium or low BMI) using sliders to subdivide the range. This enables sensitivity analysis of range-category subdivisions to ensure that, for instance, distribution tails have sufficient data points for valid statistical analysis.

Box-and-whisker plots³⁰ are coupled to the map displays so the boxes represent distributions (means, confidence intervals) within map subareas. These plots support the ‘check area distributions’ task; for

example, long and thin or short and fat boxes indicate sparse distributions with high standard deviations (long and thin) or high kurtosis (short and fat). The graphs and maps are coordinated and queryable surfaces, so users can point and click on subareas of the map to express a location query. The multi-panel display affords rapid data inspection and exploration of epidemiology datasets, while patterns in the charts indicate sparse and non-normal distributions when statistical analyses and other inferences may be invalid.

Statistics advisor

The aim of the statistics advisor is to warn health analyst users about sparse distributions where false inferences may be drawn from low numbers. However, there are occasions when looking at low numbers is unavoidable, for example when investigating a rare disease, so the advisors are configurable and can be turned off under user control. Some advice is given passively by highlighting areas in the presentations that warrant attention, with pop-ups to explain why attention is needed.

A monitor alert function compares map area populations and densities (populations/area) and

distribution statistics (standard deviation, skew, kurtosis) to alert the user when any of these values exceeds a pre-set threshold. The figure or map area is highlighted to warn the user. A pop-up containing the threshold value appears when the user's mouse is placed over the figure/area. The alert reminds the user about properties of the underlying data distribution, and thus contributes to closing the rationale gap. As the validity of distribution depends on the nature of the dataset, the alert function is configurable so the rules can be edited to deal with general health (normal datasets) or rare events (disease epidemiology: non-normal datasets).

Visualization advisor

Design of the visualization advisor was motivated by the requirement to display more than one variable on a map. Visual coding requires psychological knowledge; however, the knowledge can be formalized so the expert advisor module automatically codes the range categories on the maps and graphs. Complex research questions may involve two or three variables, e.g. 'What is the distribution of type II diabetes and obesity for different levels of socio-economic deprivation in different areas of the North West health region?' This association-location question implies visualization of the average density of diabetes patients and overweight people in each health district. Assuming range-category subdivisions by quintiles, the visual coding has to represent 5×3 coding combinations in any one area.

HCI knowledge from the visualization literature^{20,31,32} was applied to specification of an automated visualization coding function. Shape and size was ruled out as this attribute was constrained by the map areas, e.g. different line sizes are not reliably discriminated and common area boundaries made this solution unworkable. Three-dimensional encoding (e.g. histogram bars on map areas) was avoided because of the occlusion problem, leaving colour and texture. Advice on colour coding favoured a single colour saturation scale rather than rainbow spectrum codes.³² Guidance on texture coding was not so specific, so we decided to use single texture density gradients (e.g. dot stipples, bar density) rather than several different textures, to avoid imposing a learning burden on users.³³ Two variables could be represented on one area, one by colour and the other by texture. As some colour-texture combinations produced discriminability problems, ends of the ranges could not be used; however, this still left sufficient encodings to represent five or six range categories for each variable (see Figure 6).

The visualization expert inspects metadata associated with the dataset to determine whether the

variable has a continuous distribution, is discrete or is an enumerated set. This indicates the number of categories for each variable, so in the case of continuous distributions a default quintile range split is assumed. The visualization expert automatically selects the codings, favouring colour if only one variable is displayed. When small map areas are present, a warning is given that discrimination of categories in small areas may not be reliable, as the texture gradients will not be easy to discriminate. Other elements of the design include an annotation tagger, which enables users to label and save results displays.

Implementation

The system was implemented in C# using MS Silverlight for graphics and animating map displays for trend questions so that successive displays gradually morphed into each other to enable users to see the trend change over time within different map areas. A distributed architecture was adopted and developed as a set of web services, with major class packages in the following functional areas:

- *Dataset access*: loads datasets from remote servers.
- *Map display*: loads shape files from the UK land registry server and displays maps using MS Charting libraries. Map displays can be overlaid so point data (e.g. location of health clinics, sports facilities) can be displayed at appropriate locations.
- *Charts and statistics display*: runs basic statistical analysis scripts (R script calls) then displays range split histograms, box-and-whisker plots, etc., using MS Charting.
- *Dialogue management*: handles the query interface, interactive query-by-pointing and sliders.
- *Expert advisor*: classes that implement the statistics and visualization experts, with dataset monitors to trigger advice.

Map shape files, databases, query handling and statistical analysis components were remote services; other components were client resident. However, it is worth noting that several functions were not implemented, in particular a set of configuration editors that would have made the ADVISES system into a portable, flexible toolset that could be configured for different domains to support other scientific data-driven research requiring visualization, e.g. population dynamics researchers.

Evaluation: prototypes and process

The prototype was subject to three cycles of evaluation after the requirements exploration-design phase.

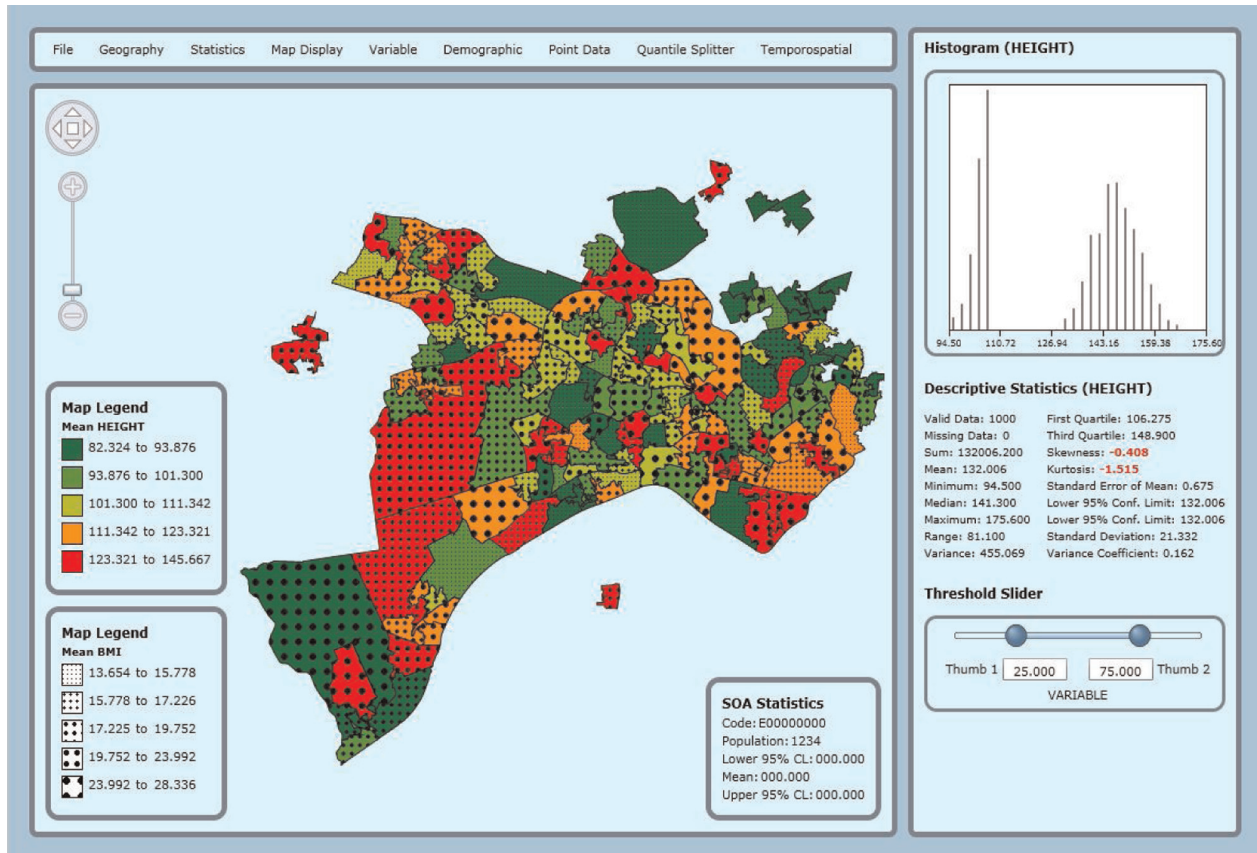


Figure 6. Visual encoding using red–green colour saturation and texture gradients.

Round one was formative for usability debugging and design improvement while the second round was more summative in nature and captured users' attitudes and satisfaction ratings for the prototype. In both rounds, users completed a representative set of tasks that enabled assessment of system performance. These tasks were to perform queries on epidemiology datasets, display the results on maps and graphs then compare the geographic distribution of obesity in several healthcare areas. The latter task involved further interactive query–display cycles using the sliders to perform a sensitivity analysis.

During each round of the evaluation, all participants (eight users: two academic epidemiologists and six health analysts) quickly and confidently created their first map and, without being asked to do so, went on to explore the map, looking at trends, subdividing data into smaller categories (e.g. males and females), switching between geographic boundaries, and then reviewing the associated statistics to help them understand the significance (or otherwise) of observed patterns. The users' comments were coded as positive and negative and categorized as impressions, usability

and attitude to future use, as illustrated in Table 1. The comments were very positive in both evaluations, although the total net positive comments were similar in both rounds. One reason for this was that users made different, new negative comments in round two after the problems perceived in round one had been fixed.

Participants found the combination of geographic visualization and descriptive statistics powerful and easy to explore:

I love stuff like this; it's nice having the descriptive stats, when you put data into [commercial GIS package] it can be misleading.

(Health analyst 3)

It's really easy to figure out; it's at your fingertips.

(Health analyst 4)

After working through the set of tasks, users were asked about their experiences with the system. The majority felt that their experiences were positive, but some users felt that, although they had successfully created a map, the system was not welcoming:

Table 1. Summary of participants' responses.

	Round one responses		Round two responses	
	Positive	Negative	Positive	Negative
First impressions of the system?	5	3	6	2
System easy to understand?	7	1	7	1
Enjoy using the system?	8	0	8	1
Would you use the system in your job?	7	1	5 (2 possibly)	1
Total net positive comments	22		23	

Interviews were transcribed and the participants' answers coded as positive, negative or neutral. Total net positive comments were calculated by summing all positive comments, subtracting negative comments, and scoring 'possible' as 0.5 positive.

Table 2. Users' rating of system qualities in the final (round three) evaluation, where 1 = very poor and 7 = ideal.

Question	Average rating
Overall terrible/wonderful	6
Difficult/easy to understand	5.7
Frustrating/satisfying to use	5.5
Dull/stimulating	6.5
Rigid/flexible	5.5
Difficult/easy to navigate	6

It's very blank and a bit unfriendly looking. Once the data is in it looks much better.

(Health analyst 1)

It's not clear where to start; there should be a big 'start here' sign.

(Health analyst 3)

These comments led to additional design changes that were tested in the final prototype. The initial map design was evaluated, and the mixed reaction to the redesign led to additional changes, which were tested in the final round of evaluation. Thus, each round of the evaluation directly influenced the next iteration of design and development.

In the final evaluation (four users: two health analysts, two academic users) all tasks were completed successfully apart from minor difficulties in viewing statistics and adding point data on maps. The users' rating of the system on a range of qualities was highly positive; see Table 2.

Comments were also positive apart from some difficulties relating to features added after round two (point data on maps) such as controls for turning the display of leisure facilities on and off, although users liked the effect:

It's useful, I'd use schools. I'd like bus routes too.

It'd be useful to use this to look at hospital provision.

(Health analyst 3, 6)

Other comments were positive with suggestions for further improvements, demonstrating that development needs to be a continuous process:

I enjoyed using the system; it's useful, but it needs titles.

I like having two maps side by side, the two colours and dots, it's OK, but a bit crazy, like crazy ladybirds.

I'd like to be able to hide the descriptive statistics so you can see the map bigger.

I could use this in my job, but it'd be more useful if I could export the map as a jpeg. The map and legends, and the forest plot.

(Health analyst 2, 4, 5, 6)

The current state of ADVISES is that roll-out of the product version is currently under way in a programme managed by Northwest e-Health funded by the North West Development Agency to promote collaboration between the University of Manchester and NHS Trusts in the North West of England. This initiative provides evidence that our approach to user engagement is appropriate, as our users are prepared to sponsor the final development of the prototype; this involves re-engineering some of the code to increase robustness and reliability as well as implementing the code in the users' software environment.

Of the techniques we employed, the combination of storyboards, scenarios and prototypes integrated in a UCD cycle was the key to user engagement. Visualization of realistic design enables users to critique and contribute ideas in their own terms without having to understand software engineering notations. Our experience has been that even simple notations such as use cases present a barrier to understanding; furthermore, abstract models are less meaningful for users. The second reflection is the importance of conversation and dialogue, especially when it is anchored in the user's domain and language. Talking through and demonstrating working practices are important motivators for end users. In workshops, conversations have the added advantage that users outnumber software professionals,

and hence have more chance to ‘own’ the dialogue and thus direct it towards their own goals.

Discussion

The contribution of ADVISES visualization design has been to explore multiple concurrent views of maps and graphs to provide flexible support for both health analysts and academic epidemiologists. Multiple displays enable different users to scan the maps and graphs according to their needs, and hence different workflows can be accommodated without changing the display. Linking research questions to display templates supports the users’ workflow more directly, by providing all the necessary information related to the question and users’ analysis tasks. Although concurrent multi-panel displays may appear to increase complexity, none of our users complained about the displays being too complex. While multiple concurrent visualizations are provided by GIS systems and commercial products which have evolved from Shneiderman’s research,^{19,34} our contribution has been to integrate dynamic querying with GIS as well as introducing high-level ‘questions’ interfaces. The design has adapted design concepts in the Lifelines visualizations,^{21,35} and extended interactive visualization for spatial as well as temporal data analysis. Map visualizations with colour-coded maps and inter-variable relational links similar to those of Shneiderman and Aris²⁶ have been developed for cancer research,³⁶ although this application did not implement dynamic querying and colour coding was manual rather than automated as in ADVISES.

Although the elements (graphics, maps, query sliders) of the ADVISES interface in isolation were not new, their integration in a practical solution was. The success of ADVISES in migrating towards a product, sponsored by the NHS user organization, demonstrates the effectiveness of our approach. ADVISES shared many design features with the *Pennsylvania Cancer Atlas*: both systems have map displays, temporal animations and multiple graphical displays; although only ADVISES implemented sliders for dynamic ‘what if?’ queries, and expert advisors are a testament to its HCI design heritage. However, the *Cancer Atlas* did have a population pyramid graph for epidemiology analysis, which appears to be an omission from ADVISES. Bhowmick et al.¹⁶ report a set of design guidelines from their experience, including interactive queries and multiple displays. The convergence of the two systems may have been the consequence of a similar UCD process. The *Pennsylvania Cancer Atlas* team carried out three rounds of prototyping and evaluation, although they did not report using storyboards or scenarios.

The mix of designer-led initiative and responding to changes in user requirements worked well. The basic design paradigm of multiple displays and dynamically coupled queries and displays introduced research-inspired design into health informatics tools. These design concepts stimulated interest, and hence engagement, among the users. The expert advisor modules, which were a designer initiative in response to problems discovered during the requirements analysis, were not seen as an imposition by the users, as they might have been; for instance, the statistics advisor might be viewed as criticizing users’ judgement. We attribute user acceptance of these ideas to the process of engagement where the problems and proposed solutions were discussed openly with the users and illustrated in storyboards and prototypes so that the design implications were explicit. On the user-led requirements side, several aspects of the design arose directly from users’ suggestions: for example, the two maps comparative displays, changes to the forest plots, and functions for subdividing continuous distributions into range categories. Iterative UCD made the changes in response to users’ requests visible in a short time period, which was a positive motivation for engagement. Design, or more realistically emergent transformation of working practices, evolved throughout the process as users responded to presentations of the tools, and tools and tasks co-evolved during the project.

The design process we adopted was inspired by HCI patterns,³⁷ for example the multi-panel display affords quick visual scanning, while the alpha slider yoked query and display is a well-known design in the visualization community. Clearly many visualization patterns could be articulated from knowledge produced by the visualization research community,^{20,26,31,32,38} however, such knowledge does not appear to have been encapsulated in HCI patterns. One barrier may be the link between the problem context, usually expressed as tasks or scenario, and visualization design. One future area of work may be to generalize our experience by documenting concrete scenarios, more general queries intended to map to information search scenarios, and appropriate visualization designs as patterns. Generic task and visualization design frameworks^{39,40} could organize such patterns into a pattern language.

The visualization tools we produced are not as generic as automated visual user interface development tools; however, we believe the combination of high-level questions linked to appropriate display templates provided a generalizable approach to visualization design. Although the visualization design was not particularly novel, the high-level query interface with question types such as ‘trend’, ‘association’ and ‘difference’ was more innovative. Our implementation

linked to each question type with pre-set combinations of charts and maps, such as trend being linked to a series of maps for time-based queries. In future work we intend to adapt a more plan-based approach⁴¹ to dynamic configuration of visual displays linked to more flexible question types. Development of automatic visual coding of variables represents a modest advance in design of automated visualization tools, which could be extended to coding a wider range of data types. The visual coding using colour and texture has been explored by others,^{33,38} although texture was used to code separate categories rather than categories based on partitioning variable ranges. However, we believe that users should be able to maintain control over visualization design, so our approach has been to develop configurable tools rather than sophisticated layout planners.

The user-centred approach adopted in ADVISES shared iterative cycles of storyboards, prototyping and user evaluation with the web application for obesity management reported by Stevens et al.,¹⁸ who note the importance of using early prototypes to clarify design ideas, while acknowledging the importance of experts in contributing to system models. We also found that the expert role was essential to ensure a statistically correct analytic process. The combination of techniques in a user-centred approach combined with active user involvement also facilitated acceptance of new working practices, similar to the experience of Beuscart-Zephir et al.,¹⁷ in re-engineering workflows in a medication management application. We also concur with their findings that developers and human factors experts need in-depth understanding of the domain to realize effective process redesign.

Our users responded positively to their involvement in the design process; however, time was the main barrier to more in-depth participation. The academic users were busy but at least co-located in the university so arranging requirements analysis sessions was relatively easy. In contrast, access to the health analysts on various sites around Manchester was more difficult. The academic users were engaged in the design process more positively and articulated specific requirements, such as the need for a 'statistics advisor' function as well as design details concerning layout and format of graphical displays. Health analysts were less directly engaged and made fewer design suggestions, although they did contribute ideas for the map and graphical layouts. Generally, the health analysts preferred simpler user interfaces, whereas the academic users wanted more functions and complexity. On reflection, the lower levels of participation of the health analysts may have been due to lower frequencies of visits and meetings, although there may also have been a reaction to the design ownership being

perceived as being 'too academic'. In future we recommend targeting designs on specific users rather than trying to adopt a 'one size fits all' solution.

Our workshop-orientated approach, with a technique combination of storyboards, scenarios and prototypes, was successful; however, some key decisions, such as inclusion of the statistics advisor, reflected the interests of the academic users rather than the health analysts. Geographic and organizational separation of the two user groups led to a 'two-track' approach that militated against joint workshops and hence discussion to reconcile divergent stakeholder views. The user-centred approach shared iterative cycles of storyboards, prototyping and user evaluation with the web application for obesity management reported by Stevens et al.,¹⁸ who noted the importance of using early prototypes to clarify design ideas, while acknowledging the importance of experts in contributing to system models. We also found that the expert role was essential to ensure a statistically correct analytical process. The combination of techniques in a user-centred approach combined with active user involvement also facilitated acceptance of new working practices, similar to the experience of Beuscart-Zephir et al.¹⁷, in re-engineering workflows in a medication management application. We also concur with their findings that developers and human factors experts need in-depth understanding of the domain to realise effective process redesign.

The visualization design, while it satisfied the users, was not innovative and was disappointing for academic members of the design team who wanted to suggest more adventurous visualizations using three-dimensional and multiple-view design (e.g. refs 22, 23) and more complex query interfaces. More advanced visualizations were suggested and rapidly rejected by the academic epidemiologists, who had firm views that the visualization should be based on simple maps and charts. Although the designers were frustrated in their initial ambitions, the multi-panel, query slider prototypes were accepted as a considerable advance over the commercially available GIS packages with separate charts and maps. Our experience reflects the difficulty in transferring advanced visualization research into practice. One interpretation is that practical visualization design needs to be driven by thorough requirements analysis and user participation, as exemplified by our approach; an alternative interpretation is that advanced visualization design needs to be introduced incrementally as users learn to exploit the potential of more advanced designs. Our experience also demonstrates that innovation in visualization design may conflict with more conservative user preferences, raising an interesting question about how far designers should go in promoting their ideas on the one hand, or serving the interests of users on the other.

The vision of Internet-based e-health support tools we started with was tempered by the practical constraints of implementing distributed services; however, we contend it was better to have succeeded in delivering a more localized solution that was valued by stakeholders than a more ambitious, distributed solution that might have failed. Indeed, the track record of innovative solutions in e-science is uneven, with success in coordinated communities but failure in areas with divergent stakeholder interests.⁴² In our experience, investing in user engagement paid off in acceptance of a limited but effective solution, but scaling this approach to coordinate interests of multiple distributed stakeholders is difficult. A common shared interest may be the prerequisite for success of multi-party Internet collaborative e-science.

In future work we will extend the statistics advisor as a more proactive recommender system that suggests appropriate algorithms to complement statistical analysis; for example, in spatial representation of disease data when questions of proximity, gradient over space and density are important, smoothing algorithms can be applied to mitigate problems of uneven spatial distributions.⁴³ LifeLine visualizations^{21,35} will be integrated with maps for trend questions and we intend to explore the use of maps with semantic substrate visualizations²⁶ for more complicated associative queries and bridging the rationale gap. Contextual evaluations in users' workplaces will explore the fit of the ADVISES architecture with the working practices of diverse stakeholders to deliver effective support for health informatics. We also intend to make the ADVISES tools a shared e-science resource so the abilities and insights of both health analysts and academic researchers in epidemiology can be combined to investigate both country-wide and local perspectives on epidemiological problems. This will require implementing configuration editors so end users can customize the tools for different databases, query terminology and layout of different combinations of (map, charts, tables, etc.) displays. Integration of such configuration tools presents a considerable future challenge to realize an end-user scientific visualization toolkit.

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