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Human-Centered Approaches in Geovisualization Design: Investigating Multiple Methods Through a Long-Term Case Study
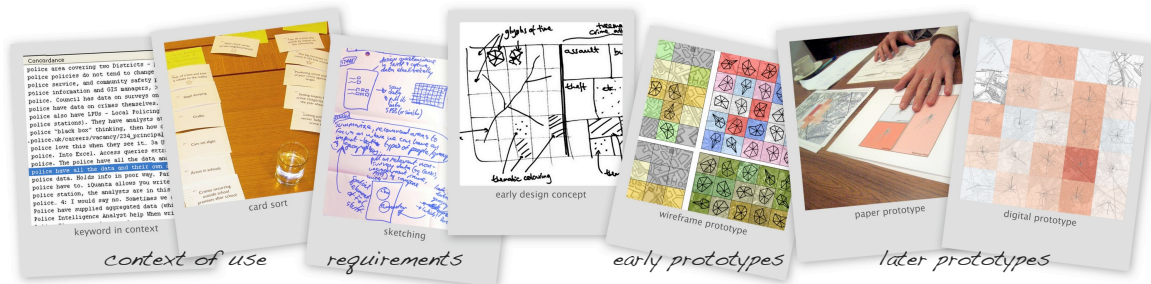
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Fig. 1. Graphical approaches used in a long-term investigation into using human-centred methods in geovisualization design include, from left: keyword in context; card sorting; requirements and design concept sketching; and wireframe, paper and digital prototypes.

Abstract—Working with three domain specialists we investigate human-centered approaches to geovisualization following an ISO13407 taxonomy covering context of use, requirements and early stages of design. Our case study, undertaken over three years, draws attention to repeating trends: that generic approaches fail to elicit adequate requirements for geovis application design; that the use of real data is key to understanding needs and possibilities; that trust and knowledge must be built and developed with collaborators. These processes take time but modified human-centred approaches can be effective. A scenario developed through contextual inquiry but supplemented with domain data and graphics is useful to geovis designers. Wireframe, paper and digital prototypes enable successful communication between specialist and geovis domains when incorporating real and interesting data, prompting exploratory behaviour and eliciting previously unconsidered requirements. Paper prototypes are particularly successful at eliciting suggestions, especially for novel visualization. Enabling specialists to explore their data freely with a digital prototype is as effective as using a structured task protocol and is easier to administer. Autoethnography has potential for framing the design process. We conclude that a common understanding of context of use, domain data and visualization possibilities are essential to successful geovis design and develop as this progresses. HC approaches can make a significant contribution here. However, *modified approaches*, applied with flexibility, are most promising. We advise early, collaborative engagement with data – through simple, transient visual artefacts supported by *data sketches* and existing designs – before moving to successively more sophisticated *data wireframes* and *data prototypes*.

Index Terms—Evaluation, geovisualization, context of use, requirements, field study, prototypes, sketching, design.

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1 INTRODUCTION

Visualization applications can present users with novel challenges: they aim at insight through exploration, have high complexity, multiple (usually interlinked) components and, in the case of geovisualization – *geovis* [17], a focus on spatial data with attendant issues of scale, spatial dependence and heterogeneity [2]. Exploration can involve tasks that are hard to define, broad in nature, time consuming and difficult to master – often with uncertain outcomes [45]. Visualization tools are various, complex and unfamiliar to most potential users, they present data in (often novel) ways designed to amplify cognition that can make significant cognitive demands on users. The diversity and complexity of different domains, of specialists' tasks and data, means no single solution fits all and compromise or customization are inevitable [16]. Generic visualization applications have their place and

are increasingly being formally evaluated, although such tests can be challenging or problematic [8, 20, 47]. But when customization or specific solutions are necessary, then the inevitable knowledge gap between designers and prospective users with domain expertise must be bridged [67]. A range of human-centered (HC) approaches can facilitate this process and provide '*grounding*' [26], but despite a convincing call to arms [62], limited progress has been made in determining those appropriate in a geovis context.

To address this knowledge gap, we evaluated a broad range of HC approaches '*in vivo*' by going through the initial HC processes to define a geovis application. We excluded summative evaluation, which has featured significantly in the visualization and geovis literature. Rather, we aimed to determine which HC approaches were applicable to the early stages of geovis design and how they might need to be tailored. Such approaches can only be studied *in vivo*, in the context of real prospective users of geovis, situated in their work environment. Our research was therefore conducted as part of an in-depth case study undertaken over a three-year period during which a variety of methods were evaluated in a number of contexts of use [36]. Three domain specialists – *specialists*, working in crime and disorder reduction in a leading UK local government organisation participated. These researchers were interested in using visualization to address the underutilization of potentially valuable large data sets – their current GIS and static data graphics packages were deemed inflexible and in-

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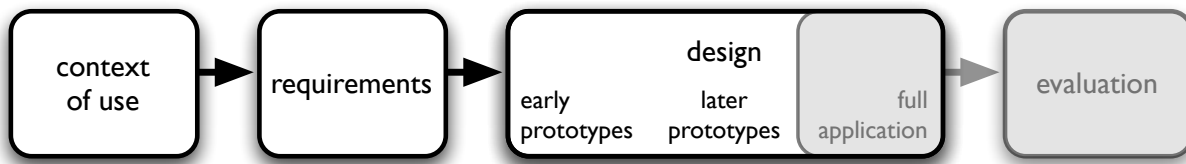
Fig. 2. Stages of the Human-Centered Design process described in ISO13407 [27]. Those addressed in our study are highlighted in white, with 'snapshots' of some of the graphical approaches investigated throughout the process shown by way of example in Fig. 1.

adequate for exploratory analytical activity. The domain and organizational contexts are likely to reflect the situation of a large number of similar cases. We interacted with these three specialists for several weeks during each stage of our research over the three year period. Mutual understanding was developed through this process as a long-term relationship developed. We used a number of methods structured as related case studies that linked together in a cohesive way by employing Gerring's design typology [22]. This methodological design [36] enabled comparisons to be made between HC approaches. Qualitative and quantitative analytical techniques were used to evaluate the effects of the methods, with findings triangulated where possible with evidence from multiple strands of inquiry to give us confidence in our results. This corresponds closely to the mixed-methods [24] approach.

ISO standard 13407 on human-centered design processes for interactive systems [27] identifies key activities as: *understanding context of use*; *determining requirements*; *producing designs*; and their *evaluation* (Fig. 2). The HC literature reveals an evolving repertoire of tools, approaches and nomenclature in support of ISO 13407 [41]. Historically, visualization practitioners have not adhered to any one HC school of thought and we too adopted a pragmatic approach, drawing upon common techniques that seemed plausible in the contexts of our cases. The majority of data we collected were qualitative in nature and analysis was carried out using audio transcription [6, 33], coding [34] and qualitative data analysis techniques [43]. These were underpinned by approaches for generating meaning and for testing and confirming findings [43]. The outputs from each stage of the ISO13407 process investigated provided input to later stages, in terms of the evolving development of a design, as our knowledge of the specialists' context and data grew and as we experienced and reflected upon how well successive HC approaches worked in a geovis situation. It is important to emphasise that the focus of our research is how HC approaches work in a geovis context, although inevitably we have gained insights into the processes of constructing a geovis application along the way that will prove to be of benefit to visualization researchers. We have reported aspects of our research in detail as it has progressed [37, 38, 39, 36]: this paper lacks some of that detail but represents a reflection upon the wider body of work in which we are able to draw higher-level conclusions by triangulating between experiences and the multiple cases involved in the long-term study and thus make broad recommendations that may be of use to others in geovis design and beyond.

2 UNDERSTANDING CONTEXT OF USE

We considered ethnographic field research methods and used Contextual Inquiry (CI) [5], with a range of data collection methods [48] such as interviews, observation, questionnaires and examining documents to understand specialists' context of use. We employed content analysis [31] techniques including calculating word frequencies, examining keywords-in-context [40], constructing networks of relationships between concepts and using card sorting [25, 44, 57] to study specialists' task categories identified through these approaches. CI is a pragmatic approach for researchers: Beyer and Holtzblatt describe the core premise as "*go where the customer works, observe the customer as he or she works, and talk to the customer about the work*" [5] and advocate a 'master-apprentice' model when working in the field. We found that this worked well in practice. The roles are assumed easily and useful information is gleaned on both sides. Enabling the domain specialist to assume a dominant role in a familiar context at the out-

set of a collaborative project can also be a useful device in terms of developing trust and confidence and team-building.

Interviews provided insights on specialists' skills, experience, tools, aims, inputs and outputs that would be of use to a visualization designer. Observation provides a less systematic approach to gathering contextual information, with a smaller coverage than interviews. It did however lead to avenues of inquiry and to insights that it is hard to imagine surfacing in an interview and it can lend additional weight to interview evidence. Studying internal documents was an effective way of learning about specialists' context without taking up their time. Studying external documentation, such as academic literature on the domain, provided corroboration of insights obtained from specialists and grounded their context to the domain generality.

One HC approach where the nature of geovis made a difference was card sorting. Using it to understand how specialists grouped plausible domain tasks enabled us to include spatial tasks next to others and see how they were categorised – to get a sense of the importance of the spatial components of information in the context of task. Cluster analysis made comparing different tasks possible, and including a geovis designer in a card sort yielded a quantitative benchmark against which to compare the specialists' categorisations. This provided a check on the designer's concept of the specialists' domain early on in the process, before specialists' requirements were explored, designs produced or code was cut and was useful in identifying disconnections between the specialists' and designer's views of the domain. Card sorting also identified clusters of tasks in the crime domain that we were able to use subsequently as focii for prototyping.

Word frequency counts from interview transcriptions yielded useful quantitative information, identifying dominant concepts. Keyword-in-context analysis is particularly valuable as it provides insight into specialists' motivations. Both techniques offer the potential for insight into subject context for visualization designers. In one example, a frequently occurring word – "*police*", led us to discover its use in a context that gave insight into the balance of power between the specialists and their major data provider (the local police force) and from there to the kinds of value-added analyses required to differentiate our specialists from those of the police force.

ISO13407 refers only to "*users, tasks and the organizational and physical environment*" in understanding context of use. But an important aspect of designs for data analysis is to acquire specialists' data. The heterogeneity of geographic data and its dependencies on scale and space make this particularly important. This has significant implications for the relationship with specialists and requires a focus on 'data in context', of which geographic context may play a key component, alongside those of specialist and organization. However data in context is not a substitute for context of use. Specialists' data needs to be studied explicitly in a process akin to 'studying documentation' – an off-line activity disconnected from the data owners. In working with domain specialists we found the need to be explicit about understanding both their context of use *and* their data in context, which entailed collecting metadata relating to lineage, confidentiality, format, volume, etc. Geovis designers need early access to domain data so that it may be studied in detail. This requires domain specialists' trust. Engaging them as 'masters' in a CI master-apprentice manner is therefore appropriate: a '*(geovis) researcher – (application domain) subject*' or consultant/client style approach may be an unhelpful way of framing the relationship at this stage.

3 ESTABLISHING REQUIREMENTS

We anticipated that the novelty, complexity and characteristics of geovis would make establishing requirements a challenge. We therefore employed alternative approaches as well as a widely used standard, the Volere method [54], in which a structured template of generic questions is used to elicit requirements. In the first of two alternative approaches, we attempted to provide the specialists with an understanding of the possibilities of geovis in order to elicit methods that might engage with their context of use. This builds on a HC tradition of involvement through participatory, collaborative engagement with users. Van Wijk suggests that "*domain experts could make steps to cross the bridge*" by using visualization experts to "*educate domain experts to define visualizations themselves*" [67]. While pedagogic literature recommends active approaches to learning, in line with the HC tradition, we prepared a lecture for the specialists with the aim of describing a comprehensive set of geovis tools and interactions, in the expectation that domain specialists might 'cross the bridge' by deciding which had promise in their context of use. This didactic means of education contradicts our usual pedagogic practice, which tends to be much more 'hands on' in the tradition of active learning. There was some scepticism regarding the suitability of this more objective method, however, lecturing is time-efficient and a de-facto standard in education. Card sort [44], sketching [65] and a recall [1] interview after two weeks were used to elicit information from the specialists regarding candidate methods and designs. Sketches allow for "*a dialog between the sketch and the viewer. . . that facilitates better understanding of the problem and in turn generation of new ideas*" [65] and have been used in an information visualization context [12]. We asked the specialists to "*define visualizations themselves*" by sketching a data exploration application using techniques described in the lecture for three major crime domain themes established during the context of use phase – *fear of crime*, *racial crime* and *the 'night-time' economy*.

The second alternative approach was a response to our developing understanding of the difficulty of eliciting requirements as we tried first Volere and then the didactic approach to bridge building. Instead of attempting to bridge the gap [67] by taking geovis to the specialists, we reversed the direction and took a representation of the specialists' context to geovis designers. Whilst not a scalable method, this gave us a series of suggestions, 'grounding' in geovis methods with which to compare the specialists' solutions and an indication as to whether an objective geovis solution to a stated visualization need may exist [36]. It also provided multiple opportunities to evaluate our representation of geovis context of use – a *scenario* [9, 53] developed from the information gathered in the earlier context of use stage.

Analysis of these three HC approaches (Volere, lecture and scenario) developed a body of evidence from which to triangulate. Quantitative methods included counts of methods used in designs both by geovis experts and the specialists and the tabulation of the results of a summative questionnaire from the geovis experts [36]. Qualitative information came from the coding and analysis of audio recordings made of the Volere sessions, the scenario interviews with the geovis experts, the post-lecture sessions in which card sorting and sketching were used and the recall interviews [36].

The requirements template elicited only the most peripheral information from the specialists. The possibilities of visualization were not captured – the potential of geovis and the effective use of geography to structure and interact with information represent 'undreamed of' requirements [52] that slipped through the net during our 'trawl'. This was despite our specialists being involved in spatial analysis, using geographic information systems, and having knowledge of analytical graphics. The Volere template also fails to give weight to the collection of domain data and metadata – an important need already established.

The results of the lecture were mixed. During the card sort held immediately afterwards the specialists appeared overwhelmed by the possibilities. They identified virtually all the tools and interactions as being useful in their domain but were unable to differentiate in terms of suitability or priority. In the recall interview a fortnight later, just a few tools were remembered, but the recall prompted useful commentary on some of these: "*the glyphs I liked. I think I could see a use*

for them straight away. . . you could, use them in quite a simple way to look at those areas. . . that have quite a similar characteristics and quite similar problems. I thought that would be quite an interesting way to do it."; "*I thought [the tree maps] would be particularly useful . . . [to have as] quite a simple, straightforward way of demonstrating [our problems are] . . . mostly criminal damage and violent crime. . .*". Specialists were observed during their sketching and they described the difficulty of representation, of the task and general (post-lecture) fatigue: "*. . . difficult to draw/visualise things like zooming. . . how to describe what you want to do on paper*"; "*I can't think in this way, [I've] got too many things in my head.*" While these sketches could not be considering as requirements, it was possible to study the tool and interaction components in order to gain an insight into what specialists might find useful in such an application. Tohidi *et al.* outline an exploratory analysis based on counting ideas found in sketches [65]. In our case, seven user sketches produced 78 elements for the three crime tasks: 'the night-time economy' produced over twice as many as the other two crime types. The most frequently drawn tools were *star plot/glyph* (three times) and *line graphs* (four) and there were 15 interactions associated with *filtering* and *aggregation* – an insight into the importance of these functions to the specialists. This reductive way of examining the sketches showed promise as a quick means of determining the relative acceptability of tools with domain specialists and associated discussion helped establish knowledge.

We developed a scenario by iterating drafts that incorporated the key elements learned from studying context of use with the domain specialists. The leading specialist confirmed that the final draft fairly represented the team's exploratory work. The scenario was sent to nine individual geovis experts – potential (and proven) designers of geovis applications – to garner suggestions for tools and interactions that might be of use to the crime prevention team in their exploratory work. Their suggestions, recounted in a subsequent prompted interview, showed this to be a fruitful exercise. While two experts found the scenario too broadly scoped, all were able to make suggestions on tools and interactions, as well as providing commentary on the process and their approach to geovis design. Significantly, all nine requested access to supplementary information in the form of sample data with metadata and maps explaining local administrative geography. The experts made 334 suggestions for tools (153) and interactions (181) after considering the scenario during interviews lasting typically for about an hour. Some consistency was apparent – the 'top eight' tools and interactions accounted for over 60% of all mentions. The top ranked interactions were *aggregating* (23 mentions), *filtering* (22), *comparing* (17), *linking* (13), *zooming* (11), *symbolising* (11) and *classifying* (6). The top ranked tools were *map* (35 mentions), *spreadsheet/table/grid* (18), *density/hot spots* (12), *small multiples* (11), *cartograms* (9), *animation* (6), *parallel coordinate plot* (6) and *histogram* (6). These sixteen suggestions were combined into a concise statement of use to a designer building a geovis application for the specialists, and indeed used in our early designs. However the most mentioned tools and interactions may owe their position to being those with the widest scope, the most popular, those with the greatest past use where crime data is involved, or those mentioned in the scenario. It is also possible that highly ranked interactions owe their positions to their relatedness to highly ranked tools, or vice versa. This needs further research. We found the scenario approach was useful in geovis design but should be modified to include supplemental information, especially domain data and metadata and the graphic depiction of the geographic context through maps and data characteristics in other graphics. The geovis experts expressed their ideas differently – some were data-centered, some task-centered and some tool-centered. Some had a strong preference for communicating ideas through sketches whereas others did so orally. This suggests that awareness of personal styles may be important in interactions when experts work with each other or with domain specialists and indicates that despite some consistency, alternative, personal designs are likely to be developed by geovis designers.

Reflecting on the 'bridging the gap' approaches, it is clear that sketching carried out after the geovis lecture and the expert interviews produced a comparable number of tools (78 sketched elements in 3 x

30mins; 334 suggestions in 9 x 60 mins). The Volere template, post-lecture card sorting and the recall interview did not produce results at anything like this level. Clearly creativity is not lacking on either side of the 'gap', but no one approach created the 'bridge'. Our experiences with the lecture suggest the need for geovis specialists to navigate potential users of geovis applications through the design space with 'waymarks' that are indicative of possibilities rather than offering a comprehensive set. Whilst this may engender bias, objectivity is neither possible nor necessary in our view: geovis designers can not be independent of process, and designs should be developed through discourse – with designers guiding the way and reflecting upon their effect on the process. Responsibility and flexibility on the part of the designer are essential however. Emphasizing transience and the *possible* nature of suggestions through sketches and alternative arrangements (e.g. card sorts) is important here. Just as contextual inquiry through shadowing and master-apprentice results in a sample of domain context, so geovis education in the context of establishing requirements may best focus on a narrow set of examples described in detail rather than a comprehensive set of possibilities. Indeed to turn the process on its head, CI approaches and educational sessions in which they are simulated – such as a geovis designer being shadowed whilst working from a specialist's scenario – may be effective for mediating geovis possibilities to specialists, particularly as they are more likely to involve active learning and if they can establish engagement by using relevant data identified through analysis of context of use. A complimentary approach [42] emphasizes the need to augment and apply knowledge by encouraging creative thinking during the requirements process. This has since proved successful in geovis [18], with a more interactive approach to learning used in developing design ideas.

The combined outputs from the process to establish requirements yielded a few methods deemed suitable for combination in a design: thematic maps, density maps, tree maps, glyphs, statistical graphics and a series of interactions for spatial and attribute selection and focus. Studying data in context reveals the particular combination of spatial, temporal and crime attribute data used. Factors that stand out from the context of use study include the limited linking of crime data to external (non-crime) data and being able to combine and filter/aggregate in terms of space, time and attribute to theorise about causality and policy effect. In addition to the composite guidance from the geovis experts, these high-level elicited suggestions comprise the inputs to the design stage of the HC process. Developing these enabled us to investigate typical HC approaches to design and prototyping for geovis.

4 EARLY PROTOTYPE DESIGNS

Early designs are frequently communicated to prospective users through a 'wireframe prototype' – *wireframe*, "*designed to provide an early approximation to a software idea*" [66]. Such early designs are "...*best considered as sketches. They illustrate the essence of an idea, but have many rough and/or undeveloped aspects ...the team recognizes it as something to be worked on and developed further*" [23]. However, the complex and interactive nature of geovis militates against simple paper sketches, presenting a conundrum. We also faced the issue that the heritage, practice and guidance from both the HC and visualization traditions is a formidable body of knowledge from which to create practical designs. We experimented with rough designs for early prototypes in keeping with the uncertainty associated with initial design stages. These were based upon and continually evaluated against guidance from the body of HC and geovis knowledge to ensure relevance and *cognitive plausibility* [61]. This was often an internal process and we were influenced by Duncan [15] to document design choices by "*capturing the inner dialogue of the creative process*". This approach was inspired by autoethnography, an "*autobiographical genre of writing and research*" [19], that provided a helpful framework for reflecting on design ideas emerging from this diverse and sometimes conflicting body of knowledge. The method has been used in interactive design [15] and supports documented reflection as advocated by Krygier *et al.* [32]. Our experiences led us to reflect on how visualization researchers learn design. The importance of "*learning through doing*", building portfolios, criticism and

Fig. 3. Wireframe prototype (foreground), containing spatial (map), temporal (glyphs) and crime attribute (tree map) data. Other sheets (background) show alternative states of the wireframe.

redesign [4, 29, 30] are often emphasized, and compliment our reflections on learning earlier in the process. But without methods to frame (re)design it can be difficult to justify candidates. The geovis literature on how exactly designs come into being is surprisingly silent, despite the cartographic tradition – a possible blind spot for the discipline. The route to the summit may be less spectacular than the view from the top, but both are of service. We propose that designers expose more of the process that leads to a final design to help the learning of others. Our geovis experts showed willingness and ability to communicate design decisions and possibilities effectively. Duncan's autoethnographic approach [15] helped us to describe our own, detailed design journey [36] and may be of use here.

We considered various ways to modify the wireframe concept for geovis. We employed an analog light box and produced our ideas as sketches in the form of stacked transparencies. The layers were far from wholly transparent however and difficult to handle meaning that we were unable to effect smooth transitions. This technology was engaging and emphasized the underdeveloped and transient nature of designs but did not allow their dynamic nature to be represented adequately. We returned to the medium of paper and had an insight that we could represent different states of an application effectively as multiples on large sheets. A typical state for a design would be supplemented by additional sheets containing stand-alone multiples of tool components and states. Interactions would be conveyed verbally, for example, explaining that "*when the amount of data gets below a certain level, the squares affected turn grey, as in this picture*" (Fig. 3). We wished to see whether these *geovis-modified* paper wireframes could engage the specialists to generate ideas, suggest improvements and offer opinions to advance the design process.

Based on the specialists' context of use, the high-level output from both sides of the 'bridge' obtained during the requirements phase and our reflective design practice, we created two early prototype sketches on paper, critiqued them and iterated both. In these, images of geovis tools were created from a range of existing applications. Background maps in the wireframes reflected an area familiar to the specialists, whilst the data represented was synthetic. These designs were again critiqued and iterated into geovis-modified wireframes – containing real and relevant geographic context – which were shown and explained to the specialists individually. They were asked to react through a 'think aloud' protocol, a method that consists of "*asking people to think aloud while solving a problem and analysing the resulting verbal protocols*" [21]. Sessions were audio recorded and transcribed for analysis.

	Specialist	Wireframe 1	Wireframe 2	Specialist total
	1	3	4	7
approval	2	3	4	7
	3	1	4	5
	1	5	5	10
idea	2	2	6	8
	3	2	5	7
	1	0	5	5
limitation	2	2	3	5
	3	2	2	4
	1	1	5	6
opinion	2	2	8	10
	3	4	5	9
	1	0	0	0
query	2	6	4	10
	3	4	3	7
	Total	37	63	100

Fig. 4. Counts of text blocks containing different interaction types from specialists for the two wireframes designs, showing extent of engagement. The same text block can appear under multiple headings.

Our *geovis-modified* wireframes proved successful in communicating an understanding of the design to the specialists as strongly evidenced by the richness of their engagement with the wireframes and their narratives (see Fig. 4). Indeed seeing a tool (temporal glyph) in a wireframe completely changed a specialist's mind about it at this stage of the HC process: "*I looked at those [the glyphs] a fortnight ago [at the geovis lecture] and I hated them . . . I really hated them. I thought they were inelegant and I thought that they were hard to interpret. But. . . I mean, [now] I really do like it, because you've got the interaction of it here, I do like it. But it is kind of. . . you are trusting in your eye, like you are saying.*" We found that as trust was developed over time and methods were employed using familiar and interesting data in 'sketchy' interface mock-ups that were evidently suggestive rather than definitive, mutual understanding of the problem domain increased markedly. A significant result from the work with these specialists using wireframes is the crucial importance of *real domain data*. Evidence comes from another participant, who despite being told the data were simulated, was unable to hold back from attempting to interpret the data given the geographic context: "*One of the things that is perhaps hampering my limited imagination is because it is random data. . . I immediately try and make sense of it, kind of thing. 'Ah, theft from vehicles is very similar to. . . oh no it isn't - it's just random'. I immediately start to try to interpret it instead of just trying to leave it at the level of [an example of a possible technique]. . . *"

The need for real data in a geovis context can lead to contradictions. Real data wireframes take longer to produce than simulated data wireframes, undermining their 'quick production' nature. Longer production times contradict the important 'throw away' and 'unfinished' characteristics. Quality of paper, printing and the way in which the wireframes are introduced may also have an effect. Rough edges can disclose their status as being open to development, suggestion and change. A wireframe with higher production values may mislead a subject as to its 'finished' state and discourage criticism and interaction. Such a wireframe may lead to a greater degree of attachment in the designer, who may be reluctant to amend or discard it. The specialists did not make amendments, annotations, additional sketches, or the like on our paper wireframes even when encouraged to do so, perhaps indicating that their production values discouraged changes.

When choosing which of the two wireframes they wished to pursue, specialists gave reasons that indicated how strongly their choices were rooted in their context and current tool use. Their chosen design integrated spatial, temporal and crime attribute data and enabled aggregation of all three aspects at a variable range of scales. These specific considered needs were not acquired through our use of more standard HC methods at the formal 'requirements' stage but confirmed through interaction with the wireframes. Whilst iteration is key to HC design, the importance of these sizable 'loops' between (as well as within) stages of the process in the geovis context were notable and important devices to account for learning on both sides.

The paper wireframes were simple and only scratch the surface of what geovis could deliver. In one sense this is disappointing in that more advanced tools and interactions were not discussed with prospective users. Nevertheless, it was pragmatic and "*novelty is relative*" in visualization [67] – it also changes rapidly, re-emphasizing the need for iterations. One could conceive of more complex geovis tools and interactions to explore other possibilities and more advanced software may be used effectively to suggest ideas here [58]. But this is likely to contradict the need for early designs to be underdeveloped and with 'rough edges'. The comparative success of *geovis-modified* wireframes that situated data and method concurrently in the context of known places suggests that a focus on specific methods through early design sketches may be appropriate even earlier in the process of engagement with domain experts if 'sketchiness' can be afforded.

The importance of real data to engage specialists is clear from our results. Only real data carries the subtle spatial and temporal correlation artefacts that these specialists expect to find in thematic maps and that were absent in our glyphs of simulated crime incidents (Fig. 3). Including this in wireframes, without over-committing resources to something that should have 'sketch like' qualities, is challenging. We have previously highlighted the need to remove barriers to entry for those wishing to create geovis applications by "*increasing efficiencies, sharing software components and reusing resources*" [16]. We suggest developing *data sketches* to quickly and flexibly produce transient and uncertain visual representations of domain data to support the HC design process by scavenging existing applications for functionality and exploiting advances in rapid graphical application development such as Processing [50, 49] that allow data, interactions and functionality to be quickly and flexibly combined. Graphical toolkit advances such as ProtoVis [7] may also be effective for rapidly creating viable early designs. These loosely bounded collections of data, functionality and ideas develop through the design process. Whilst the persistence of design elements through the process contradicts the emphasis on transience, 'patchwork prototyping' [28] offers some efficiencies and is supported by data sketching. We have since combined hand-drawn sketches, data and interactive functionality with positive results [49].

The feedback received from the specialists on our early prototypes (Fig. 4) was useful and drove the development of more refined designs in which we investigated additional HC techniques.

5 LATER PROTOTYPE DESIGNS

As designs for a geovis application developed we examined the effectiveness of different types of design format and the protocols through which specialists encountered them. ISO13407 suggests a number of approaches including paper and software prototyping. Paper prototyping [51] is a "*variation of usability testing where representative users perform realistic tasks by interacting with a paper version of the interface that is manipulated by a person 'playing computer' who doesn't explain how the interface is supposed to work*" [63]. A software, or digital interactive – *digital*, prototype is "*almost a digital version of the paper prototype. Except, digital prototypes can range from a series of low-fidelity, narrative click-through screens for quick visualization of a design concept to a high-fidelity interactive portrayal of an evolved design. . . *" [3].

We were interested in two kinds of feedback from the specialists shown a more realistic and functional prototype to establish how these devices might be used in a geovis context. We wished to find out whether useful suggestions for functionality and enhancement were forthcoming – the purpose of any prototype; and also to determine whether prototypes elicited exploratory behaviour that would be seen in users of a geovis application. The HC literature suggests a number of ways to approach prospective users with prototypes that vary in the extent that the tasks carried out are determined in advance by the researcher or are left to the user; whether users are helped to use the interface by the researcher – *chauffeured prototyping* [46] – or not; and whether aspects of the interface are concealed – *Wizard of Oz prototyping* [13] – or not. Dumas *et al.* suggest an active intervention approach "*in which a member of the [research] team sits in the room with the participant and actively probes the participant's understanding of what is being tested*" [14]. North argues that "*researchers [should] observe what insights users gain on their own*" [45]. Clearly only a limited number of variants can be employed with the domain
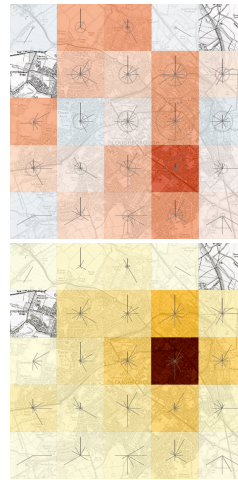
Fig. 5. Later prototypes being used in active intervention sessions. Paper prototype and interface (left). Digital interactive prototype screen examples (centre) and set-up following an active intervention session with a digital interactive prototype accessed through a paper interface (right).

specialists available, but we attempted to cover as many approaches as possible in order to compare the extent that they yielded suggestions for functionality and enhancement and allowed exploratory behaviour.

A user testing with active intervention approach was employed with both paper and digital prototypes, as shown in Fig. 5, and a free exploration approach used additionally in the case of the digital prototype by way of comparison, also with active intervention. We used real domain data, having determined the importance of this during the wireframe analysis, and designed a series of simple tasks involving the spatial, temporal and attribute characteristics of reported crimes to act as probes for the active intervention approaches. Seven sessions with three specialists typically lasted two hours each. We used 'think aloud' with audio transcription and coding to elicit users' instances of exploration and to capture suggestions for enhancing the functionality of the prototypes. This had been effective earlier in the process. Order of presentation of prototype was randomised and we used two related, but different, crime attribute datasets to avoid a learning effect. Summative questioning followed these sessions to gather supplemental information from specialists. To free the specialists from the need to learn an interface and to focus on functionality rather than access to it, participants interacted with both prototypes through a simple paper interface in the user testing with active intervention conditions. This was interpreted by a researcher acting as a 'chauffeur' [46]. When the digital interactive prototype was used with free exploration, the interface was under specialist control.

In excess of 300 suggestions for functionality and enhancements were elicited from 15 hours of individual prototyping sessions with the three specialists. Suggestions were subsequently coded using an emergent scheme into 35 main areas for improvement after an initial pass through the data [55]. These were in turn grouped into four categories relating to: data, interface, interaction and novelty – 'new-related' (see top of Fig. 6), with geovis related suggestions placed in the *new* category. The active intervention protocol data in Fig. 6 shows 162 suggestions for the paper and 109 for the digital prototype, with the paper version scoring more highly in three out of the four categories. To establish whether these differences were significant we created a null hypothesis that the category of suggested functionality and enhancements was independent of prototype type (paper vs. digital in the active intervention protocol) and used a one-sided chi-squared test to compare suggestion types made for functionality and enhancement of the prototype. This yielded a chi-squared value of 10.66 – the critical value at the 0.05 significance level being 7.81 (DF=3). This enabled us to conclude that the difference in number of suggestions made was unlikely to be independent of prototype type. The paper prototype yielded more suggestions than the digital interactive prototype except for interface-related improvements. In particular, it produced more

	active intervention						free	(n=3)	(n=3)	(n=1)	(n=7)
	paper	digital	paper	digital	paper	digital	digital	paper total active int.	digital total active int.	digital free explore	Total
	Specialist 1		Specialist 2		Specialist 3						
data-related	33	14	11	21	26	8	10	70	43	10	123
interface-related	4	8	1	3	5	9	3	10	20	3	33
interaction-related	13	8	20	13	14	9	13	47	30	13	90
new-related	9	5	10	3	16	8	6	35	16	6	57
							Total	162	109	32	303

	active intervention						free	(n=3)	(n=3)	(n=1)	(n=7)
	paper	digital	paper	digital	paper	digital	digital	paper total active int.	digital total active int.	digital free explore	Total
	Specialist 1		Specialist 2		Specialist 3						
exploratory activity	6	8	7	5	5	6	12	18	19	12	49
hypothesising	17	10	9	9	5	0	10	31	19	10	60
insight/ ideation	31	23	18	20	10	9	22	59	52	22	133
confirmation	6	3	3	7	1	7	1	10	17	1	28
expectations confounded	4	0	5	0	2	0	5	11	0	5	16
							Total	129	107	50	286

Fig. 6. Counts of instances of (top) suggestions for improvement by category for each later prototype and (bottom) observed geovis behaviour during the course of the paper and digital interactive prototyping sessions, by subject, prototype and protocol.

than twice as many suggestions for improvements related to *new* features than did the digital prototype (35 vs. 16) even though this was relatively 'interface free'. The relative success of paper prototyping in eliciting suggestions for design needs is in line with existing work [10, 35, 68, 69] and may be important in enabling domain specialists to focus on domain and analytical process rather than the means of access to functionality. *Data-related* suggestions for functionality and enhancements were the most frequent overall from these specialists. There is evidence from counts of coded statements that both paper and digital prototypes generate considerable breadth of engagement, hypothesis formation, exploration, ideation/insights and opportunities for expectations to be confirmed or confounded (see bottom of Fig. 6). Paper and digital prototypes yield similar numbers and types of exploration through an active intervention protocol with tasks. There is some evidence that the paper prototype is capable of driving data exploration; promotes reflection on current work practices; can replicate the shortage of screen real estate that would occur with a computer-based application; and can handle multiple tool representations. It was also engaging and the fact that geovis designers acting as 'chauffeur' were being controlled (driven!) by domain specialists may have had a positive effect in terms of the power relations and establishing that geovis designers external to the organisation in which this work was situated were able to respond (rapidly) to domain specialists partic-

ular requests. What specialists learned from prototypes, and indeed what we learned from their interactions with them, was heavily data-dependent. Different specialists have different spatial knowledge and different responses to different spatial data sets. We found strong evidence that not all crimes are equally important to all specialists and some seemingly similar crime categories remained relatively unexplored as they were deemed less "interesting" than others – partly due to their more predictable geography: car crime in parking lots; purses lost at pubs on Friday evenings. Whilst crime types used in the prototypes were randomised within the evaluation framework, this issue could have confounded our efforts to isolate the paper and digital conditions and the means of reporting. It draws attention to another contradiction in evaluating HC methods for geovis design: that real data is essential for establishing needs and yet real data sets are not comparable in terms of their spatial characteristics or levels of familiarity and interest to participants – even when their geographies are consistent. A significant depth of interaction, engagement and exploration were apparent as specialists used the digital prototype – as evidenced by a large number of quotations captured during free exploration. The overall level of exploratory activity here was about twice that observed in digital active intervention in sessions of comparable length (see bottom of Fig. 6). Clearly, these prototypes supported exploratory activity and thus worked as a basis for developing geovis designs – though as indicated above many of these related to additional requirements as knowledge was developed and possibilities identified.

Specialists were able to engage in geovis and make suggestions for improving both prototype types. A key difference with the later prototypes was that specialists saw real domain data presented 'geovisually', which resonated with them and invited engagement, explanation and exploration. One typical comment expressed this clearly: "*I have been drawn into these [areas] by being able to manipulate the resolution of the data... the more you go on with it, the more you get sucked in to particular areas*". This may be true both of geographic areas and metaphorical 'areas' of the design space and process.

We found that understanding context of use is a communications process that is not finalised in the initial ISO 13407 phase – emphasizing the importance of iterations in the design process. There is a high possibility that tasks may not be fully understood without data rich (early and late) prototypes, which may lead to problems in prototyping sessions. The user testing protocol with active intervention requires task construction by the designer. It requires more resources to administer especially where a chauffeur undertakes interface control. This affects the operating speed of the prototype and may place a barrier between it and the specialist. Free exploration yields a similar quantity of geovis related suggestions for functionality and enhancement as active intervention with a digital prototype. It needed fewer resources to administer and the tasks could be selected by the specialist. While it was necessary to tutor them in operating the rudimentary interface to the prototype, this was not a problem in practice. Methodologically, a long sequence of interviews, questions, observations, geovis wireframe and prototyping sessions, even over a long time span, placed a large burden on these domain specialists. Most of the interactions with them were 'one shot' as the act of showing a wireframe or a prototype changed perceptions. Consequently, there was a balance between trying to extract as much as possible from these valuable participants and exhausting them, perhaps to the point of them withdrawing their cooperation. Using tasks as a means of elicitation feels like 'user testing' – an approach that may be fundamentally at odds with the notion of 'partnering' with domain experts and attempting to understand their context of use over a long period of time. The free exploration protocol appears to offer significant advantages over task-based user testing in this respect, with active intervention useful in both cases. We observed that individual geographical knowledge played a part in how specialists interacted with prototypes – the background map was important in all cases and should clearly be chosen with care. We have evidence that the specialists might find geovis intimidating and prototypes (and indeed applications) may benefit from a clear pathway for neophytes. Reducing the tools available at first sight with "*extras on demand*" [64] may be advantageous.

While the success of the paper prototype is encouraging, it relied on a system to produce multiple paper representations containing real domain data. In practice, this meant that our paper prototype relied on the prior existence of our digital prototype. Developing data sketches (see section 4) supports this process with efficiency. While designers who use this approach may be tempted to 'cut to the chase' with the digital prototype, we recommend they consider the advantages of paper over digital prototyping: its less finished aspect and potentially less intimidating nature, as well as our evidence of its superior results with the domain specialists. Work with these prototypes produced further evidence for conclusions drawn earlier on: the importance of real data; the importance of domain knowledge (especially as tasks become more complex); and the emerging context relating to specialists, tasks and data. Using a rudimentary interface to support free exploration in a digital interactive data prototype in conjunction with paper data prototyping that uses low fidelity output derived from the digital design may be an effective 'discount' approach to geovis design.

The transcriptions of participant's interactions with prototypes totalled over 150,000 words. While this detail was necessary to understand the way specialists interacted with geovis prototypes for the purposes of this research, it is not required if the aim is to establish possible improvements. An experienced "*note taking observer*" [63] who records these in real time against a prior coding scheme is an important member of the team. Better still would be sessions where specialists and designers discuss and agree prototype development as part of the reflective design process. The HC technique of affinity diagrams [5], may be helpful here. More generally, geovis researchers working with domain experts should seek to develop ways to achieve flexibility in application design, with continual iteration, quick prototyping and the infrastructure to support this. This needs to be built on a foundation of creating bonds, understanding and confidence with specialists.

From these prototyping sessions, we compiled a list of 35 suggested features that built upon the designs and sought HC approaches to prioritise these. The Analytic Hierarchy Process (AHP) [59] is a well established [70] method to achieve this through a quantitative measure of user consistency. Our work on using the AHP as an HC means of prioritising suggested characteristics in the later stages of design is reported elsewhere [39].

6 CONCLUSIONS

The complex and composite natures of the geographic, visualization and HC domains make effective geovis design a challenge. Learning must take place on all sides in the contexts of organisation, application domain and power relations. Our contribution is an in-depth appraisal of various HC approaches that were poorly represented in the visualization literature in the context of geovis when our work commenced. This is based upon a long-term engagement with a group of domain specialists and our work with them to evaluate means of developing design ideas for applied geovis. As a result of this experience we report some specific results that relate to individual techniques, but also offer some general recommendations for this kind of activity. While our focus has been geovis, few of our findings have been unequivocally spatial in nature and many may be applicable to other visualization and design settings. This is not unexpected as many methods used in geovis are shared by or derive from graphical statistics and information visualization – and vice versa. It emphasizes the difficulty of developing requirements that relate to the representation of and interaction with geography and suggests the importance both of iterative geovis development and the need for guidance in design by geovis experts rather than design objectivity. We summarize our findings and recommendations in Fig. 7 where geovis specific issues are highlighted.

Thorough analysis of context of use is essential – though not straightforward given that geovis possibilities are likely to be 'undreamed of' in many contexts. The master-apprentice means of gathering information through CI was effective in the early stages, but information arises whenever there is contact between researcher and specialists. Researchers need to be alert to this and respond flexibly – the master-apprentice roles may be usefully reversed. Various means of contact and communication through which trust is developed are key

	HC Approaches	Data Collection	Data Analysis	Summary Process Findings	Summary Research Findings & Recommendations
Context of Use	Contextual inquiry (CI) Card sorting: domain tasks	Interviews; Observation; Studying docs; Card sorting: domain tasks	Transcription; Word frequency; Keyword in context (KWIC) Classifying (card sort)	1. Word frequency & KWIC are useful & efficient analysis tools 2. Specialists' internal documents & broader academic writing on the domain provide insights & context.	1. Need to study broad context, **including data**, to develop subsequent situated design ideas in light of likely unknown (geo)vis requirements. 2. **Card sorting can elicit varying spatial emphases in specialists' approaches to tasks.** » It is essential to study data & (geo)vis in context with known (spatial) data & tangible visual artefacts. » Experiment with ways of introducing tangible visual artefacts of specialists' data as early as possible.
Requirements	Template (Volere) Scenario used by geovis experts Lecture for communicating geovis to specialists	Questionnaire conducted orally Interview & think aloud; Summative questioning Card sorting: geovis methods; Sketching; Recall interviews	Transcription; Deductive coding Counts of geovis methods in card sort & in sketching	1. Transcription with deductive coding is highly labour intensive. A trained note-taker recording & coding during data collection is an alternative, although prior coding schemes are difficult to achieve. 2. A scenario of specialists' context provides 'common ground' - information that enables geovis experts to suggest relevant methods. 3. Geovis experts express their ideas differently. Awareness of personal styles might be important when experts meet domain specialists (or other geovis experts). 4. Sketching & counting instances of tools & interactions can elicit information to supplement card sorting & summative interview. 5. Sketching can establish relative acceptability & comprehension of geovis methods (which may in turn contribute to learning).	1. **Failure of generic Volere template to establish requirements** for a geovis application & to elicit information about specialists' data. 2. **Failure of lecture on geovis** to establish from domain specialists which methods might be of use. 3. **Consulting geovis experts to establish methods for specialists** is effective, but with caveats. 4. Scenarios are effective, but specialist **data (including spatial)** & metadata is important to geovis experts to supplement a scenario. » Requirements may usefully be informed by known (spatial) data & vis/geovis examples & prototypes. » Scenarios & sketching can generate useful design ideas if supplemented with data in context. » Transcription is costly - consider using a trained note-taker with a prior coding scheme. » Early use of tangible visual artefacts is conducive to mutual information sharing & building trust & teams.
Design Early Prototypes	Early design Wireframe prototype	Documenting design process Think aloud; Summative questioning; Observation	Reflection (autoethnography) Transcription & deductive coding; Counts, & representative comments, coded by approval, ideas, limitations, opinions & queries; Counts of tools, interactions & data; Summative questioning & observation for effective additional evidence	1. Autoethnographic inspired approach to reflection in the geovis design process is useful. 2. See *transcription* above. 3. Specialists interact effectively with modified wireframe prototypes, which elicit a rich body of information, creativity & understanding.	1. **Wireframes need to be modified to represent multiple tools & multiple states** to successfully communicate a geovis application to specialists. 2. Specialists engage poorly with **dummy data map wireframes -- they do not represent spatial correlation**. Real data is important. **Using known phenomena in known areas exploits tacit knowledge.** 3. Phenomena & data vary hugely. Using a **variety of real data sets with different characteristics** is recommended, in discussion with specialists who understand the vagaries of data & geography. 4. Despite **data realism** wireframes must afford uncertainty by retaining provisional visual characteristics. » Designers of (geo)vis applications are encouraged to systematically record & share their 'design narrative'. » Use a variety of prototypes & data sets in a number of states & select a range of phenomena for study. » Means of reusing designs & affording uncertainty are important for flexibility, interaction & efficiency.
Design Later Prototypes	Paper prototype with user testing & active intervention protocol; Digital prototype with user testing & active intervention protocol; Digital prototype with free exploration protocol	Think aloud; Summative questioning; Observation;	Transcription & deductive coding; Counts, & rep. comments, coded by instances of exploratory activity, hypothesis forming, insight/ideation, expectation confirmed/confounded & suggestions for improvement; Summative questioning & observation for effective additional evidence	1. See *transcription* above. The later prototyping required transcription of 150,000 words, taking several months. 2. Both paper & digital prototypes engage specialists successfully, elicit exploratory activity, hypothesis forming, confirm/confound expectations & establish possible improvement, with both protocols. 3. A paper prototype with multiple representations of real data relies on the prior existence of a digital process, if not a digital prototype. 4. A free exploration protocol yields results with fewer resources & less researcher intermediation than a user testing protocol. It may also address some of the power/partnership issues, stimulate interest & help with trust & team-building. See *requirements* above.	1. Paper prototype produces more suggestions for improvement than digital **and twice as many related to novel features (such as geovis)**. Paper prototypes seem effective in stimulating creative thinking. 2. The free exploration protocol yields twice the level of exploration as user testing with active intervention protocol & may have other advantages. See *trust & team building* above. 3. Detailed domain knowledge **(including spatial knowledge)** is needed to make hypotheses & extract meaning from patterns in data. 4. **Where cartography is used to aid spatial navigation, maps also convey attribute information** to specialists that supports ideation & design. » Use paper prototypes to stimulate interaction & generate ideas about novel features. » Free exploration is efficient & effective for exploring ideas & results in learning about domain, data & methods. » Extras on demand may reduce the intimidating nature of geovis prototypes & contribute to learning. » Use 'data sketches' with rapid development methods to create wireframes, & prototypes as the process iterates.

Fig. 7. Summary of HC approaches used. Stages follow chronologically, row by row, showing main data collection and analysis methods, summaries for process findings (of use to researchers building an application for domain specialists) and our research findings (here, entries in bold are most specific to geovis) and associated recommendations. Color indicates which approaches may be helpful to researchers: red = not recommended; green = recommended; amber = intermediate. The coding does not apply to use in pursuit of our research aims, where transcription, for example, was a good way to amass information for analysis, but is too time-consuming for everyday use.

here as participants become partners in in-depth studies [60]. We find that keyword-in-context analysis is a strong technique in addressing a corpus of textual domain information; that internal and external documentation supplement interviews and observation effectively; and that card sorting is a valuable technique to understand conceptual models of tasks and techniques. Strong evidence was generated in our case study that the communication process between specialists in domain and visualization must be firmly embedded in the domain context with real data that domain specialists know and own from an early stage.

We report that domain specialists had 'undreamed-of' requirements that could not be effectively established from a standard HC approach (the Volere template), nor from the card sorting or recall interviews after a lecture on geovis tools and interactions. The levels of detail and engagement here were inadequate. Sketching by specialists did produce a large number of geovis elements within sketches that were not, in themselves, useful as early designs. Developing a *scenario* supplemented with *data* proved effective both in transferring our understanding of the specialists' context of use and needs and in communicating these to geovis experts – the scenario resulting in credible suggestions for tools and interactions to include in a design with some consistency. As such, we recommend that structured requirement elicitation and didactic methods of knowledge sharing such as the lecture be eschewed in the case of geovis in favour of early and repeated exposure to simple 'sketchy' approximations based on visualization experts' experience, assembled from appropriate low-cost/investment components that provide access to domain specialist's data. Confirming patterns in known data may be a useful process [56] even at this early stage as designers guide prospective users subjectively through design possibilities.

Synthesising design elements for a plausible initial design was challenging. Highlighting the introspection and reflection on design, which is infrequently explicit in the visualization literature, may be beneficial as may sharing this information both with specialists and other geovis designers. We recommend designers externalise their justification, as did our geovis experts. Autoethnography could be considered as a means of framing reflection when reporting discourse.

Our work showed that specialists engaged particularly well with tangible visual artefacts containing real domain data, including wireframe, paper and digital prototypes under different protocols. They undertook many exploratory activities, formed hypotheses, gained insights, confirmed known facts and confounded others. Specialists generated many suggestions for enhancements through prototypes. Both

paper and digital prototypes were effective at encouraging exploratory activity with real data sets, but paper was better at delivering suggestions for functionality and enhancements, particularly for suggestions considered 'novel' – it should not be discounted as a means of emphasizing early designs as possibilities, engaging specialists in the process and establishing their likelihood to have effect.

We recognise that the activities reported here took place within our research framework, that emphasized the need to develop knowledge about HC process rather than a working design. This may have influenced participants in terms of their engagement. Giving domain specialists confidence in the potential effect of their suggestions is essential. This can be supported in a number of ways, such as by giving domain specialists control over the process through, for example: 'show and tell' approaches to developing visualization awareness; 'imagination exercises' [18] with no 'wrong answers'; and the inversion of power relations involved in specialists shadowing geovis developers as they design, and externalise the design process, or instructing them to act as chauffeurs through paper prototypes and interfaces.

A key theme in these conclusions is the strong recommendation that real data that are known and of interest to subject specialists be utilised early in the geovis design process. We recommend that it be utilised as a framework for discussion *from the outset*. Tangible visual artefacts depicting real and known data are likely to be the most effective at engaging participants in discussing the issues of distance, spatial dependence, scale and heterogeneity that they deal with in their analytical roles and around which any geovis solution should be designed. They are likely to inform designers about choices that relate well to important structure in data as they explore change, cause and effect. Indeed undeveloped prototypes that combine data, interactive functionality and hand-drawn sketches may meet many of the needs of early geovis design and work particularly well as 'discount' methods used to inform the HC design process (e.g. [49, 11]).

We have considered the HC design process in a predominantly linear fashion (Fig. 2), but it is intended to be more cyclical than this, as shown in Fig. 8. However, Isenberg *et al.* [26] are somewhat critical of the 'traditional approach' to information visualization that typically begins at point B with a design (Fig. 8, left) and follows a trajectory through to evaluation (green arrow). Such an approach is reasonably critiqued for lacking 'grounding' in social context. The associated proposal that largely qualitative work should provide this context by applying HC approaches fully by commencing the development cy-
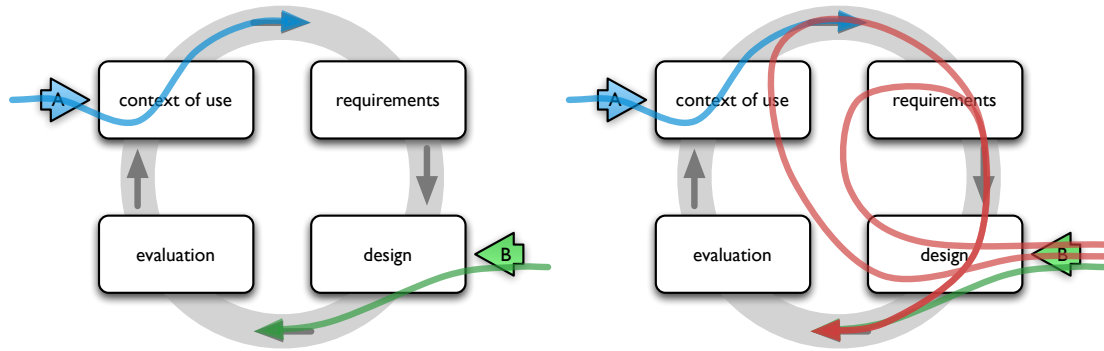
Fig. 8. The Human-Centered Design process [27] development cycle, with alternative entry points and process trajectories. The green trajectory (left) may be considered a 'traditional' use of HC approaches [26] beginning at point **B** as opposed to HC design that begins at **A**. We identify the need to use informative example designs to establish context of use and requirements in geovis as shown by the red trajectories.

cle at point A (Fig. 8, left – see blue trajectory) represents a view that underlies much of this work. However, note our recommendation that an engagement with data, graphics and interaction is so important in grounding geovis applications in geographic phenomena when establishing context of use and requirements, that tangible visualization examples containing real data are essential at these stages. Thus we suggest that low level data prototypes containing relevant and interesting data, including the paper designs (with simulated interaction) that were so effective in our study, and even existing (evaluated) applications (clearly presented as design *possibilities*) [58], be brought into the stages at which context of use and requirements are established. The potential costs of bias are mitigated by the likely benefits in terms of creativity, knowledge sharing and team building – particularly if identified as a risk. Fig. 8, right, shows two (red) trajectories that start at this stage, with designs, and draw them in to the vital stages that 'ground' development and establish needs to inform more specific designs that are subsequently suitable for formal evaluation. Establishing a means of rapidly generating flexible visual artefacts that do not represent high levels of investment (in terms of time or ideas) or suggest permanence but that increasingly use relevant known data is key here.

In summary, the ISO13407 taxonomy is useful in the geovis context, if applied flexibly and the following are considered in detail and with sensitivity: the relationship between designers and 'users'; their mutual learning; geography and the data that describes it; a wide range of possibilities in terms of design and function. In light of this we make a series of broad recommendations for using HC design geovis:

1. make the design process interactive, creative and interesting with buy-in from all parties;
2. use a range of real data that is known to domain experts in designs – do so early on in the process with example designs;
3. emphasize transience in designs that affords suggestions – showing data in designs on paper works well;
4. scenarios (with data) and shadowing can be effective – the latter may work both ways to address the contexts of both domains and challenge power relations (CI for geovis education);
5. develop digital sketches to create visual artefacts such as paper and digital interactive prototypes – be efficient in terms of re-use where you can, but not at the cost of a lack of flexibility;
6. free exploration with prototypes or existing software meets many of these needs, being engaging for specialists, informative for designers and developing the knowledge of each concurrently;
7. a think-aloud protocol can be effective for establishing reactions to visual stimuli, for mediation and learning;
8. build a team through co-discovery and by breaking down power relations – you may not even realise they exist;
9. reflection in design is essential – autoethnography can externalise and systematize this;
10. iterate within and between levels of the HC process – for example through an 'extras on demand' approach in prototypes.

Finally, the participants in this research are described as geovis '*researchers*' or '*designers*' and subject domain '*specialists*'. While indicative of academic objectivity, terms such as '*subject*' do not convey the reality of the engagement required between the parties over a lengthy period for *in-vivo* design work, even when it involves the kinds of structured experiments described here. A relationship had to be forged and understanding and confidence built. We consider *co-discovers*, *colleagues* or *partners* [60] to be more appropriate terms. HC approaches that feel like user testing are uncomfortable when domain specialists who have come to regard themselves as *co-discovers* are asked to act as 'subjects'. The free exploration protocol was more appropriate in this respect in later prototyping, where it was as effective as active intervention with tasks and simpler to administer. Like Robinson *et al.* [56], we find that the development process is likely to occur across multiple projects and the relationships and trust developed in establishing the designs described here have proved to be an excellent basis for continuing work.

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