EMPIRICAL EVIDENCE OF ADVANCED GEOGRAPHIC VISUALIZATION INTERFACE USE

Hedley, N.R.

Department of Geography and Human Interface Technology Laboratory,
Seattle, USA. E-mail: nix@u.washington.edu

ABSTRACT

Several advanced visual interface technologies have emerged in the past few years. Interfaces such as immersive virtual environments (VE) and augmented reality (AR) provide unique forms of interaction with spatial data that have often not been empirically investigated in the geographic visualization literature. At the same time as new interfaces emerge, we must develop an understanding of how they influence spatial knowledge acquisition. This requires an integrated approach to studying the relative influence of geographic visualization content, interface affordances, and user context.
This paper describes the findings of a recently completed empirical study of how people develop mental models of visual representations of spatial information, mediated by different kinds of geographic visualization content, interface type and user context. The behavior, performance and task responses of individuals using an Augmented Reality (AR) geographic visualization interface were compared to identical activities undertaken by users of a desktop 3D geographic visualization interface. Combining theoretical perspectives and empirical techniques from spatial cognition, interface research, geographic visualization and geographic information science, an array of quantitative and qualitative data were gathered from 101 participants during 250 hours of observation.

This work provides evidence that suggests how the combination of visualization content, interface affordances and users may interact to influence the development of spatial knowledge. This may in turn inform how a transformational view of the classification, representation and display of spatial phenomena may be enhanced by a commensurate understanding of how people interact with geographic visualizations to acquire spatial knowledge.

Keywords: Augmented reality, visualization, spatial cognition

1. INTRODUCTION

For over 20 years, immersive virtual environments (VE) have provided compelling visual and sensory experiences with visualizations. In the context of interface research, it has been necessary to study immersive VEs in order to realize that in many respects they represent too much of an abstraction from reality to be a realistic part of it. VE's are potentially powerful tools, yet they can foster an "untethered" experience on the part of the participant. Immersive VEs are often a dramatic and engaging visual experience, but they suffer from limitations of expense, accessibility, user disorientation, in addition to enclosing the subject in a computer-generated world that prevents any outside interaction. In the Virtual World the user is immersed in the interface, their natural senses replaced with computer generated sights, sound and touch. The interface is transparent because it is all-encompassing and is the user's only perceived reality.

In the past 10 years, a new generation of advanced visual interface technologies have evolved. An interesting example is augmented reality (AR). AR interfaces provide unique forms of interaction with spatial data that have not been empirically investigated in the geographic visualization literature. At the same time as new interfaces emerge, we must develop an understanding of how they influence spatial knowledge acquisition. This requires an integrated approach to studying the relative influence of geographic visualization content, interface affordances, and user context.

In contrast to an immersive VE, AR interfaces may include graphics and text annotating views of the world (such as Columbia University's Touring Machine, see Feiner, 2002) – which may be considered a form of "annotated vision". Another type of AR allows virtual objects to be attached to real objects that can be touched and manipulated (Figure 1). The latter approach is investigated in this research, and achieves significant interface transparency in a very different way than immersive virtual environments – this form of AR is sometimes called "Tangible AR". AR transparency is achieved through real-world metaphors (pick it up and interact with it like an everyday object) and spatial metrics (in a room-scale environment with familiar or known dimensions). 3D AR is not the same as annoted vision, as it places 3D objects in real-world settings, anchoring them to real-world surfaces, resulting in changing orientation and size, whereas annotated vision simply labels real world views with 'billboarded' (always facing user) text and graphics. Tangible AR is also different from annotated vision and earlier areas of research such as holograms, as the user can physically manipulate the virtual content by picking up and moving the object to which it is attached. These interface technologies have significant implications for how we extract and exchange spatial knowledge with them, and may allow us to magnify the spatial analytical capabilities of exiting geographic visualization tools, with more powerful interfaces.

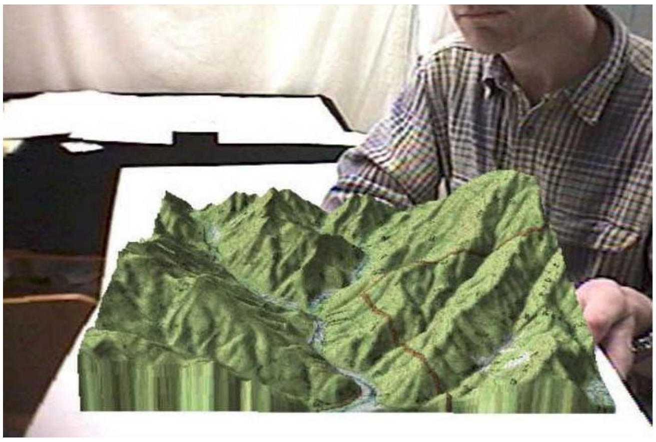


Figure 1. Non-immersive Augmented Reality Interface. Users investigate and study 3D landscape by simply holding and moving the white card (real) to which the 3D landscape (virtual) is attached. (Hedley et al., 2002).

2. PREVIOUS WORK

Several applications involving spatial data and geographic visualization have been implemented using augmented reality. These include Archaeoguide (Stricker, 2001), Columbia's Touring Machine (Feiner, et al., 1997), Media Interface and Network Design Laboratory's 'Mobile Infosphere' at Michigan State University, to name a few examples. By far the most prolific producer of geospatial applications of AR are military researchers, namely the Naval Research Laboratory in Washington, D.C. VE and AR systems have been developed to simulate military operations for training and visualization, and AR has been of particular interest as a tool to enhance the capabilities (such as awareness, objectives and goals) of individual and groups of battlefield units – as seen in the Battlefield Augmented Reality System (BARS) (Julier et al., 2000; Julier et al., 2001).

Very little work on AR has been done within geography. Examples of AR use and augmented interface use within geography include: the work of Hedley and colleagues to develop interfaces and interface metaphors for interacting with geographic content individually and collaboratively (Figure 1; Hedley 2001; Hedley et al., 2001; Hedley et al., 2002); the extension of University of Santa Barbara's personal guidance system prototypes for vision-impaired users (Golledge et al., 1998), to augmented vision based ubiquitous wearable computing system prototypes, such as the Wearable Mapping System; and the recent work of Shelton and Hedley to study the role of AR interfaces in conceptual and factual learning of spatial phenomena in an introductory geography class (Shelton and Hedley, 2002, Figure 2). The Santa Barbara system (Golledge et al., 1998), is an "augmented vision" system. That is, see-through images super-imposed on the real world allow hands-free computing (Clarke, 2001). This system was developed as a prototype way-finding and spatial information aid during movement through geographic environments. Further empirical evaluation of its role in spatial knowledge acquisition is needed.

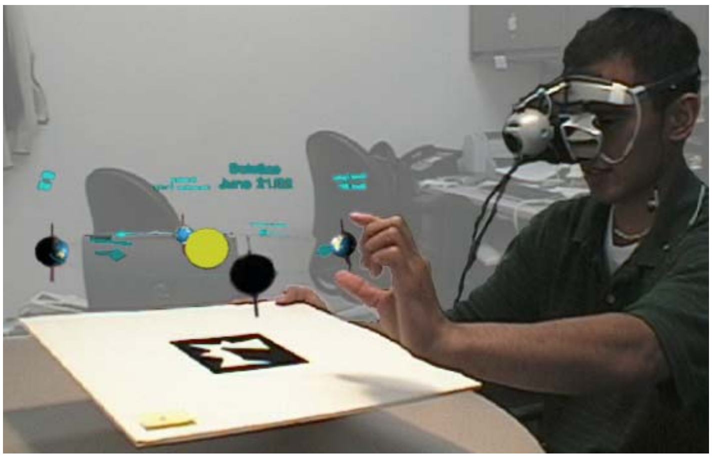


Figure 2. Using AR to teach introductory geography.

Recent empirical work found improvements in conceptual and factual understanding as a result of AR interaction with the Earth-Sun system in 3D, in an everyday spatial setting. (Shelton and Hedley, 2002).

The work in this paper focuses on the properties of augmented reality systems that are manipulated by the user, and aims to understand the role of powerful visuo-motor coupling of visual and sensorimotor feedback found in the interface. Several phases of empirical work have already been undertaken, and suggested that this is indeed a powerful interface (Hedley, 2001). The power of AR may be in the user's ability to physically manipulate the interface and virtual content (using the cards, seen in Figures 1 and 2), as opposed to simply viewing text superimposed over views of the external world.

Most studies of AR have focused on perception or interaction. Studies focusing on perception have considered how users perceive information overlaid in the real world, and what perceptual cues can be used to distinguish between real and virtual content. Studies have been conducted on judgments of distance and size of virtual imagery presented in AR displays. Researchers have compared depth perception in stereoscopic AR displays to monocular displays, the ability of individuals to align real and virtual objects, and performance differences between optical and video see-through displays. Interaction studies have considered how users interact with virtual information overlaid on the real world, and how real world objects be used to interact with augmented content. These have often involved virtual or real object positioning and movement tasks, to study visual and haptic feedback in reaching and grasping for objects in table-top AR environments, or interaction and object positioning experiments. In these types of experiments, the main performance measures are movement time and peak hand velocity.

The majority of AR applications that integrate behavioral and cognitive assessment have been conducted in the military research community. These include the specification of user-centered, task analysis approach to evaluating the AR interface in military scenarios, and wearable AR systems for infantry (Rosenblum, 2001). Exceptions do exist in the manufacturing and maintenance literature (Neumann and Majoros, 1998), and recently in educational research (Shelton and Hedley, 2002), where AR interventions have been found to improve conceptual and factual understanding of visualizations of spatial phenomena. Other usability studies have been done, but they seem to 'stay outside the head' of the participant – only external observed behavior is considered, rather than trying to assess how external experiences with AR mediate and influence the form of internal representations, and what the linkages are.

Of the cognitive studies, the most useful work to date concerning cognition is that by Stedmon and colleagues (Stedmon *et al*., 1999a; 1999b). They have conducted early experiments comparing conventional VDU displays to AR displays using basic text and hieroglyphic content, and assessing performance using basic short term memory tasks. They found no significant difference in user performance (recall of text/symbols) using AR displays over conventional VDU displays, though they did find that the AR display performed as well as the conventional display. Building on these findings, they are currently working on considering the potential information display conflicts from combined conventional and AR display settings. The findings of the Stedmon group's work is highly significant for this work, as the augmented reality interface used in their study is passive – that is, while it does update, the user does not directly manipulate content as if holding an object in their hand. If this study finds any differences between AR and desktop display performance, it may well be due to the fact that the type of AR interface in this study is used interactively, through direct user manipulation. The implication of this might be that an additional cognitive pathway is being used, and that it has a significant impact on spatial knowledge acquisition.

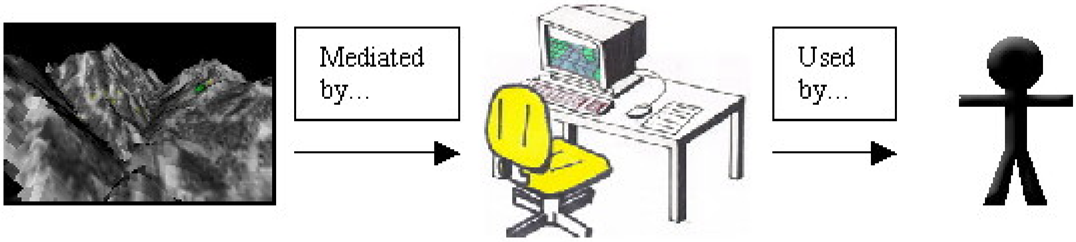
Neumann and Majoros (1998) considered how AR can eliminate the detachment of instructions (requiring cognitive activity to read, understand and relate to a maintenance activity) from actual performance of maintenance (which predominantly involves psychomotor and kinesthetic). They provide a useful cognitive conceptual framework for framing the potential for AR in manufacturing and maintenance. They demonstrated how AR could integrate previously detached instructions and activities, and reduce cognitive loads. However, they did not go on to empirically evaluate these ideas. The other issue was that it involved passive viewing of augmented views of large immovable objects, augmented by virtual content. This would likely yield a fairly passive experience. Their interest was not in the development and retention of spatial knowledge, rather a moment-by-moment set of annotated instructions in linear task settings.

3. EMPIRICAL WORK

An empirical experiment considered between-groups (i.e. AR versus desktop) differences in performance, behavior and cognitive maps due to the mediating effects of desktop versus augmented reality interfaces. This was supplemented by a within-treatments analysis of the influence of visualization content and user characteristics on cognitive representations. Two groups of participants engaged in identical experimental activities. The only difference between treatments was that one group used a desktop interface to interact with 3D visualization content, while the other group used an AR interface to interact with the content. The behavior, performance and task responses of individuals using an Augmented Reality (AR) geographic visualization interface were compared to identical activities undertaken by users of a desktop

3D geographic visualization interface (Figure 3). An array of quantitative and qualitative data were gathered from 101 participants during 250 hours of observation.

Treatment 1: 3D visualization mediated by the use of a desktop interface



Treatment 2: 3D visualization mediated by the use of an augmented reality interface

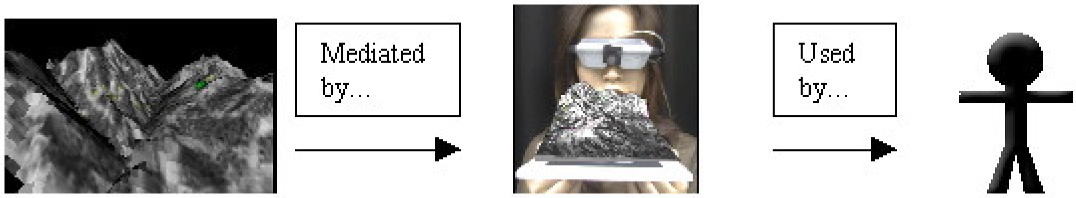


Figure 3. Identical experimental activities, varying only desktop (DT) and augmented reality (AR) interfaces between treatments.

Visualization content and interface were predefined, controlled and manipulated during these treatments. User training and spatial ability were measured. Participants' perception, judgment and internalization responses were measured during experimental activities, providing data about completeness and detail of users' internal representations, speed and accuracy of timed and untimed spatial perception and problem-solving tasks.

Quantitative analysis focused on relationships identified between interface characteristics, visualization content, user characteristics, and the resulting cognitive representations, judgment and performance observed and measured during user activities. Cognitive representations were measured and evaluated in terms of completeness and level of detail. Users' performance and judgment in spatial perception and problem-solving tasks were also evaluated. In all cases, the data were gathered during or in response to a set of five visualization stimuli, and also during timed problem-solving tasks immediately preceding and following the sequence of 3D model interactions.

Preceding analysis, a Mann-Whitney test for independent samples was applied across desktop and AR user groups' pretest scores. This was done to establish any significant differences between the means of the distributions of users' experience and training as measured by pretest activities. These measures included spatial training, spatial experience, visualization training, visualization experience, technology training, technology experience, AR experience virtual environment (VE) experience, and a test of spatial ability (Vandenberg MRT). No significant differences were found between AR and desktop groups for any of these measures (Sig.=>0.05). This test established that there were no confounding differences in user experience or training between interface treatment groups that may have had an influence on other tests in the analysis.

4. FINDINGS OF EMPIRICAL WORK

AR interface use resulted in significant beneficial influence on perception, performance and inferred cognitive representation of 3D geographic visualizations. Significant differences in the distributions of users' representation scores showed that AR interface users' minimum scores in spatial visualization tasks were higher than the equivalent activities performed using desktop interfaces. Significant results were also found in investigating the role of visualization content and physical manipulation of the AR interface, over the use of desktop interface. The combination of significant results comparing interface with user and visualization content, combined with the significant yet small differences inform theoretical positions, confirm suspected relationships between people, interfaces and 3D geographic visualizations, and indicate that there are many methodological challenges to overcome to develop better research methods, and techniques to engage elusive cognitive representations.

AR interface users produced higher feature scores. Subtle displacements in the distributions of features scores were found to be significantly different across interface treatments for some of the stimuli. AR users consistently produced greater levels of completeness in representations. This displacement was clearly visible in the analysis of cumulative frequency distributions. In addition to this observation, the minimum number of features by AR users was represented consistently higher than the minimum performance exhibited by desktop interface users. Lorenz curve analysis provided a visual means to study the quantitative difference in equality of distributions, and showed the relative inequality of feature score distributions and where the majority of feature score performance existed for each interface type, within the respective distribution. AR interface users were seen to have less balanced performance across the population, with performance being weighted towards higher performance than desktop users. Finally, regression analysis found AR interface use significantly predicted higher feature score performance. The advantages found by AR users over desktop users were attributed to the multisensory interactions AR interfaces provide. Direct manipulation of cards augmented with virtual content provides a more transparent interface (one with few layers of metaphor, etc.). At the same time, the coupling of visuo-motor feedback and proprioception provided a powerful sense-making experience, grounded with a stable frame of reference. AR use was seen to result in higher level of detail in representations than desktop interface use. More AR users produced higher level of detail representations than desktop users, and differences were found to be significant for two of the stimulus cases. A significant positive correlation was found between AR use and higher levels of detail in representations for three of the stimulus cases. AR use was found to significantly predict higher levels of detail sixty per cent of stimulus cases.

In a standardized spatial problem-solving activity repeated at the start and end of the experiment, AR users were seen to accurately complete spatial problem-solving tasks 1.57 seconds (22%) faster than desktop users at the start of the experiment, while this margin reduced to 0.3 seconds (5%) percent faster than desktop users when the activity was repeated at the end of the experiment. While this was not a familiar spatial problem-solving task, the idea was to use 3D model content of sufficient abstractness for it to be unfamiliar to all users. By minimizing the potential confounding effects (such as specialized training) on a measure of cumulative exposure to the interface, it allows one to be more certain about the results of the primary visualization activities studied in more detail in this study.

The difference in speed of accurate response suggests that, all other things being equal, AR interfaces have less cognitive inertia than desktop interfaces. That is, in an unprimed setting, user X will be able to understand and interact with content via the interface faster than with a desktop interface. If this is the case, this might have significant importance for situations where user expertise cannot be assumed (such as museums and educational settings), and in other situations where maximum speed of content internalisation and task performance is critical (such as air traffic control and strategic decision making). Cognitive load theory may help to inform an understanding of what is going on. Cognitive load suggests that learning happens best under conditions that are aligned with human cognitive architecture, and aims to achieve this through the evaluation and design of learning practice and technologies, among other things. In this instance, performance for less adept participants may be due to the multisensory nature of the AR interface. That is – the cognitive load is spread across multiple sensory pathways. This does not guarantee better performance, but may maximize the potential of different users' cognitive architecture. The second finding noted above identifies that performance increased longitudinally through the experiment, with time. This training effect is to be expected, as one might expect that with repeated use, user familiarity and skill with interface, content and protocols might increase. However, it appears that the effect was not significantly different between interface groups. This reinforces the previous finding about inertia.

In an assessment of interface manipulation on accuracy of spatial judgments, AR users achieved higher levels of accuracy in static and dynamic spatial tasks than desktop users. However, when the differences between AR and desktop performances were considered in each of static and dynamic treatment, desktop user performance converged with AR user performance. The relationships between 3D model content and static or dynamic manipulation treatment showed AR performance to be higher in both. While using the same 3D model stimulus, the combination of desktop interface and manipulation a stronger effect than for AR and manipulation. The desktop score converged with the AR score in the dynamic treatment. The fact that the desktop score converged with the AR score in the manipulation experiment suggests that manipulation is a more important variable than simply changing from desktop to AR. This finding supports previous findings in studies of virtual environments, where interaction was found to be a more important variable than immersion (Byrne, 1996).

In addition to interface convergence, manipulation produced a larger increase in accuracy when the visualization content was mismatched with structural content, versus when it was matched. This suggests that manipulation activates 3D visualizations used in desktop interface settings. Movement of the 3D model on the display will help users make sense of the 2D image, which provides the illusion of displaying a 3D model. This observation parallels Wood and Fels' (1986) application of semiotic theory to describe how maps operate both intentionally and unintentionally through symbols systems. Without manipulation, visualizations displayed through 2D interfaces (such as paper maps or computer screens) operate through visual codes and symbol systems (Wood and Fels, 1986; MacEachren, 1995). When manipulation is added to this, different perspectives and transitions between viewpoints can be seen, and so additional visual and spatial symbol systems begin to operate. These visual relationships are critically associated with multiple sensory pathways – in order to manipulate the 3D model via the interface, the use of input devices and interaction metaphors are fundamental to both control and feedback. In this case, the influence of physical manipulation was seen to be a significant factor in determining completeness of representations. The evidence here suggests that the activation of visualization-based performance by manipulation is due to the operation of emergent symbol systems embedded in the human-visualization relationship. Though these findings are encouraging, further work is required to more deeply engage and triangulate this relationship.

Manipulated mismatches between thematic and structural information appeared to influence the level of detail and features scores of subjects. It appeared that the 'cognitive signal' in the mismatched thematic model was being interfered with – either through misinformation or confusion or uncertainty resulting from conflicting evidence in participants' perceptions of the 3D model.

The influence of user context variables was also considered. No significant differences were found between the distributions of AR and desktop users' pretest measures of spatial training and experience, visualization training and experience, technology training and experience. This was fortunate, since any significant differences might have undermined the validity of observed trends elsewhere in the study. The Vandenberg Mental Rotation Test (MRT) was completed by all participants as a means to establish a baseline of spatial ability. A significant difference was found between the distributions of results. Men performed better than women on this activity. Female gender was correlated with lower MRT scores (coeff.=-.413, sig.=<.01). This finding was not a surprise, as this difference between male and female spatial ability is well established in studies of spatial rotation tasks including the Vandenberg MRT (Peters et al., 1995) and of spatial visualization tasks (Goldstein et al., 1990) for example. User pretest measures of experience and training, and MRT performance were correlated against feature scores in each of desktop and AR treatment groups. Across all subjects (i.e. regardless of interface type), significant correlations indicated that higher spatial ability was correlated with greater completeness of representations for three out of five 3D stimuli cases, and also visualization training was positively correlated with higher levels of detail in one of the stimulus cases. When the desktop users' completeness (feature) scores were correlated with user characteristics, significant weak positive correlations were found between spatial ability and completeness for three of the five stimulus cases, and spatial experience and completeness for two out of five stimuli. No other significant correlations were found. Across all subjects (i.e. regardless of interface type), significant correlations indicated that visualization training was positively correlated with higher levels of detail in one of the stimulus cases.

When the desktop users' level of detail scores were correlated with user characteristics, significant weak positive correlations were found between:

- spatial ability and detail of representation for one of the five stimulus cases
- spatial training and detail in two of the five stimulus cases
- spatial experience and detail of three out of five stimulus cases
- technological training and level of detail for two out of five stimuli
- technological experience and level of detail for one of the five stimulus cases

Perhaps what we are seeing here is that AR supplants human cognitive ability as result of the combined visual and sensory feedback provided by and embodied in the interface itself. The number of correlations found between the Vandenberg MRT and desktop versus only one correlation between MRT and AR suggests that perhaps the symbol system of AR does cognitive work for low ability subjects that they are not capable of doing for themselves. If there were more participants in this study, a 2-way factorial analysis of high and low MRT scores (omitting intermediate scores) could possibly corroborate this claim. With so few subjects, low statistical power is problematic to perform that analysis for this study.

Other user factors observed during the experiments include unique experience/background-based effects. For example, during the use of a DEM of Honolulu, one subject provided a highly detailed description of the coastline, including numbers of inlets, detailed descriptions of the shape of inlets. His description of the areas away from the shore were unremarkable, if not poor compared with other participants. The post-test interview provided an opportunity to try and unpack not just an emphasis on the coastline, but a sophisticated approach to detailed representation. As it turned out, the subject was an amateur sailor. This reveals the possibility for highly-tuned active search and perception of meaningful features of interest or for action. This observation is informed by the work of Lowe (1993), who compared the ways in which meteorologists construct mental representations from weather maps. Distinct differences were found between the performance of professional meteorologists and non-meteorologists. Non-meteorologists were found to focus on superficial, domain-general, visuo-spatial features, and could recognize spatial patterns in the diagram but were not adept at translating this spatial knowledge into weather knowledge. Professional meteorologists were more skillful at selecting those visual features that are essential for developing an understanding the state of the weather system being depicted, and were better able to decode the semantic analogies -- between the visuo-spatial characteristics of the diagram and the physical characteristics of the weather system encoded into the maps.

Spatial ability (measured by Vandenberg MRT) and AR interface use in the experimental activity were the most important predictors of more complete, detailed and accurate responses. Spatial ability and AR interface use alternately were the most significant predictors of higher levels of representations, detail and task performance. It was as if when the interface was not carrying the cognitive load, the user's spatial ability kicked in, and when spatial ability was not useful, the interface did the work. Visualization experience and spatial training were next in importance. This suggests then that the interface and spatial ability may be more influential on spatial knowledge acquisition from geographic visualization interfaces, than spatial training or visualization experience. There may be a symbiotic relationship here – spatial ability in users is activated by the inherently spatial AR interface, whereas the desktop interface operates through understanding a set of controls, metaphors and symbols which result in rotation and manipulation of 3D visualizations. In the case of the less frequently significant predictors – AR and VE experience – inherently spatial interface characteristics and basic familiarity must play a role.

This evidence suggests that the combination of visualization content, interface affordances and users may interact to influence the development of spatial knowledge. This may in turn inform how a transformational view of the classification, representation and display of spatial phenomena may be enhanced by a commensurate understanding of how people interact with geographic visualizations to acquire spatial knowledge.

5. DISCUSSION

The findings of this study suggest that AR provides an increase in completeness and level of detail in representations of geographic visualizations over a desktop interface. The differences detected were modest, but were validated by knowing that they are not a result of confounding effects of user context, nor are they an independent result of visualization content. Thematic and structural content had a significant effect on memorization of 3D visualizations, but these differences existed regardless of the AR or desktop interface.A hierarchical cluster analysis of all users found some structure in the user characteristics. Between desktop and AR treatments however, an independent t test showed no significant difference in these populations.

The implications of this study's findings in the AR literature are as follows. The most recent study that aimed to look at the cognitive model development from AR was that of Stedmon and colleagues (1999) involving learning visual content using augmented reality. In that study no significant difference was found between AR and conventional VDU displays. In this study, differences have been found in task performance, task speed, completeness and level of detail. One of the main interface characteristics that may have caused this difference is the fact that AR interface used in this study can be held, allowing direct manipulation of the 3D model. This provides constant visuo-motor feedback (combinations of coupled visual and sensor-motor feedback, as reviewed by Jacobson, Kitchin and Golledge, 2002) to user queries. Like Neumann and Majoros' (1997) discussion of augmenting workspaces, AR displays used in the Stedmon et al. study (1999) were passive and static. That is, no physical manipulation of the AR display occurred. The result of this may be that less information (than is possible) is allowed to be integrated in the internal representation, as only the visual (and by default, the vestibular) sensory pathways are being used.

From a methodological viewpoint, this study experienced many of the challenges identified by Kitchin and Blades (2002) to measuring, characterizing and analyzing cognitive maps, and has attempted to respond with convergent measures of different kinds. This approach has been useful in order to accommodate participants of different preferences for expressing internal representations, thereby ensuring that representations are not accessible simply because the option to express it in a certain way does not exist. One of the biggest challenges of this study has been the limited work that has preceded it – this is the first study of 3D AR use that integrates geographic visualization, cognition and interface perspectives in a social behavioral study. The intent was to develop standardized approaches to evaluating combinations of interface 3D visualization and user in understanding the development of cognitive maps. In order to do so, this initial work was necessary to identify interesting relationships and factors that appear to be significant, as a first step towards establishing a set of priorities for further research.

The implications of this work for spatial cognition are as follows. The evidence found with regards to interface manipulation may suggest that the coupled visual and sensorimotor feedback that AR provides, results in a sort of cognitive salience or reinforcement, producing an anchor-point like node in internal representations. First, this work has seen a number of compelling indicators that Golledge's (1978) anchor point theory may be extended to geographic visualization interfaces – notably the role of manipulation and thematic visualization content in providing foundations which may assist the development of structure in internal representations. This was significant, since some authors in geographic visualization research have provided sweeping overviews of theoretical context to practical work, rather than considering how they might be made operational, implementing them, and integrating them into practice in order to study them. Work needs to be done to refine it, but if spatial anchors can be extended to multi-sensory anchors in interaction environments, then it may be possible to build a new theoretical framework which allows us to understand emerging interface technology from geographic and spatial cognitive perspectives, at the same time as forming a transformational link between the powerful conceptual frameworks that have been developed and refined in cartography, and the state-of-the-art in geographic visualization interface technology.

This work suggests that through multisensory interaction (Figure 4), the AR interface may indeed spread cognitive load for users, thereby reducing cognitive inertia. Greater sensory possibilities provided by interfaces raise the possibility of additional symbols systems with which to present and understand information - that symbol systems affect knowledge acquisition as a result of different aspects of visualization content, recoding by the individual, and the symbol systems inherent in the components of the media type in question.

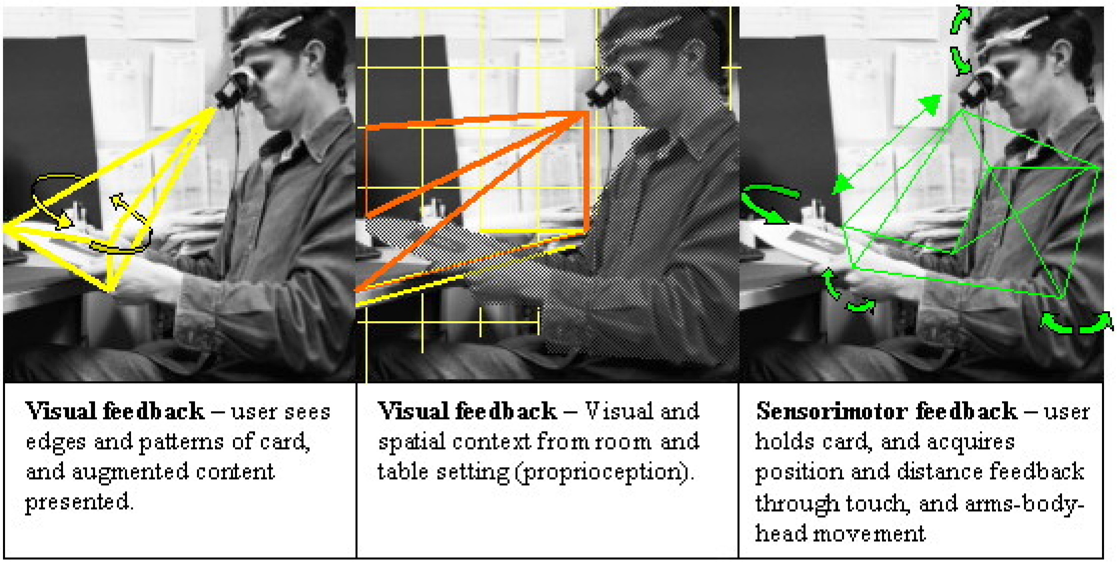


Figure 4. Dimensions of AR multisensory feedback in 3D AR interface use.

The topic of symbol systems provides a fitting link back to geography. This work demonstrated the individual and differential effect of interface, visualization content and user on the development of internal representations with geographic visualization in mind. While this is a very new area for geography, these findings do not refute existing literature. On the contrary, they rather suggest strong potential for a new theoretical framework which extends accumulated critical cartographic understanding of map and GIS use to the point of translation into the new media economy of geographic visualization. Anchor point theory (Golledge, 1978), and semiotic theory (operationalized by Wood and Fels, 1986; reviewed and emphasized by MacEachren, 1995) can be extended to geographic visualization interfaces and combined with other theoretical approaches in order to maximize an understanding and the potential of new geographic visualization technologies. Most importantly, this project provides cartographic, interface research and spatial cognitive perspectives from which we may begin to better understand the role of explicit and emergent properties of GVIS interfaces as geography enters a period of rapidly progressing visualization interfaces. These needs are evidenced in the recent acknowledgement by Jacobson, Kitchin and Golledge (2002) that new multi-modal interfaces have extremely high potential in for geographic information interaction, characterization, display and analysis of geographic information. It is hoped that the research presented in here provides an early step towards responding to this call, and to assist geographers in embracing new interface technologies.

6. CONCLUSIONS

The evidence identified through empirical work described in this paper suggests that augmented reality interfaces do indeed appear to provide advantages over desktop interfaces in a range of perceptual and task-based activities for users in of geographic visualizations. The measures of internal representation used (video analysis, sketch and verbal protocol analysis, timed and untimed perceptual and judgment tasks, survey responses, interview responses, forced choice and recall tasks) suggested that individuals develop more complete and detailed internal representations when AR is used, than when desktop interfaces are used.

Visual content and interface aspects seem to play a significant role in these settings, and there is indirect evidence in this work suggesting that user context does also. However, accurately characterizing the nature of internal representations is a significant challenge. What should be measured in order to characterize a cognitive representation? There is certainly little consensus in the spatial cognition literature (Kitchin and Blades, 2002). Kitchin's suggestion of convergent measures, echoing Waller (1998) is a useful approach to take, and may help us triangulate these relationships from different perspectives.

This work may help to establish a working knowledge base of how these individual components and aspects of interface, user and visualization influence an understanding of geographic information. These are the first steps towards developing a means to understand what kinds of spatial features have what kinds of cognitive signal, how different types of interface influence the cognitive signal, and what factors amplify it or modify it. That is, given the stimuli, what kind of internal representation is likely to result? Given certain kinds of interface with these kinds of affordances, what kinds of internal representations are likely to result? Given certain user skills, what kinds of internal representations are likely to result?

As geographic visualization interfaces become viewed as interfaces, rather than as individual tools, then the geographic community will need to more fully engage their multi-modal nature. This will require the development of hybrid conceptual frameworks that couple interface, geographic visualization and cognitive perspectives. These frameworks will need to be investigated for robustness, and so sophisticated techniques for empirical evaluation will be needed. This need has recently been identified by Jacobson, Kitchin, and Golledge (2002) in the first book in geography to be dedicated wholly to virtual reality (Fisher and Unwin, 2002). It is hoped that the work reported in this project provides a contribution to research in geographic VE research by the development of just such a conceptual approach to these issues, and a first attempt to engage these dimensions simultaneously as a starting point from which to improve an understanding of this kind of technology.

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EMPIRICAL EVIDENCE OF ADVANCED GEOGRAPHIC VISUALIZATION INTERFACE USE

Hedley, N.R.

Department of Geography and Human Interface Technology Laboratory,
Seattle, USA. E-mail: nix@u.washington.edu

Biography

Nick Hedley engaged in PhD work in the Department of Geography at the University of Washington, Seattle USA. He is currently a researcher at the Human Interface Technology Laboratory (HITLab.) at the University of Washington, and an interface research and development consultant for a number of international organizations. His research interests lie at the intersection of geographic visualization, geographic information science, spatial cognition and advanced interface technologies. This includes design and development of new interface technologies, theoretically informed empirical work and usability evaluation. He is currently engaged in developing new visualization interfaces for applications which include classroom and museum geographic education, geographic visualization, decision-making and analysis.