Title
Multiple Modalities and Multiple Frames of Reference for Spatial Knowledge, Final Report

Authors
Freundschuh, Scott M.
Taylor, Holly A.

Publication Date
1999-02-01

Multiple Modalities and Multiple Frames of Reference for Spatial Knowledge

Final report on Varenius Meeting, Santa Barbara CA, 18-20 Feb 1999

By Scott M. Freundschuh and Holly A. Taylor

Multiple Modalities and Multiple Frames of Reference for Spatial Knowledge

Final report on Varenius Meeting, Santa Barbara CA, 18-20 Feb 1999

By Scott M. Freundschuh and Holly A. Taylor

I. Executive Summary

A. Introduction

A 3-day workshop titled Multiple Modalities and Multiple Frames of Reference for Spatial Knowledge was held in Santa Barbara, California on 18-20 February 1999. This workshop was supported by the National Center for Geographic Information and Analysis' (NCGIA) Project Varenius. It is was the third of three workshops organized under the auspices of Project Varenius' Cognitive Models of Geographic Space panel. The other two workshops, Scale and Detail in the Cognition of Geographic Information and Cognitive Models of Dynamic Geographic Phenomena and Representations took place May 14-16, 1998 and October 29-31, 1998 respectively. Scott Freundschuh from the Department of Geography at the University of Minnesota, Duluth and Holly A. Taylor from the Department of Psychology at Tufts University we co-leaders of this initiative. A steering committee, along with the co-leaders, was responsible for setting the meeting agenda and identifying critical issues, for reviewing proposals submitted by potential participants, and for reviewing seed grant proposals submitted by participants. Members of the steering committee included:

Reginald Golledge from the Department of Geography and the NCGIA at the University of California at Santa Barbara;
Sucharita Gopal from the Department of Geography at Boston University;
Roberta Klatzky from the Department of Psychology at Carnegie Mellon University;
Robert Lloyd from the Department of Geography at the University of South Carolina;
David Mark from the Department of Geography and the NCGIA at the State University of New York at Buffalo;
Timothy McNamara from the Department of Psychology at Vanderbilt University;
Nora Newcombe from the Department of Psychology at Temple University;
Eric Pederson from the Department of Linguistics at the University of Oregon; and
Barbara Tversky from the Department of Psychology at Stanford University,

B. Theme of Workshop

The workshop focused on research issues concerning various modalities for experiencing geographic space and the influence on the spatial knowledge acquired, as well as issues pertinent to reference frames used to make sense of geographic information. The original Call for Participation described the meeting as follows:

Knowledge about space can be obtained directly, through actual navigation for example, or indirectly, through depictions and descriptions. Direct experience includes locomotion through the environment (crawling, walking, running, bicycling, driving, flying, etc.) as well as stationary viewing (at an entrance or scenic overlook). Additionally, direct experience is multimodal, including proprioceptive, kinesthetic, auditory, visual, and other sensory input. Secondary environmental experience can be derived through both static and dynamic mediums. Static pictorial representations include maps, diagrams, paintings, photographs, and 3-D physical models. These representations are smaller scale models of environments and are typically sensed via vision, but can be experienced through other modes, such as tactile and/or auditory. Dynamic representations take maps, diagrams, paintings, photographs, and 3-D models and animate them to show change over time, rather than "snap-shots" in time. Advances in technology have made these dynamic representations, in the form of virtual tours or virtual reality models, a significantly more common experience. These secondary representations can also be sensed multimodally, although visual input is generally primary. Finally, although the furthest removed from the actual environment, language, either written or spoken, is often used to convey spatial information. Although the specific conventions for relating spatial information vary throughout the world's languages, all can be used for this purpose, including systems considered special cases of language, mathematics and gesture systems.

In conjunction with the various ways of experiencing space, environments can be viewed from different perspectives, and conceived of from perspectives that have not or cannot be viewed. These perspectives include the vertical ("bird's eye" or survey) view of a map, the oblique perspective as if looking in a valley from a hilltop, or the horizontal (route) perspective experienced via locomotion through the environment. Spaces can be perceived as surrounding or engulfing people or objects, such as buildings or cities, or spaces can be experienced as if separate from, or outside of the space, such as a map or scenic overlook. Today, the ability to use computer-generated representations to switch between perspectives allows nearly simultaneous views of different perspectives and scales.

Multiple modalities and multiple frames for the acquisition of spatial knowledge raise a number of new questions, as well as revive a number of old questions, about spatial perception and cognition. For example, how do children acquire spatial knowledge and expertise with different modalities?; how does the ability to acquire and use spatial knowledge vary over the life-span?; do people integrate and reconcile spatial information from various modalities?; are there relative advantages or disadvantages of different kinds of spatial knowledge for different tasks?; how is spatial information from different modalities and different perspectives reconciled? These and other questions have arisen in linguistics, philosophy, computer science, anthropology, and psychology, as well as in theoretical and applied contexts in geography. The answers, however, remain largely unclear, especially with respect to human behavior and learning in natural situations. Understanding how people combine or juggle spatial information from a variety of sources and in multiple forms is important to geographic information science in general, and for geographic information systems (GIS) in particular.

At one level, a greater understanding of how various spatial information is acquired, integrated and utilized will allow researchers more intimate access to the seemingly complex, spatially motivated, human decision making processes (e.g., where we live, work, recreate, navigate, etc.). At a more practical level, understanding the influence of various spatial information on decision making processes will foster the design of computerized systems (such as GIS, vehicle navigation aids, real-estate guides) that provide spatial information in a way that is useful to the human user. The result, therefore, is a better understanding of the "spatial world" on the part of the human user, and subsequently, enhanced decision making and increased user satisfaction.

The following list of research topic areas and questions were put forward in the *Call for Participation* to provide a basic framework for workshop presentations and discussions.

Topical Research Areas

Multiple Modalities:

- learning environments via maps, navigation, and virtual navigation
- tactile, auditory, and visual localization and navigation
- learning environments from spatial descriptions

Multiple Reference Frames:

- relative, intrinsic, and absolute reference frames for describing locations
- orientation-free vs. orientation-specific representations
- heads-up and north-up maps in navigation systems
- mixing gaze, route, and survey perspectives in descriptions
- expressing differing modalities or frames through language
- cross-cultural differences in the use of reference frames.

Potential Research Questions

- How do children acquire spatial knowledge and expertise with maps, navigation (real and virtual), and spatial descriptions?
- How does the ability to acquire and use spatial knowledge vary over the life span?
- How do people integrate and reconcile information gathered via various input modes?
- What are the relative advantages and disadvantages of the various types/modes of spatial information?
- How does information gained through one modality transfer to other modalities for recognition?
- Do people integrate spatial knowledge acquired via different perspectives? What is the nature of the representation(s) and what process(es) does it support?
- How do people conceive of perspectives other than those that have been directly experienced? What impact does the experienced perspective have on the conceptualization of other perspectives?

C. Purpose and Structure of the Workshop

The purpose of the workshop was to identify and prioritize a research agenda for exploring multiple modalities and multiple reference frames for spatial knowledge. This was achieved via the proposals submitted by applicants to the workshop, by summary presentations at the workshop that framed discussions, by discussions in breakout groups during the workshop, by research activities that were developed at the workshop (several subsequently supported by seed grants awarded after the workshop), and finally by the completion and distribution of this report.

The structure of the meeting included a combination of summary presentations made by members of the steering committee and by one of the workshop applicants, small break-out-group discussions about specific topics identified in the summary presentations, and presentation of summary reports of breakout group discussions to all workshop participants.

D. Participation in the Workshop

Potential participants responded to a *Call for Participation* that was distributed electronically to various email lists multidisciplinary in nature, that were subscribed to by a broad and diverse group of researchers. Applicants were asked to submit:

- a brief indication of why they wanted to participate in the meeting, why they were interested, and/or what they would contribute;
- a position statement or research abstract, describing a particular element of or perspective on the topic (3 pages); and
- a brief curriculum vitae with up to five (5) selected publications most relevant to the topic (1 page).

All submissions were reviewed by the initiative co-Leaders and by the Steering Committee. Thirty-eight proposals were submitted, of which 20 applicants were invited to attend. In addition, representatives from NSF and the Federal Government were invited to attend, as were the members of the steering committee and the Varenius Cognitive Panel members. In all, there were 38 participants in the workshop. In addition to these attendees, 7 graduate students from the University of California at Santa Barbara and 1 graduate student from Tufts University participated in the workshop, serving as raportuers. The participants represented the disciplines of geography, psychology, human factors, computer science, cognitive science, engineering, information sciences, education, linguistics, and environmental design. Project Varenius provided the financial support for lodging and food, and for travel to the workshop.

E. Schedule of Workshop Activities

Thursday, February 18:

8:45 - 9:30	Opening Remarks and Introduction to Meeting (Scott *Freundschuh and Holly Taylor*) Introduce Varenius and NCGIA (*David Mark*) Discuss Goals of Meeting: To Set Research Agenda (*Holly Taylor*) Seed Grants and Visiting Scholars (*Scott Freundschuh*)
9:30 - 10:30	Introduction of participants – participants give 2 minute introduction of themselves and how their research fits into the meeting topic.
11:00 – 12:30	Summary Presentations by Selected Attendees: Multi-modes *Roberta Klatzky* *Daniel Montello*
1:45 – 3:30	Breakout Discussions on Multi-modes
4:00 – 5:30	Reports and Discussion of Break-out Groups

Friday, February 19:

9:00 – 10:30	Summary Presentations by Selected Attendees: Multi-frames *Timothy McNamara*

	Nora Newcombe
11:00 – 12:30	Break Out Discussions on Multi-Frames
2:00 – 3:30	Reports and Discussion of Breakout Groups on Multi-Frames
4:00 – 5:30	Summary Presentations by Selected Attendees: Intersection of Multi-Modes and Multi-Frames *Barbara Tversky* *David Mark*

Saturday, February 20

9:00 – 10:30	Breakout Discussions on Intersections of Multi-modes and Multi-frames
11:00 – 12:30	Reports and Discussion of Breakout Groups
2:00 – 3:00	Small Group Discussions Focused on Specific Research Agendas (group sizes 3 or 4)
3:00 – 4:00	Discussion to Pull Together Main Issues for Research Agenda

F. Outcomes of the Workshop

The outcomes of this workshop range from the production of this report, to collaborations arising from bringing together researchers to discuss research issues. Here is a detailed list of outcomes:

- a list of researchable questions that was generated throughout the workshop (and is presented at the end of this report);
- new interdisciplinary collaborations between researchers;
- the awarding of seed grants to four groups of participants in the workshop;
- the bringing together of renowned researchers, both national and international, from the disciplines of psychology, information science, cognitive science, computer science, and geography, as well as the National Science Foundation and NASA Ames Research Center to assemble a research agenda for the topic of this workshop;
- publications arising out of ideas formulated at this meeting;
- the integration of graduate students from Tufts University, University of Texas, University of Surrey, University of Hamburg, and the University of California into discussions and break out groups, therefore nurturing future scholars.

G. Overview of Report

This report consists of six sections: the Executive Summary, the Plenary Papers presented by members of the steering committee, reviews of the breakout sessions, the formulated research questions, a list of the workshop participants, and acknowledgements.

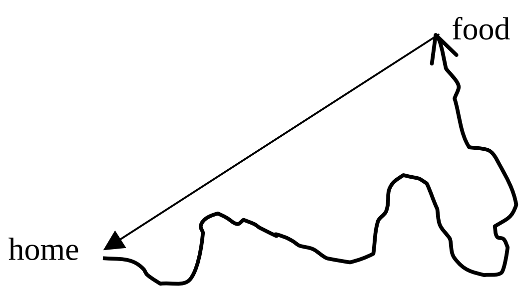
The breakout summaries in this report are based on notes taken by raportuers, by notes taken by the co-leaders during the summary presentations, and by notes provided by the various presenters and breakout session facilitators. These summaries reflect the dialogues that occurred during the breakout sessions, during the presentation of the plenary papers, and during the presentation of the summaries of the breakout sessions. The summaries here are not meant to be a full account of what was said by participants, but rather highlight the main points of discussions.

II. Plenary Papers

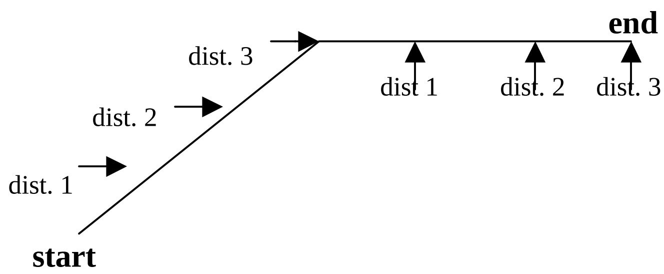
A. Roberta Klatzky — Plenary paper on Multiple Modalities

We have a number of reference frames that are explored in psychology, including route and survey, allocentric and egocentric, Cartesian and polar. Do we need more distinctions? We can consider differences in reference frames used by people based on task level distinctions. One level of tasks is stimulus directed actions that are driven by perceptual events. People are good at some of these actions, even when the stimulus does not persist. For example, people can site a target, close their eyes and walk straight towards the visual target very accurately. In contrast are auditory targets, or sound cues. With eyes closed, people are not nearly so good at reaching a target accurately. In this instance, they misperceive the auditory distance, trending toward a slight underestimation of distances for shorter distances and higher underestimations for longer distances—in other words, the underestimation of target distance increases with increasing distance to target.

Another level of tasks is path integration, which is the process of knowing based on optical flow, velocity and time (this is distinguished from landmark integration). Path integration is characterized by an encoding problem, but execution of the task (i.e., the process used to solve the task) is flawless. A number of studies with animals and humans illustrate different abilities with regard to path integration tasks, especially when the immediate stimuli (i.e., destination/ home) are not perceptible. For example, foraging ants can search for food along a highly irregular and winding foraging path from their “home”. Once food is located, ants are able to walk, along a straight line, directly back to “home”, or to the starting point (see the following figure).



Ants are able to build a fairly accurate representation of what the outbound path is. Studies have shown that humans, in comparison, struggle with this task. One study found that when people attempted to navigate back to “home”, there were errors in the representation that they constructed to represent the space. In this study, subjects were taken blindfolded out one of three different distances along the first leg of a triangle, walking. They were then taken out one of three different distances along the second leg of the triangle. Subjects then had to turn and walk back toward the start (see the next figure).



Error in subjects' orientation toward the beginning point was a function of the representation they had built of the first leg of the triangle. In other words, error is based upon the representation of the outbound path. This fits the "encoding error model". Path integration, therefore, is characterized by a misrepresentation of the first leg of the route.

This experiment was repeated on a table top (i.e., table top space) that rotated slowly. Subjects traced, by finger, the legs of the triangle and then the "path" back to the start. Translation and rotation were added conditions to the experiment. Subjects were asked to imagine a triangle shifted, and then traced the last leg of the triangle back to the origin. Translation modestly effected angle estimates, but had little impact on distance error. For the rotation condition, subjects had to trace the last leg of the triangle back to the origin, after the tabletop had been rotated. Rotation had a much larger effect on angular error, which was caused by a major change in the shape of the triangle. In this case, the encoded representation was enormously truncated—the rotation "blew apart" the internal representation of the triangle.

The questions that multiple modalities raise include how does modality constrain the reference frame used? What are the implications for scale of geographic space and modalities? What is the nature of the integration of spatial knowledge gained from visual, auditory and haptic modalities? How do training, experience and level of expertise impact the use of multiple modalities for acquiring spatial knowledge?

B. Daniel Montello: Multiple Modalities in the Apprehension of Geographic Information: Senses, Motor Systems, and Presentation Media.

What and how people think about geographic space depends in important ways on how knowledge of the properties of that space, and of the objects and events within that space, has been acquired. The premise is that understanding human perception and cognition of space is necessary in order to arrive at a complete understanding of human reasoning, decision-making, and behavior that involves knowledge of space. In particular, it is necessary to understand how spatial knowledge and its use differs as a function of the source from which that knowledge is acquired. Does this idea have implications for the design and use of geographical information systems? I believe that it does.

The scientific study of spatial perception and cognition began in the 19th century, but of course was derived from the philosophical theories of earlier times. In the present century, psychological questions about space have focused on several issues: the responses of sensory systems that pick up spatial information, the development of spatial knowledge from birth to adulthood (ontogenesis) and upon first exposure to a new place (microgenesis), the accuracy and precision of knowledge about distances and directions, processes and structures used during navigation, as well as perceptual and cognitive issues in cartography, and very recently, geographic information systems (GIS). With the advent of new technologies like GIS, new questions about spatial perception and cognition develop, and old questions (both basic and applied) become focused in new ways. We believe that several interesting and important questions for GIS research and design are related to issues of human perception and cognition of space and spatial information. Nonetheless, the potential of this research area has only been hinted at thus far. Spatial knowledge about environments may be acquired from any of several different sources. The following is a comprehensive list of sources of spatial knowledge organized into four categories:

1. *Direct environmental experience*. Being the "original" source of spatial knowledge about the environment, and probably the most common and fundamental, people acquire a great deal of spatial knowledge about environments from direct experience in those environments. There are several variations that may have important implications for the nature of resulting cognitive representations. Does the experience include locomotion through the environment or just stationary viewing? If locomotion, is it mechanically aided (bicycle, wheelchair, car, plane, etc.) or not (crawling, walking, running, etc.)? Furthermore, it is important to realize that spatial properties of directly experienced environments are not just "seen". They are sensed multimodally: proprioceptively, auditorily, and perhaps other ways to lesser extents.

2. *Static pictorial representations*. These are the relatively small external representations, which have long been used to store and communicate spatial information. They vary in their abstractness, from maps and diagrams to paintings and photos. We also include 3-D physical models as "quasi-pictorial" representations, as they suggest topography directly but are still primarily about a 2-D planet surface. And though most often designed for vision, pictorial representations are also available for the tactile and auditory modalities.

3. *Dynamic pictorial representations*. When movement depicts changes in features or variables over time, we can speak of dynamic pictorial representations. The variations described above for static representations apply here, including the possibility of dynamic 3-D models. Some dynamic representations are more map-like (animations), others are more experience-like (movies and videos). We consider the new technology of virtual reality (or virtual environments, etc.) as an increasingly important example of this last category. It constitutes a terrain-level simulation of direct environmental experience, viewed at the same scale as those environments.

4. *Language*. Finally, people often obtain spatial knowledge through language. It may be spoken or written (even sung). Sign languages for the deaf and Braille for the blind are special cases. Although natural language is most often the concern here, we include mathematical and gestural languages as well.

Like any taxonomic system, the categorization offered here is but one interpretation. Alternative organizations are possible that could highlight other characteristics. Any such system can be misleading, insofar as it suggests shared properties that do not hold. An important point not captured by this categorization is that multiple sources often operate, either simultaneously or sequentially. A critical set of research questions, still largely uninvestigated, relates to the integration or combination of multiple sources of spatial knowledge. It may be more useful instead to focus on the factors that differentiate the myriad sources with respect to the cognitive/perceptual processes involved and the resulting knowledge structures. Here are several plausible candidates for such factors, suggested by our list of sources and by the literature:

1. *Sensory/motor systems*. Sources vary with respect to the sensory systems involved. Possibilities include one or more of the following: vision, touch, hearing, kinesthesia, and vestibular sensing. Smell is less likely, and the existence of "magnetoreception" is questionable. In addition, motor systems that might be involved include everything from eye, head, and hand movements to climbing and walking. To the extent that the nervous system can monitor its own motor commands, "motor efference" can also provide knowledge about space.

2. *Static vs. dynamic information*. There are two ways in which the sources can vary in terms of a static/dynamic factor. Some sources depict dynamic information, information about change over time. In addition, some sources depict dynamic information statically, such as a map with arrows showing movement, while others depict it dynamically, such as through animation.

3. *Sequential vs. simultaneous acquisition*. The various sources differ with respect to whether they promote relatively simultaneous or sequential pickup of spatial information. A pictorial representation is a typical example of the former, language of the latter. However, this distinction should not be overstated, as it often is, because all spatial information pickup is sequential to some degree. Even simple viewing of a map or photograph occurs over time as the eyes scan from one place to another, foveating small areas for maximal resolution.

4. *Symbols and their arbitrariness*. The interpretation of spatial and/or nonspatial information via some sources requires that symbols be translated. Symbolic representation occurs when a pattern or feature on a representation "stands for" something else. The location of objects in a room is nonsymbolically perceived when you are looking at them in the room, symbolically perceived when seen on a blueprint. But importantly, symbols vary in their arbitrariness/iconicity. This is essentially a question of the degree to which symbols resemble what they represent, their "referent". Relatively iconic symbols have shape or other properties that are similar to those of the referent. A USGS topographic map, for instance, represents 2-D location in an iconic way because places further away from a station point in the world are further away on the map, etc. Arbitrary symbols stand for their referent according to convention only. Contour lines on the topographic map represent elevation in a largely arbitrary way. Language represents spatial information in a completely arbitrary way.

5. *Scale translation and flexibility*. Given a symbolic source of spatial knowledge, a question is whether the space of the representation is at the same scale as the space of the referent. If not, the user will need to perform a scale translation to obtain some of the spatial knowledge available. Further, some sources that require scale translations will be flexible in allowing

multiple scales to be shown, either simultaneously or sequentially with little or no lag time, perhaps at the user's discretion (with a well-designed computer mapping package). Although the question of scale typically focuses on space, time would also be an issue with dynamic representations. Is the change shown at the same speed as the actual event, or is it slower or faster?

6. *Viewing perspective*. Sources of spatial knowledge may be differentiated according to the perspective from which their spatial information is viewed. This includes the traditional vertical perspective of a map, the horizontal perspective of much terrestrial locomotion, and the oblique perspectives in between. Among other things, viewing perspective may influence the degree to which a person experiences space from the "inside" or the "outside" (as might the factors of scale and detail). The "internality" or "externality" of a source apparently has implications for the storage and processing of spatial knowledge in several ways, as some of the articles discuss. Although sources of spatial knowledge have historically allowed viewing from only a single perspective, modern technology holds the promise of allowing viewing from multiple perspectives just as it allows for multiple scales. Interestingly, viewing perspective is even a question for linguistic sources.

7. *Precision*. Sources of spatial knowledge differ a great deal in terms of the precision with which they represent and communicate spatial information. Even when a spatial property such as location or distance is precise in the world, it need not be perceived or represented as precise. Probably the most important example of this is natural language about space. To say "the bike is in front of the school" does not specify the bike's location very precisely, but it is a common way of speaking even when the speaker knows the bike's location much more precisely. It is important to remember that one does not always want to maximize precision in a knowledge source; efforts are sometimes made (or maybe should be) to reduce the communicated precision of the information. For instance, boundary representations on maps commonly mislead by suggesting a sharper separation than actually exists in the world.

8. *Inclusion of detail, some irrelevant*. Finally, sources of spatial knowledge vary a great deal in the degree to which they include details, possibly irrelevant. Much of the information we are exposed to as we directly experience environments is irrelevant to our understanding of spatial properties (or any useful properties). A photograph of a house contains more detail than a simple sketch of that house. Verbal navigation instructions ("directions") always leave out details about properties of the space that are not relevant to the purpose of navigation; unfortunately, they not uncommonly leave out relevant detail too. In addition, what is relevant varies from person to person.

Research by Montello and Richardson with subjects who learned two floors of a building layout via walking through the building (1/3 of subjects), from maps (another 1/3 of subjects), and virtual simulation of a walk through the building (1/3 of subjects) was summarized. After learning the building layout, subjects performed a number of ‘pointing to landmark’ and ‘distance estimation’ tasks. For pointing error (absolute error in degrees), the map and walking learners had the least amount of error (the same), and the virtual simulation learners had significantly more error. The virtual simulation learners also had the most error performing orientation tasks between floors. There was also an alignment effect. Map learners had misalignment problems in their estimates, where the virtual simulation and walk learners did not.

For the distance error, all three groups of learners performed about the same in route distance estimates, with the correlation of 0.7 between route distance estimates and the actual distances. For straight-line distances, the map learners had a significantly higher correlation between estimated and actual distances (0.7), with the walk learners next (correlation of 0.5) and the virtual simulation learners having a correlation of 0.3. These results indicate that how a space is learned impacts how the spatial knowledge is encoded and remembered.

C. Nora Newcombe – Plenary Paper on Topic of Multiple Frames of Reference

What is the developmental course for using spatial frames of reference? The primary reference frames in development include 1) the self and 2) non-self objects. Two dimensions, each dimension with two values, can define previous research on this topic: associativity (associative or non-associative) and reference frame center (self or landmark). The following table illustrates evidence supporting different reference frame systems:

	Self	Landmark
Associative	Sensorimotor stage Egocentric responding Response learning	Cue learning
Non-associative	Dead reckoning Inertial navigation Path integration	Place learning

In examining the type of system children use, Newcombe and her colleagues hid objects in a long, rectangular sandbox. After watching the objects being hidden, children (aged 16-36 months) searched for the hidden objects either from their present location, or from the opposite side of the box. In some cases, visual landmarks were available, or they were presented in a curtained environment. The curtained environment required direct knowledge of the objects' locations rather than relative knowledge. Children did not seem to make use of the landmarks until after 21 months of age. The performance decrement due to moving did not lessen as a function of age. In general, children 16-24 months were quite good at the task. It appears that their coding of distance is not dependent on outside landmarks. Further, it is not heavily dependent on the child's own position.

Further research examined performance on this task by older children (aged 4-5, 6-7, and 10-21). Evidence suggests that older children and adults code the space hierarchically, creating subdivisions within the space. However, the nature of the search space also influenced the age at which children imposed these subdivisions.

Memory for spatial location goes beyond the simple coding of location and also incorporates representation of the space. Successful use of maps requires understanding of the mapping between the physical representation and the actual environment. Additionally, perspective taking requires the ability to manipulate a mental representation of an environment. The problems children have with Piaget's 3-Mountain task can be defined as a conflict between frames of reference. Children have the perceptual frame of reference of their current location and must suppress that to determine an alternate perspective.

In the development of spatial cognition, there are a number of concepts that need to be mastered. There seems to be some developmental progression relative to these issues. The starting points in this developmental progression involve response learning, cue learning, coding of various types of information (proprioceptive, efferent, visual, and distance), the construction of categories, and understanding of hierarchical relationships. Within the developmental progression, a transition appears to occur around age 2 to 3 years. This transition involves place learning, understanding of configurations, understanding of durations, and representational insight. Beyond this point and up until about 10 years of age, children begin to use mental subdivisions, categorical coding, and functional representations.

D. Tim McNamara – Plenary paper on topic of Multiple Frames of Reference

When individuals learn a spatial array, such as a set of objects placed on a table, their viewpoint on the array can serve as a framework for remembering the objects. Research conducted by McNamara and his colleagues has examined the question of whether individuals use this framework for remembering spatial locations. In initial studies, participants learned a set of objects placed on a square mat in a room. The sides of the mat were aligned with the sides of the room. Participants learned the array from a single vantage point (referred to as 0°). Results from a pointing task indicate that memory for the array of objects is viewpoint dependent, i.e. participants more accurately determined the relative location between two objects when they were aligned with their original vantage point.

When learning a spatial layout, however, more than one reference frame generally exists. In the experimental situation described above, the participant's vantage point provides one possible reference frame. In addition, the mat on which the objects are placed can serve as a reference frame as can the room itself. These two additional reference frames are hierarchically arranged such that the room serves as a *global* frame of reference and the mat as a more *local* reference frame. In the original experiment, the local and global reference frames were coincident. Does evidence suggesting that participants use one or both of these alternative reference frames emerge when they do not provide redundant information? Follow-up studies examined this question by having the local and global frames misaligned. The mat was rotated 45°within the room. Participants learned from one of two vantage points (0° or 135°). The 0° vantage point aligned with the global (room) reference frame. The 135° vantage point aligned with the local (mat) reference frame. Results again showed viewpoint dependence. Participants again showed better pointing performance when aligned with their original learning viewpoint. In addition, the results indicated savings with respect to the local reference frame.

Thus, individuals can use different reference frames simultaneously in remembering a spatial array. When learning actual environments, individuals, however, usually do not view the environment from a single vantage point. What happens when individuals learn a spatial array from two different incidences involving their own reference frame? Do two views lead to viewpoint invariant representations? In another set of studies, McNamara and his colleagues had participants learn a spatial array from two different viewpoints (0° *and* 135°). Results indicated that participants maintained two different viewpoint dependent representations. Participants more accurately pointed to locations when aligned with either of the learned viewpoints than when in alternative orientations. In addition, the results suggested a primacy effect for the first viewpoint learned, this viewpoint showing better accuracy. Again, the participant framework is not the only available framework. Thus, in follow-up studies, participants learned from two viewpoints and the local and global frameworks were either aligned or misaligned. Results differed depending on the alignment of the local and global frames. If the local and global were misaligned, results supported two viewpoint dependent representations. If the two frames were aligned, however, results differed. In this case, participants performed best when at the 0° orientation, the orientation where their individual reference frame was also aligned with the local and global reference frames. Participants performed more poorly at all other orientations, including the other learned orientation (135°).

Summarizing to this point, individuals use multiple available frameworks for defining and remembering spatial information. The reliance on available frameworks depends on the relationship of the frameworks to one another. These issues can be tied to the other general topic of the Multiple Modalities and Multiple Frames of Reference Workshop, namely multiple modalities. What happens when individuals get information about different incidences of their own viewpoint from different sensory modalities? McNamara and his colleagues conducted a study where participants viewed a tabletop array of objects (0°). They then either reconstructed the array haptically from a different viewpoint (135°) or wrote a description of the array from this different viewpoint. In tasks of relative direction and scene recognition, participants who had haptically reconstructed the array showed a priority of the tactile viewpoint (135°). This study, in combination with the others described here, indicates that multiple sources exist for reference frames and individuals take advantage of multiple reference frames.

E. Barbara Tversky – Plenary Paper on Intersection Between Multiple Modalities and Multiple Frames of Reference

In putting together issues of multiple modalities and multiple frames of reference for spatial representations, one should note that there is no unitary spatial representation system. Keeping in mind that multiple systems are possible and potentially available, the system selected for use need not be the most obvious one. For example, even when you can see an environment, you may be relying on your memory as a significant source of current spatial information. There is an important connection between representation and action that can be examined by looking at the role memory plays during navigation.

To start examining issues involved with mental representations of space, one can examine maps. Maps are external representations of environments. They serve as a cognitive tool to amplify memory for those familiar with an environment or as a cognitive tool to relate information about an environment for others. Maps have been used in these ways since ancient times and serve as a permanent and public record of cities from societies long gone. Additionally, because they are necessarily schematized, they provide an interesting analogy for mental representations of spaces.

Maps are not the only way to communicate information about environments. In general, there are two modes of communication, visual and verbal. What similarities exist between these two communication modes? Is the structure of route descriptions and route depictions the same? Both rely heavily on categorical and schematized information. Both also require integration of incomplete bits of spatial information, such as snap shots or route segments. This integration requires a common underlying structure. Interestingly, incomplete integration may not be noticed immediately. This has been seen in the change blindness phenomena noted by researchers such as Ron Rensink and Dan Simons.

In addition to integrating across different, potentially incomplete bits of spatial information, coherent spatial representations require integration across multiple reference frames. There is abundant evidence suggesting that this type of integration is common. Single-cell recordings suggest multiple local and global reference frames. Patients exhibiting unilateral neglect also suggest simultaneous reference frames in the fact that not only entire halves of scenes may be neglected, but also halves of objects within these scenes may also not be apparent to the patient. On a more overt level, maps can relate different perspectives. Different spatial perspective can also be related through language. Taylor and Tversky have examined this (1992a; 1992b; 1996). The integration of different reference frames is not always straightforward. In most cases, this integration requires additional inferences. Inferences in general are difficult and open up the potential for errors. Inferences of this type also require mental transformations of spatial information (e.g. mental information, perspective switches), although, some types of mental transformations are easier than others. “Natural” transformations are easier than “unnatural” ones, e.g. moving the self through an environment versus moving the environment around the self.

In conclusion, the integration of multiple modalities and multiple frames of reference shows us that spatial cognition is a microcosm of cognition more generally. Spatial cognition involves partially overlapping systems, creating important redundancy. These systems involve functions for pattern recognition and for mental manipulation of information. Finally, there is evidence of dissociation between implicit and explicit spatial processing. Thus, the questions involving multiple modalities and multiple reference frames for spatial knowledge have broader implications for understanding cognition in general.

F. David Mark: Intersection of Multi-modes and Multi-frames

Mark proposed a number of questions and issues that he believed needed to be considered and/or addressed with regard to multiple modes and multiple frames of reference when experiencing and representing geographic space. What are reference frames? With regard to map use in navigation, there is the dichotomy of ‘North-is-up’ versus ‘heading-up’ orientations for maps. When we consider spatial cognition and reference frames, some of the best evidence of ‘cultural differences in spatial cognition’ relates to the relative priority of different reference frames in language and behavior. This pertains mainly to the priority of the viewer/speaker centered, object centered, and geographic centered reference frames. In geography, we also have Cartesian versus polar coordinate systems. So now let’s add modalities to reference frames. How do reference frames relate to modalities? When do sensory modalities matter for reference frames…on input/learning…on output/remembering/production…on both? So the question is, what do we mean by the intersection of multiple modes and multiple frames? Do we mean *interactions* between *kinds* of modalities and *kinds* of reference frames? Sensory modalities are easy to identify: vision, sound, touch (sensorimotor, haptic), smell, and taste. The more difficult question is *the kinds* of reference frames. Are there different kinds of reference frames, or are all reference frames just different *instances* (typically rotations or translations) of the same kind of phenomena? We need to make the distinction that reference frames are *included* in reference systems…they are not the same thing. If there are different kinds of reference frames, what are they? Euclidean versus non-Euclidean? Geometric versus topological? Others??? We can assert that if all reference frames are the same, (Cartesian), then transforming between reference frames is not problem for computers (GIS), given coordinates. If this were the case, would we expect different preferred orientations of reference frames for different sensory modalities?

Another way that sensory modalities and reference frames interact relates to reference frames at different orientations that are derived from different sensory modalities. Some of Tim McNamara's research shows that sensorimotor/haptic experience has priority over visual experience. It seems that some of the most interesting scientific questions regard internal representations of configurations. In this case, the question might become "How do sensory modalities, reference frames, *and internal representations* interact when learning, and when recalling and reasoning"? Are there different kinds of internal representations of configurations? If so, do different sensory modalities favor particular internal representations? And, what does simultaneous mean here…

There are definite implications of modalities and reference frames for geographic information systems and geographic information science. The GIScience research community sometimes looks to cognitive studies for help in designing the content of spatial databases, or the nature of GIS query operators and languages. In the case of multiple modalities and multiple reference frames, perhaps the implications are limited to human-computer interaction and interface design.

III. Breakout Sessions

Breakout Session #1: Multiple Modalities

Group 1A: Modalities and distortion in the cognition of spatial knowledge

Participants in this breakout session included Bobby Klatzky, Charles Spence, Carol Lawton, Terry Caelli, Lynn Robertson, Lorraine McCune, Christopher Habel, and Lynn Nadel.

The task of this group was to consider how the learning of spatial knowledge via one modality might distort that knowledge. The first issue that was raised was "can representations created via different modalities (and therefore maybe in different formats) communicate?" The group discussed if there is a possible correlation between the visual and auditory systems in terms of the acquisition of spatial information. For example, distance estimates based on visual input are quite good out to about 20 meters. Humans are not that accurate using sound for determining distance, or direction for that matter. When perceiving sound, humans may experience the "ventriloquism" effect. For example, in a movie theater, moviegoers perceive that the sound is coming from the screen, when in actuality, the sound is comes from some speakers. It was suggested that with multiple sources of information, the most reliable source will dominate the other sources, and will be relied upon by the perceiver. People cannot co-register signals from multiple modes without more knowledge of the world.

Distortions in perceptions come about between expected and realized signals. Different modalities (senses) have particular strengths. For example, the auditory signal has a stable temporal resolution, therefore is useful for the perception of time in process. The visual signal, on the other hand, is less stable at night than it is during day. Humans have visual dominance for the spatial domain; other senses augment the acquisition of spatial knowledge depending on the situation. Research with rats raised in a non-Euclidean world support the theory of vision for the acquisition of "where" (location) knowledge, and audition for the acquisition of "when" (time) knowledge. These studies illustrated that lights were important for facilitating the acquisition of spatial locations, and that sound was important for facilitating the acquisition of temporal information.

Is there a computational problem of integrating spatial knowledge gained from multiple modalities? The point was made that "representation" is different than "procedure". In other words, the cognitive representation that people possess is different that any task they might perform based on the representation. For example, the results of performance tasks (such as distance traversal) often times do not agree with the results of estimation tasks. Typically, performance models are more accurate than estimation models.

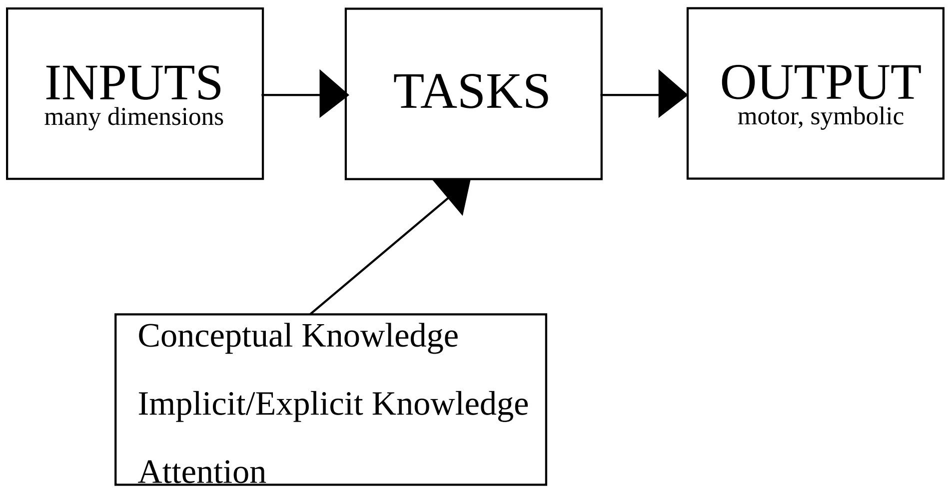
The question of multiple representations was also raised. It was suggested that people attend to different things by shifting to another map when multiple maps are visible. It was also suggested that integration of spatial knowledge (what is known + what is new) is updated and checked real-time in the real world. The discussion ended with the following question:

Subjective information + integration of information + multiple modes =????

<u>*Group 1B: Modalities and access to different kinds of information*</u>

Sucharita Gopal guided this breakout session.

This group began their discussion trying to frame or structure their problem. They used the following diagram to help visualize how modes and access fit together with regard to spatial information:



Inputs in this model include:
- The different modalities: visual, tactile, auditory, smell, taste, kinesthetic;
- Metric or quantitative information versus qualitative information;
- Linguistic input modes versus sensory input modes.

Levels of input include:
- Differential input selection;
- Distance, angles, size, orientation, speed of an object;
- Distance can be computed from any mode;
- Shape can be computed from vision, or from tactile.

The spatial tasks in this model include:
- Orientation: oriented to origin, destination, or to stops along a route;
- Wayfinding: destination guided planning;
- Route Learning: sequential production systems, e.g., delivery route of a newspaper boy, or that of a garbage collector;

- Discovering the Configural Layout: learn spatial relationships between different objects;
- Object Placement/Recovery: hiding a toy dog under a chair, and having a child retrieve that toy based on the placement of the same toy in a small-scale 3D model;
- Mobile Object Identification

Specific research questions raised by this breakout group were:
1) How does attention affect task performance?
2) What input information is processed, and what information is not processed?
3) What are the consequences of different inputs being given for the same tasks?
4) Does the feedback/experience improve with performance on a task?
5) How do we differentiate tasks and the sensory system used?

Group 1C: Scale and modalities: level of detail in spatial information from different modalities and different sources of spatial knowledge

Tim McNamara guided this breakout session.

Spatial information can be experienced at different scales via different modalities. These scales can be overlapping. For example, tactile experience is used mostly to experience small-scale spaces that contain manipulable objects. Tactile experience is often used to experience shape, texture and pattern. Vision, on the other hand, is used to experience contour, and both large and small scale spaces (from table-top spaces to geographic sized spaces). Vision is also used to experience textures and patterns. Language, on the other hand, is not as efficient for generating and experiencing spatial information. For instance, describing the complex spatial layout of an environment can be laborious, tedious, and very confusing for both the describer, and the listener.

An interesting aspect of language is that it is scale free, unlike many other modalities. Language is specialized for communicating, re: “important stuff”. Language can be very precise in context. There is a big difference for what language is used for, and what it can do in principal.

Certain modalities are useful for experiencing/acquiring spatial information, and for navigating, for instance, haptic mode versus smell. Haptic information is useful for acquiring spatial information, but smell is more useful for navigating through a space. One uses touch (feet on pavement, hands along walls…etc.) to assist in the acquisition and coding of spatial information. Recalling the smell of a local bakery can assist in the location of cinnamon buns. Is there a unitary representation of sensory information? No.

Research questions raised by this group:

1) Where do scales overlap (scale as it relates to modal experiences)?
2) What can be obtained from one modality and not another modality?
3) Are all tasks (and sensory modes) task dependent?
4) Is information learned via various modalities integrated? What is known about this?

5) In what ways does language inhibit or facilitate cross-model transfer, and the ability to navigate?
6) Are there individual differences in modal experiences, and how do we know?

Group 1D: Links between sources of spatial knowledge and modalities

Nora Newcombe guided this breakout session.

The sources of spatial knowledge and the modalities employed to learn the knowledge seem relatively simple to identify:

Modalities	Sources
vision	*direct* environmental experience
audition	*static* pictures/images/surfaces
haptic	*dynamic* images/surfaces
smell	*language* (written/spoken)
taste	*innate* knowledge/abilites
proprioceptive	*sound* (natural/feedback/music)

The links between them, on the other hand, are complex. What do humans need to interpret and understand information? There are a number of issues to consider. First, we must consider maturation versus innateness. Innateness refers to how early children are able to integrate spatial information—what and when does learning happen. At some level, everything has an innate basis. What does the natural world afford us? This question ties into the question of innateness. It also ties into the concept of "naïve", or common sense geography. Are links between modalities domain specific or task specific? For example, does "manipulation" utilize one set of modalities, and navigation utilize a different set, resulting in the acquisition of different kinds of spatial knowledge? Are these links scale dependent (geographic versus tabletop boundaries)? Are these links tied to the world being perceived sequentially versus simultaneously? It was pointed out that for psychology and geography, these questions may be answered differently (especially the question of scale).

Considering modalities for sensing and sources for presenting, what is the optimal combination of information for a standard user of GIS, and what is the optimal presentation of spatial and non-spatial information in a GIS? What are the features needed in a representation to draw and understanding of a given environment? For example, should information be in 2D or 3D? Should virtual environments be more prevalent in representing environments? It was pointed out that virtual reality should not be considered to be equivalent to the real world for navigation (e.g., walking). Virtual reality representations may lack texture and surface cues, necessary sonic cues, and all vestibular cues. The correspondence between simulated and real environments should depend upon the situation.

Many issues concerning design were mentioned in this breakout group. The following were mentioned as design concerns:

- Design to the lowest level of competency when designing for multiple users and abilities;
- Consider gender differences, and stylistic issues (e.g., females can be reminded to us N, S, E and W as opposed to verbal (left, right) directions);
- Design systems based upon spatial assessment of users—high versus low spatial achiever. High achievers give “better” directions than low achievers, and they also understand directions and navigate “better” than low achievers;
- Be aware of designs that lead to confusion, such as duplication of features, or misleading names of features;
- Consider abilities to mentally rotate a map as compared to physically rotating a map;
- Provide some link between distance estimates and how well they related to the real space;

In summary, this group identified three areas of research:

1) Criterion validity for our measures (sketch maps, pointing, direction giving): what generalization can we make from our measures to real world practical problems?
2) Lessons in architectural design: design buildings and environments and facilitate people’s movement through them.
3) Navigation: how much do we need to accommodate individual differences in the design of navigation aids for the average user?

Breakout Session #2: Multiple Frames of Reference

Group 2A: What are frames of reference?

Participants in this breakout session included Terry Caelli, Stephen Hirtle, Bobby Klatzky, Gary Allen, Scott Bell, Carola Eschenbach, Christian Freksa, David Mark, Susanne Jul, and Donald Heth.

Discussion arising from the two plenary papers on Multiple Frames of Reference (talks presented by Tim McNamara and Nora Newcombe) illustrated the lack of consensus when defining *reference frames.* Thus, this breakout topic plays a critical role in defining a research agenda about frames of reference for spatial knowledge. A base definition for *reference frame* arose from the discussion.

> *A reference frame is a system for the computation of parameters that correspond to spatial characteristics*.

While the definition has appeal, it leaves open other questions. The focus on frames that allow computation of parameters for spatial tasks helps define possible sets of reference frames. Parameters of interest include distance between objects or between self and objects, heading or bearing information, orientation of self or objects, and bearing differences between actual and desired location.

Considering computational criteria, frames of reference fall into three main categories, geometric frames, indexing frames, and semantic frames. Geometric frames can be used to calculate parameters of axes and heading. Indexing frames relate to subdivisions within space and alternative metrics of spatial knowledge. Finally, semantic frames provide a context for spatial information. In short, thinking about reference frames in this way provides parameters that can then provide answers to spatial questions.

Another feature of reference frames is that they can provide natural expressiveness for certain kinds of questions. Issues of function and process make up the primary questions. In thinking about functions of spatial knowledge, one must also consider that information content can differ. What content is the best for answering what questions? In some instances categorical information may be sufficient, even broad categorical information such as an object being *here* versus *not here.* Reference frames might also require continuous information. A compass could serve as a reference frame for spatial information, providing continuous angular information about heading.

Process is related to function, but also brings up other issues. Different reference frames may engage different processes or different processes may require different reference frames. In this context, four reference frames were suggested, a relative frame, a local one, a global one, and an egocentric one. Whether all four are necessary is a matter of debate. Researchers on the question of reference frames have often suggested three. The three combine relative and egocentric. This combination assumes that spatial information can be processed relative to the self or relative to another object.

Since this breakout session topic was to define reference frames, it was correctly pointed out that reference frames could be more general than those used in spatial situations. Are reference frames necessarily spatial? The answer to this question, within the scope of all possible information, would have to be 'no, reference frames are not necessarily spatial.'

Several research questions emerged from this topic. Some of the questions were more general. 1) What are the functions of reference frames? Are they used for judgements within reference frames or judgements based on the reference frame itself, or both. 2). Can one completely index the possible reference frames for spatial information? If so, what is the nature of the expressiveness of these frames? Is the expressiveness consistent? 3). What tasks can elicit certain frames?

Other questions considered errors and distortions in spatial memory and their relationship to reference frames. 1). How are errors and distortions they related to reference frame use? Are the tasks that we use sufficient to distinguish between frame selection and frame application? 2). What is the geometric structure of a specific frame? 3). Can multiple frames of reference be used? How many? How do they interact and possibly lead to errors or distortions?

Group 2B: Factors that affect conceptions/use/kinds of reference frames (development, abilities, culture)

Participants in this break-out session included: Eric Pederson, Clare Davies, Nora Newcombe, Mark Blades, Mary Hegarty, Carol Lawton, Lorraine McCune, and Michel Denis.

The goal of this session was to discuss issues of determining factors leading to difference in reference frame selection and use. Possible factors may include cultural input, linguistic input, individual differences, and developmental correlates. While many other issues arose during the discussion, it primarily centered on the following issues: 1). Linguistic and cognitive inputs to reference frame selection, 2). Task requirements in selection of reference frames, 3) developmental and individual differences, 4) experiential differences, including training of reference frame use.

With respect to linguistic and cognitive inputs, the Whorfian hypothesis brings up interesting questions. Can linguistic priming influence reference frame selection? Work by Steve Levinson (1996) suggests that it can. Tzeltal does not contain egocentric spatial terms and findings from other spatial tasks suggest that Tzeltal speakers do not use an egocentric reference frame. Implicit in this question, though, is the question of variability in linguistic input. To what extent does linguistic input about reference frames differ? There are certainly specific linguistic devices that can signal frames of reference. Canonical terms (such as NSEW) or other environmental terms (e.g. toward the ocean) generally signal absolute reference frames. Deictic systems can ground a reference frame either to conversational participants or to objects in the spatial array. This relates to figure/ground issues. Grammatically required concepts are forced on language users whereas linguistically available concepts can be selected, but are not required. Grammatical requirement and linguistic availability of concepts differ across languages.

Task differences also influence choice of reference frame. Two possible tasks are dead reckoning and route finding. Dead reckoning involves knowing the direction to home independently from route to current location. Route finding involves the ability to retrace a route, either on another trial or backwards from the current location. Individuals show variability in their ability to successfully undertake these tasks. Additionally, ability in one is not necessarily predictive of ability for the other. What reference frames are evoked in each of these tasks? It is possible that each task can be completed using one from a set of reference frames. If so, a related question arises about task instructions. If tasks can be completed using different reference frames, can instructions for using a particular reference frame influence the reference frame actually used?

Developmental and individual differences might also contribute to reference frame selection. Children engage in varying amounts of spatial play during development. Various factors might influence the amount of spatial play a child engages in, including the environment in which they live (city vs. country), the distance from home they are allowed to explore, or their interests in various play activities. Children’s behavior when lining-up objects shows some developmental course of reference frame use. Initially, the objects are not oriented. Over time, the child becomes increasingly more sophisticated, orienting objects with respect to a particular reference frame, e.g. the front of the line.

The issue of spatial experience relates to that of development of spatial ability. Experience may be based on a particular task one carries out in the environment. Hunters versus gatherers used their environmental space differently. Different pathologies change the experience one has with an environment. A blind individual receives different types of input about his/her environment than a sighted individual. Does use of different reference frames change with experience? Can experience change selection of reference frames? This question brings up issues of training with reference frames. If experience with a reference frames improves use of that frame, this suggests that reference frame use is subject to training.

The diverse factors contributing to reference frame selection brings up an equally diverse set of related research questions. Each research question is derived from the issues discussed above. From linguistic contributions come questions such as how acquisition of second person deixis relate to pronoun acquisition and perspective taking abilities. What effects does linguistic priming have on reference frame selection? With respect to task influences, other questions arise. How can task instructions shift ability or attention from one reference frame to another? Does this shift influence performance on tasks such as dead reckoning or route finding? The influence of development opens up questions of how stages of spatial play correspond to use of reference frames. Finally, experiential input evokes questions of training efficacy. What practical effects might be gained from training? How do different types of experiential input influence memory for an environment?

Group 2C: Is there integration of spatial knowledge acquired from conflicting or different frames of reference?

Participating in this breakout session were W. Jake Jacobs, Barbara Landau, Lynn Robertson, Tim McNamara, Lynn Nadel, Charles Spence, and Bennett Bertenthal.

When an individual acquires spatial information, there is generally more than one reference frame against which to encode that spatial information. If the reference frames conflict, however, one might be better off attending only to one of the available reference frames. Inherent in this question is the issue of representation of spatial information. Some researchers have argued that multiple perspectives lead to multiple different memory snapshots (see report of plenary talk by Tim McNamara). This position implies that memory is viewpoint dependent and each snapshot has a particular viewpoint. Evidence for the snapshot position comes from results indicating costs for calculating different viewpoints. Individuals respond more quickly to viewpoints they have experienced than to those they have not. Viewpoints in between those experienced do not seem to be interpolated any better than viewpoints outside the range of those experienced. Evidence for this position also comes from the object recognition literature. Individuals have difficulty generating representations of three-dimensional objects from sets of two-dimensional views. Others have argued that individuals might develop viewpoint independent representations. Viewpoint independent representations may arise from multiple experiences with a spatial array in which multiple different tasks are carried out.

Each task may be accomplished better using one reference frame over another. Thus, over time, and individual "uses" the environment from different perspectives.

The issue of representation has not been resolved, but it is influenced by the availability of reference frames. When multiple reference frames are available, are they considered for use? Work by Laura Carlson-Radvansky (1998) suggests so. Using a negative priming technique, she has shown activation of multiple reference frames and later selection of a single frame for use (see break-out session 2B for further discussion of influences on reference frame selection). One might assume that a viewer-centered frame would dominate, given its immediate availability. But, evidence supporting this assumption is weak.

Movement through space influences the availability of reference frames. Movement changes sampling rates based on speed. Dwell times in different locations increase the amount of information available from the reference frame defined by that location. Even when one moves through an environment facing the same direction, mirror image errors sometimes arise.

Data from patients with unilateral neglect give some interesting indications for use of multiple reference frames. These patients can show neglect for a scene when they are using an egocentric reference frame. In other cases they show neglect for parts of objects, indicating an object-centered reference frame. Some patients show both types of neglect, but in different situations.

Thus, several research questions arise from issues of multiple reference frame availability. 1) Is the viewer-centered frame the dominant frame? 2) Does the availability of multiple views necessarily mean the selection of multiple views for use? 3) To what extent are multiple reference frames arranged hierarchically for selection? Can situational determinants change the hierarchical ordering? 4) To what extent are multiple frames simultaneously available?

Group 2D: How does context/situation affect representations built from multiple frames of reference (e.g., scale, structure of environment, tasks)

Participating in this breakout session were Immanuel Barshi, Janet Carpman, Sucharita Gopal, Christopher Habel, Micheal Hewett, Alan MacEachren, Laura Richterich, Frances Wang, Steffen Werner, and Barbara Tversky.

This breakout topic first demanded participants to determine and define possible situations and context differences that might exist. Certainly different tasks come accompanied by different contexts. The task of knowledge acquisition differs from those of communication, action, or memory. The core differences in situation seem to revolve around task specifications, the possible set of reference frames available, and user expectations. In turn, each of these can be influenced by other situations, such as whether information is available through more traditional modes (e.g. navigation or maps) or through high-tech devices (e.g. GPS devices).

Both across and within tasks, individuals may make use of multiple reference frames. For example, to locate a specific address using some of the web-based map systems, one generally first uses a small-scale reference frame, such as the location of a state within the United States. Next, one might locate the town within the state, then the street within the town, and finally the house along the street. Each successive "zooming-in" requires a different reference frame and all of them together accomplish the task. For any given task, the required reference frames may be organized in different ways. The example above illustrates hierarchically embedded references frames. Other tasks or situations may have simultaneously available reference frames. In general, reference frames may be organized hierarchically or sequentially, simultaneously or serially.

When using and interpreting reference frames, physical aspects of the spatial situation and cognitive aspects of the individual in the environment should be taken into account. The cognitive aspects include associations, which may help or hinder memory, for example, one might naturally associate a cup with a saucer and misremember that there was a saucer on the table when only the cup sat on the table. Memory issues must also be considered. In general, storage of information is cheap, while comprehension is expensive. This obviously holds true for both humans and global positioning systems.

In short, reference frame use is influenced by many different contextual and situational variables. These include physical properties of the environment, cognitive aspects of the user, number and type of reference frames available for use, organization of reference frames, goal for using reference frames (i.e. task to be accomplished), and medium for passing on information.

Research questions that arose from this breakout session were primarily of a practical nature as applied to development of GPS mechanisms and use of databases. These questions included: 1). How can we provide GPS-type information aids, which are in relation to one's location while using it? This question takes into account implications of switching reference frames and of redundancy in reference frames. 2). How can data structures better take into account a user's reference frame to facilitate use of query databases? 3). Given that a users bring many varied reference frames to a spatial information system, how does one communicate/perceive/create reference frames in the Internet?

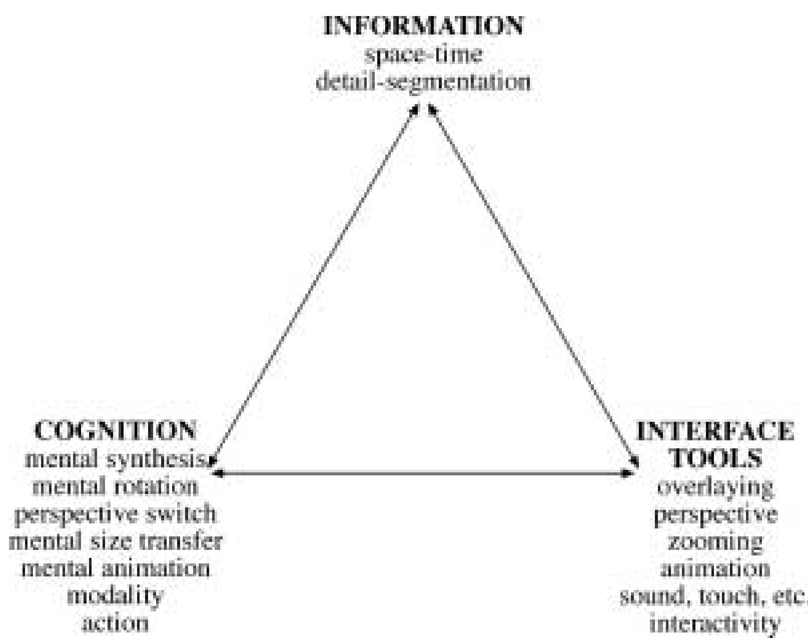
Breakout Session #3: Intersections Between Multiple Modes and Multiple Frames of Reference

Group 3A: Applications of multiple modes to GIS/human factors

Participating in this breakout session were Barbara Tversky, Alan McEachren, Suchi Gopal, Nora Newcombe, and Scott Bell.

This group began by identifying major components that should be considered in human factors, and the design of geographic information systems. The three components were

Spatial Information, Cognition, and Interface Tools (see figure below). The elements of spatial information included space, time, detail, and segmentation. The elements of cognition, as they bear on spatial tasks, included mental synthesis, mental rotation, perspective switch, mental size transforms, mental animation, modality and action. The elements of interface tools, as they link to functions within a GIS, included overlapping (overlays), perspective switch (multiple representations), zooming (scale change), animation (process), sound, touch, etc. (perception), interactivity (control of presentation). The following diagram places these major components at the vertices of a triangle. From this triangle, several issues arise. First, is it possible to match the corners of the triangle using natural correspondences between specific elements? For example, match time with mental animation and animation/process; link detail with mental size transforms and zooming. How do these elements map onto each other? Is it possible to develop training that facilitates comprehension and use of interface possibilities? Is it possible to realize the trade-offs of flexibility/complexity of interfaces—generally the less flexible, the more complex the interface? Develop a collaboration of users within same/different perspectives.



Group 3B: Modes, frames and large-scale spaces

Participating in this breakout session were David Mark, Gary Allen, Daniel Jacobson, Eric Pederson, Christopher Habel, Don Heth, Dan Montello, and Carol Lawton

This group began their discussion with a series of questions about scale and its effect on cognition. What is the relationship between tabletop and large-scale, geographic space? Is there evidence that these are distinct spaces, having unique and separate characteristics, cognitively? Are differences in scales and their effects qualitative, or quantitative? What scales are "reasonable", supported in the literature? Research supports that table-top (space of the body), geographic (regions), and map space have elements that render them cognitively different from each other. So what are the various cognitive scale classes? Note that there are differences in languages at different scales. For example, the terms “in” and “on” have different meanings at different scales. There is also the issue of qualitative versus quantitative scale differences. Are these differences in where/when scale shifts occur due to cultural differences?

With respect to frames, frames are distinct if they possess a different set of minimally sufficient information. There is translatability between frames if extra-sufficient information is encoded. Linguistics, for example, is mathematically transitive, using left/right, or south of St. Louis. Research shows a difficulty in changing frames. For example, relative rotation is not a simple task. Nor is translation, from Cartesian versus polar coordinates. Translation is computationally expensive.

The issue that was considered was mode of experience/representation. It is surprising versus trivial that maps work. Maps certainly inherit what the group termed “inappropriate features”. Another way to consider inappropriate features is to think about map generalization, making features larger than scale, and increasing the role of distortion in maps in the understanding of frames.

The last point of discussion for this group concerned the terminology/definitions/ agendas/scales from various disciplines and sub-disciplines. We need to develop a translatability of terminology, and we need to develop a relation of definitions to underlying conceptions.

Group 3C: How can more that one mode be used to augment representations?

Participating in this breakout session were Daniel Jacobson, Steve Hirtle, Barbara Landau, Lynn Robertson, Jan Carpman, Christian Freksa and Jim Marston.

Though we can identify at lease 5 senses, there are three primarily used for the perception/experience of spatial information. They are spatial (tactile), visual, and verbal (auditory). When presenting information to the user, clutter and/or too much information are not useful, and in actually can be more confusing than anything. On the flip side, sparse, or not enough information is equally useless to the user. When combining tactile, visual and auditory information in the display of spatial data, what is the correct amount of information? In addition, there are many guidelines with regard to graphic design with maps, but are there similar standards for auditory and haptic symbols? How can we best communicate to the map user?

The role of tactile and auditory symbols is to augment the information’s message for pattern recognition, spatial resolution, and for attentional capture. How do individual differences impact the information and it’s presentation to the user? Research illustrates many individual differences in map/survey oriented tasks, and verbal/route mapping tasks. When can tactile information facilitate better communication? Can tactile help in 3D perspective models? Probably yes. With 2D perspective models? Probably no.

When putting together information that requires the use of multiple modalities, what might be the additive effects? When are these additive effects negative? When are they positive? For example, in the context of navigation and wayfinding, when does verbal information help/hinder? When does a map help/hinder? When is the information/message perfect (i.e., not incomplete nor incorrect information)? When is the information/message degraded?

The last issue that this group discussed was that of filtering versus augmenting information. When multiple modes for experiencing spatial information come into play, how is the decision made to filter out unnecessary information, or to augment the information, to present more to the user? Where is that fine line? Research is needed that explores his issue—when is the user overwhelmed, or "under whelmed" by information?

Group 3D: Relationship between sensory modes, reference frames and internal representations.

Bobbi Klatzky guided this group.

Is there a difference between reference frames and reference systems? Reference frames provide parameters of spatial positions. They process relations from primitive parameters, algorithms (sometimes), and can build others. For example, from location, distance can be derived, and from distance the concepts near/far can be derived. A reference system, on the other hand, "spins off" reference frames, as needed for different tasks and functions. Do we derive reference frames as a function of the medium (i.e., a map, real world, etc.)?

Different modalities will be able to sense/experience information from different reference systems (different with respect to parameters or values). For example, audition gives parameters for location of objects behind ego, and gives different distance parameters from vision. But at a conscious level, we perceive a coherent world of space. Is this perception of a coherent world due to sensory dominance, or intersensory integration? The answer to this question seems to vary with task, and even with item. For example, consider haptic/visual integration of texture. There is visual dominance over haptic with regard to shape. In this instance, there is also visual dominance or integration with speech.

Can we learn about reference frames by asking where the brain produces them? In animals, frames of reference excite the parietal cortex. Further from the parietal cortex, reference frames become more abstract, less tied to the ego. In animals, research has found a reference frame start microspatially, and become more abstract until it is practically unspecifiable…it is a bottom up, hierarchical system which has a hard-wired Euclidean system at it's center that is not based on experience. Animals experience spatial layouts (places) in the hippocampus, coded by multiple reference frames. Space relative to ego (self) is in the parietal lobe.

In an applied environment, we can consider the insights gained with regard to representations of space. For example, we can consider air traffic control. Air traffic control personnel monitor a "volume of air", or size, depending on the business there. The monitoring of planes will likely be schema driven, e.g., by a landing event, wind effects, etc. What then is controlled? Screen position? Volumetric position? Events (e.g., landing)? We need empirical studies to explore these applied issues.

Representations are not just of space, but of semantics as well. So, don't stop at the parietal lobe or hippocampus. Consider too the frontal lobe. Task demands will derive representation and reference frame. Will they derive reference system, or is that a tool to be used by tasks, and driven by a lower biological function?

Breakout Session #4: Small-group Research Agenda Discussions

Participants in this set of breakout discussions attempted to identify research questions remaining unanswered. The set of topics arose from research questions suggested in the topic-specific breakout sessions. As such, the report of these discussion outcomes will relate the research questions suggested by breakout group participants.

Group 4A: Integration of Multiple Reference Frames to Augment Spatial Learning

Donald Heth, Mary Hegarty, and Gary Allen suggested this research agenda.

Heth, Hegarty, and Allen suggested three problem domains on which they could address the general question of integration of multiple reference frames to augment spatial learning. The first domain, search and rescue planning requires assessment of path difficulty. In a search and rescue, time is of the essence. Path planning must also take different transportation modes (ground versus air) into account. In the second domain, sailing, path planning requires integration the forces influencing the actual path taken, namely wind and current speeds and directions. The actual path should not diverge too much from the desired path. The final domain, surgery, also requires integration of different pieces of information. In this case, it is information defined by different perspectives, survey and route.

All three domains have a common goal, to plan an optimal route. In search and rescue, an optimal route increases the survival chances of the individual in need of rescue. In sailing, non-optimal routes waste valuable time and energy. Competitors in the America's Cup races are well aware of the necessity for optimal route selection. In surgery, an optimal route reduces trauma non-injured body parts falling along the path of the surgery.

They suggest a research plan investigating optimal route selection in these and other domains. The research involves augmentation of map displays with additional reference frames and/or additional information modalities. This broad question can lead to a programmatic line of research. Which reference frames lead to the best combination to facilitate optimal path selection? Does the specific task dictate the available reference frames and modalities? Can people integrate different frames or different modalities when they are simultaneously available? How does integration differ if the frames are simultaneously versus sequentially available? In all cases, actual performance can be compared to an optimal path.

Group 4B: Comprehending and Describing Space

Barbara Tversky, Steve Hirtle, Immanuel Barshi, and Michel Denis suggested this research agenda.

Presumably a number of different mental operations occur when comprehending or describing space. What are the relevant operations for different spatial tasks? Tasks where operations might differ include change of focus, change of orientation within an environment, or change of viewpoint. Obviously these tasks have some similarities, which would presumably tap similar operations. Equally obviously the tasks differ and require different or unique mental operations.

Spatial information often comes from different sources that vary in the extent to which they overlap. What are the costs and benefits of multiple sources of spatial information? Do these costs and benefits change when information overlaps? When considering multiple reference frames and multiple input modalities, the possibilities for overlap show extensive variability. Linguistically, different reference frames can be related, such as through route and survey descriptions of the same environment. Similarly, different modalities can provide input about the same spatial array. Input to spatial learning can also have very little overlap. An extreme case of differing frames and modalities comes from a contrast of learning spatial information experientially versus vicariously. The information may be the same, but the source of the information and the level of involvement in learning differ significantly.

The group suggested ways of implementing these questions within an experimental paradigm. Possible independent measures include the makeup of the communication partners, the nature of the spatial situation, and other task variables. Communication partners can differ in goals and knowledge about the spatial situation. A pilot and co-pilot have slightly different roles during flight. The air traffic controller has more information about locations of other airplanes than the pilot. One communication partner may lack some of the input senses, such as a blind individual. In terms of the spatial situation, this can involve differences in the spatial situation between the communication partners. Are both co-present in the environment or are they apart? Also, the nature of the scene itself can influence communication. For example, a scene with a few salient objects that can serve as landmarks might be described different compared to a scene with a field of similar landmarks. Finally, task variables such as time pressure may also influence the communication. In terms of dependent variables, the group suggested coding the perspective used, choice of spatial relation terms, and choice of reference objects versus located objects.

Group 4C: Individual Differences in Spatial Skills and Performance

Carol Lawton, Susanne Jul, and Laura Richterich suggested the following research agenda.

The main thrust to this research agenda involves the intersection between culture and gender as applied to spatial skills. To what extent can gender differences in spatial skills be accounted for by cultural differences and cultural expectations? Whereas current measures of spatial skill frequently find gender differences, sometimes favoring males, sometimes favoring females, the explanation for these findings leaves open questions. To what extent do gender differences seen in spatial skills result from anxiety about navigating? Additionally, results interpreted as skill differences might instead be strategy differences.

If gender differences can be partially explained by cultural differences, how large a role do the cultural differences play? It is clear, at least within U.S. culture, that gender stereotypes exist about spatial ability. The stereotypes are not limited to spatial ability, and carry over to science and technology ability as well. If the stereotypes are widespread, they could influence motivation to learn particular skills. Thus, if a spatial task is described to an individual in non-spatial terms, will the gender difference be lessened? The issues of culture and gender stereotyping have strong implications for how boys and girls are taught to solve problems. It also has implications for what toys and problems they get exposed to. So, the more far-reaching question is whether debunking these stereotypes can change women's interest and perception of success in science, technology, geography, spatial ability and other related tasks. Would changes in the cultural stereotype actually lead to changes in behavior so that men and women would exhibit greater skill similarities? While culture may play a role in gender differences in abilities, it may not be the only explanatory factor. Gender differences may exist above and beyond those accounted for by cultural differences. To what extent would debunking the cultural stereotypes still be beneficial? Changes to the stereotype could result in changes in perception of the relative value of different skills or strategies used by the different genders.

Group 4D: How Can Different Reference Systems be Disentangled?

Tim McNamara, Bobby Klatzky, Frances Wang, and Steffen Werner proposed the following research agenda.

This research agenda involves integration and use of multiple reference frames. When multiple frames are present for use, how do they interact? The group believed that in order to answer broad questions about use of multiple reference frames, they first needed to step back and clarify some more basic issues. First, they noted that some red herrings still need resolution, such as those inherent in distinctions of "polar" and "Cartesian" coordinate systems. Second, while it now seems safe to say that reference frames do influence behavior in spatial tasks, the question of how reference frames influence behavior in spatial tasks remains open.

Some of these general issues may be resolvable empirically. The first step involves collection of parametric data in order to model the weight different reference frames play in behavior. This would require collection of large quantities of well-controlled data for different reference frames. Additionally, data reflecting different combinations of reference frames would be necessary. From this data it might be possible to determine modeling parameters.

Even with information about the weighting of different reference frames on behavior, the question of the nature and characteristics of the representation and processes of using the representation is left unanswered. How might different characteristics of representations promote or defeat multiple preferred alignments within a reference system?

In many situations, the available reference frames are confounded. With three available frames, two might be aligned while the third conflicts. Thus, it is impossible to determine the independent contributions of the three reference frames to spatial processing. Only when all three conflict can their independent contributions be determined.

Once these more basic issues about multiple reference frames are addressed, other questions remain. Can information about multiple reference frames on one spatial scale translate to other scales? In particular, how would the basic information gathered and modeled apply to environmental scale? Second, if results of the data collection uphold predictions that the reference frame based on the viewer's perspective has some priority, what is the origin of this reference frame? Related, individuals often move through environments while learning, thus changing the reference frame defined by the viewer's perspective. What is the role of movement in representing space? Finally, evidence from McNamara's lab (see report of plenary paper by McNamara) indicates that people do not represent information they have been exposed to, or at least do not access it directly. Do views that are experienced, but seemingly not represented, play a role in the resultant mental representation?

Group 4E: Relationship Between Systems Supporting Different Types of Spatial Learning

Barbara Landau, W. Jake Jacobs, and Lynn Nadel proposed this research agenda.

When considering different types of spatial learning, the group focused on navigation, place learning, and spatial language. Since the same environment can support all three types of learning, it is important to consider the translatability of information between learning types. It is possible that information learned during navigation has complete, partial, or zero translatability to information learned in the other two systems. These possible translatability relationships hold for information learned in any one of the systems and used in the others.

W. Jake Jacobs and Lynn Nadel already have a well-defined, empirically validated spatial task with several components. This task uses virtual-reality (VR) technology and is akin to the Morris Water Maze task used with rodents. Individuals navigate through an arena finding the location of hidden landmarks. When the individual gets near a landmark, it becomes visible. Individuals can either be shown the locations of the landmarks or can discover them through navigation. How does the place or navigation learning interact with spatial descriptions? Pilot data from their system suggests a verbal overshadowing effect. In particular, verbal descriptions of the space and target locations given to participants before training disrupt learning. This pilot data shows that the VR system creates a means to study conditions under which spatial language and place learning interact.

They discussed a programmatic research plan. The program would first replicate basic findings and run several controls. Second, they would titrate the complexity of the spatial environment to see the effects on learning. Third, they would titrate the kinds of verbal descriptions given prior to learning. With different verbal descriptions, they could examine issues of reference frames using descriptions that take different reference frames. With a better idea of how the verbal descriptions influence learning, they would examine effects of presenting the verbal descriptions to participants at different times. Descriptions that are given simultaneously with learning, or after learning, could influence the developing spatial mental representation differently. Finally, they feel it would be important to see the translatability of learning in the VR system to learning in the real world.

Group 4F: Developing Spatial Representations

Nora Newcombe, Dan Jacobson, Mark Blades, Janet Carpman and Lorraine McCune proposed this research agenda.

When learning a spatial array, different mental processes are involved. There are encoding processes, which include both perceptual and post-perceptual processes, and there are representation processes. Representation involves longer-term coding on which other operations can be performed. What differences exist between the coding and the representation processes? This question can be asked both developmentally and situationally. In development, there appears to be a cross-domain transition around 2 to 3 years. In adult learning, different tasks may tap different types of processing. What tasks tap what processes?

In discussing representation processes, consideration of the operations that might be performed on that representation is important. One operation is *zooming in* on specific parts of a representation. The zooming in processes involves understanding a shift in reference point or perspective. Understanding that the current view seen is part of a larger view is not a trivial problem. It is an even more complex task for some populations. How do children understand zooming in? How might zooming in be explained or presented to a blind individual? In the haptic or auditory modalities it is not as natural to zoom in to a different scale. How might the zooming process be presented in these modalities to increase understanding? Environment differences may also influence comprehension of zooming in. Some environments may more difficult to understand because the zooming operation is accompanied by a rotation operation. Santa Barbara is a good example. Showing where Santa Barbara is in the State of California can be done easily with a north is up orientation. However, when zooming in on Santa Barbara itself, it makes sense to change away from the north is up convention. By re-orienting the city, it can be displayed as a rectilinear grid of streets.

Simplified GIS may facilitate learning of spatial information if incorporated into early education programs, including preschools. These simplified systems may also be advantageous for the handicapped. For both young children and many handicapped individuals, haptic control of GIS would be helpful. Some systems, such as one developed by Dan Jacobson, are already in existence. The systems would be best used if they were integrated in regular curricula. There are already topics taught in secondary education that would benefit from GIS. For example, the California schools teach fourth graders about the spread of missions throughout California. Many different grades have units on stream contamination. One issue of particular interest for this application of GIS to education is the extent to which GIS literacy transfers to other learning. It seems likely that GIS in education could have far reaching effects.

Group 4G: Computationally Applying Multiple Modalities and Multiple Reference Frames

Terry Caelli, Christian Freksa, Sucharita Gopal, and Mike Hewett proposed this research agenda.

This research agenda centers on computational applications of using multiple frames of reference and multiple modalities. They start with a general question of how applicable empirical and computational results of studies are to real-world tasks. In part, an answer to this question showing good corroboration between laboratory and real-world tasks justifies a research agenda centered on laboratory or computationally based studies. Their next issue addresses the nature of the human representation of space. In particular, what algorithms or mental operations do people use to compute metric information? Should algorithms analogous to those used by humans be adopted in computational systems? The answer relates to the overall goal of the system, whether it attempts to optimize or to satisfy. It is not clear whether the human system is an optimizing or a satisficing system

One major goal of this research agenda is to develop techniques for intelligent spatial data mining. Given that recent changes in technology have made data abundant, techniques for mining this data have become more critical. What techniques would contribute to intelligent spatial data mining? The data mining process is an interaction between the data mining system and the human user of the system. Since this interaction exists, the interface with the system is important. Interfaces can sometimes help and sometimes hinder use of the system. How transparent should the interface be? Should the user be able to customize the interface to fit their processing style?

In the process of mining data, several factors could influence results. As users of search engines on the World Wide Web are aware, different search engines employ different algorithms with more or less success, depending on the topic and key words used. In theory, optimal search techniques should be employed. What are optimal search techniques? Does the search technique depend on the data structure? More specifically, what are optimal search techniques for spatial queries in a relational representation? Search queries should be more successful when data is optimally organized, as well. How can information be optimally indexed, particularly data based on multiple modalities and/or multiple frames of reference? If optimally organized, to what extent is information gained through multiple modalities or through multiple reference frames translatable?

4H: Reference Frames in Descriptions of Geographic Information

Carola Eschenbach, Christopher Habel, Charles Spence, Eric Pederson, and Clare Davies proposed this research agenda.

For the most part, this research agenda focuses on the interaction between reference frames and spatial descriptions. Several factors can influence the nature of a spatial description, including properties of the environment, properties of the speaker, the spatial task (describing a layout or a route), and the availability of multiple reference frames. Each of these factors could contribute independently to the description and they could interact. By taking just one of these factors, properties of the speaker, one can generate several research questions. For instance, how does long-term living experience influence reference frame selection for descriptions? How does culture influence reference frame use in describing routes?

Before looking at the influences on spatial description production, the process of producing spatial descriptions should be examined. An efficient system would ideally automatically generate verbal presentations of geographic information. However, if multiple reference frames are available for use, the process of automatically generating descriptions is complicated. To create an optimal system, what restrictions would have to be put on reference frame use to facilitate the automatic generation of descriptions?

The type of spatial description generated should vary as a function of which the description is designed for and their needs or capabilities. For example, a description useful for a sighted person would be useless for a blind person. What strategies already exist for describing maps or cities to blind individuals? Are there algorithms for translating visually processed information to a linguistic description void of visually based information? Further, could the resultant description be translated to a description containing visually based information?

IV. Research Questions

How do reference systems influence behavior in spatial tasks?

Need for a collection of parametric data: many well controlled experiments investigating different reference frames and the possible parameters to model the significance of different reference frames.

What are the characteristics of a representation/process that would lead to multiple preferred alignments within a reference system?

How do reference frames differ, if at all, for different scale (size) spaces? (e.g., tabletop space vs. geographic space)?

What is the origin of the frame of reference defined by the viewer's perspective?

What happens to views that are experienced but seem not to be mentally represented?

What is the role of movement in the development/use of reference frames?

What are the differences between "coding" (perceptual or post-perceptual processes) and "representation" (longer-term coding on which operations can be performed)?
What are these differences developmentally—transition around 2-3 years?
What are these differences in adults—what tasks tap what?

What are the uses of GIS in early education—how can it be integrated across domains (geography, biology, geology, and what is the best way for children to "experience" it?

- should we begin as early as preschool?
- is haptic control helpful for handicapped students?
- should GIS be integrated into the regular curriculum (in many domains)?
- should GIS literacy be promoted in education?
- How do these skills and knowledge transfer to other domains (improved spatial skills and knowledge)?

How are GIS task, such as "zooming" understood in terms of:

- children vs. adults
- visually impaired vs. non-impaired?
- different frames of reference (when zooming into Santa Barbara, up = north changes in order to make the street grid rectilinear)?
- the haptic and auditory modalities, where zooming is not natural as in vision?

What are the relationships between systems supporting navigation and place learning, and those supporting spatial language? Are the relationships:

- completely translatable?
- partially translatable?
- non translatable?

Investigate conditions under which spatial language and place learning interact and affect each other (e.g., word by Nadel and Jacobs suggests that verbal descriptions of space and target locations that are given before "training" disrupt learning). An experimental program to investigate these conditions includes:

- replication of basic finding and run several controls
- titrate the complexity of the spatial environment
- titrate the kinds of verbal descriptions
- vary the point at which verbal descriptions are given
- repeat these experiments in real-world spatial situations

How does long-term living experience and culture influence reference frames used in descriptions of

- routes?
- city layouts?

What restrictions have to be put on the reference frames used in automatically generated verbal presentations of geographic information?

Explore strategies for verbally describing maps and cities to a blind person:

- which strategies are used and when?
- how can strategies be combined?
- how can the task be automated?

What mental operations are used in comprehending and describing space?

- change of focus?
- orienation?
- viewpoint?

What are the costs and/or benefits of overlapping sources of spatial information?

- multiple linguistic perspectives?
- multiple modalities: experiential and vicarious

What are the independent measures in communicating spatial information in:

- Communication between partners? (e.g., pilot, co-pilot and air traffic control; central-field)
- Spatial situations? (e.g., copresent - apart; structure of scene)
- Task variables? (e.g., time pressure)

What are the dependent measures in communicating spatial information in:

- Perspective?
- Spatial relation terms?
- Reference objects?

What are cultural differences in degree of gender differences in:

- spatial tasks (performance measures)?

- in anxiety about navigation?
- in navigational strategies?

How does stereotyping about gender spatial abilities in:

- navigation?
- science, technology skills/abilities?

How does cultural differences in stereotyping relate to differences in ways both boys and girls are taught to solve problems?

Can educating people about gender stereotypes with regard to spatial abilities change people's interests and perceptions of success in science/technology/geography? What are the most effective ways to educate about stereotypes? Result of this is to:

- change behavior so that all people have the same opportunities to develop proficiencies in spatial skills;
- change perception of relative value of different skills and strategies used by men and women.

Do experimental results in spatial cognition extend to "real" tasks?

What cognitive algorithms do people use to compute metrical information?

How customizable does the GIS user interface need to be, and can the interface be trained?

What are effective techniques for intelligent spatial data mining?

Can and object-centered KR be independent of frame of reference?

What are optimal search techniques for spatial queries in relational representations?

Develop optimal indexing and representation of multimodal data.

Problem domains:

Search and rescue planning requires assessment of path difficulty;

Course plotting requires integration of wind and current;

Survey requires integration of view and route;

(Augmentation of map displays by additional frames of reference and additional modalities)

Participants:

Gary Allen, Department of Psychology, University of South Carolina
Immanuel Barshi, Human Factors Division, NASA Ames Research Center
Scott Bell, Department of Geography, University of California at Santa Barbara
Bennett I. Bertenthal, Directorate for Social, Behavioral and Economic Sciences, National Science Foundation
Mark Blades, Department of Psychology, University of Sheffield
Terrence M. Caelli, Center for Mapping, Ohio State University
Janet Carpman, Carpman Grant Associates Wayfinding Consultants, Ann Arbor, MI
Clare Davies, Department of Psychology, University of Surrey
Michel Denis, Groupe Cognition Humaine, LIMSI-CNRS, Universite de Paris-sud
Carola Eshenbach, FB Informatik, University of Hamburg
Christian Freksa, Department of Informatics, University of Hamburg
Scott M. Freundschuh, Department of Geography, University of Minnesota
Sucharita Gopal, Department of Geography, Boston University
Michael Grace-Martin, Department of Psychology, University of California
Christopher Habel, Department of Computer Science & Doctoral Program in Cognitive Science, University of Hamburg
Mary Hegarty, Department of Psychology, University of California at Santa Barbara
C. Donald Heth, Department of Psychology, University of Alberta
Micheal Hewett, Department of Computer Sciences, University of Texas
Stephen Hirtle, Department of Information Sciences and Telecommunications, University of Pittsburgh
Toru Ishikawa, Department of Geography, University of California at Santa Barbara
W. Jake Jacobs, Department of Psychology, University of Arizona
Dan Jacobson, Department of Geography, University of California at Santa Barbara
Susanne Jul, Computer Science and Engineering, University of Michigan
Roberta Klatzky, Department of Psychology, Carnegie Mellon University
Maria Kozhevnikov, Department of Psychology, University of California at Santa Barbara
Barbara Landau, Department of Psychology, University of Delaware
Carol A. Lawton, Department of Psychology, Indiana-Purdue University
Kristin Lovelace, Department of Psychology, University of California at Santa Barbara
Alan M. MacEachren, GeoVISTA Center, Pennsylvania State University
David M. Mark, NCGIA-Buffalo, Department of Geography, State University of New York at Buffalo
James Marston, Department of Geography, University of California at Santa Barbara
Lorraine McCune, Graduate School of Education, Rutgers University
Timothy P. McNamara, Department of Psychology, Vanderbilt University
Daniel R. Montello, Department of Geography, University of California at Santa Barbara
Lynn Nadel, Department of Psychology, University of Arizona
Nora S. Newcombe, Department of Psychology, Temple University
Eric Pederson, Department of Linguistics, University of Oregon
Tony Richardson, Department of Geography, University of California at Santa Barbara
Laura J. Richterich, Department of Psychology, Tufts University
Lynn C. Robertson, Department of Psychology, University of California at Berkley

Charles Spence, Department of Experimental Psychology, University of Oxford
Holly A. Taylor, Department of Psychology, Tufts University
Barbara Tversky, Department of Psychology, Stanford University
Ranxiao Frances Wang, Department of Brain and Cognitive Sciences, Massachusetts Institute of Technology
Steffen Werner, Institute of Psychology, University of Goettingen

VI. Acknowledgements

First off, we would like to LaNell Lucius, Abby Caschetta and Christian Brown, NCGIA staff members for their flawless assistance and support during all phases of preparing and holding this workshop. Without their professional organization, administration, and committed assistance, this workshop would not have been nearly as enjoyable and as it was successful. Thank you LaNell, Abby and Christian.

We also want to thank the many graduate students who took notes during the many breaks out sessions, who provided assistance with many logistic components of the workshop, and contributed important ideas to the workshop—their efforts are greatly appreciated.

We would like to acknowledge Mike Goodchild, the Executive Board of Project Varenius, and the Cognitive Panel Members for their encouragement and support for this workshop. We also want to thank the Steering Committee for their time and invaluable input during the planning of this workshop. They provided critical feedback on all planning documents, they reviewed all applications for this workshop, several provided plenary papers during the meeting, and the committee-reviewed seed grant proposals.

We want to thank all of the participants for their enthusiastic participation, their willingness to spend great periods of time talking and thinking about modes and frames, their invaluable ideas that have been recorded in this report, and their willingness to engage in lengthy discussions of new ideas in an exciting interdisciplinary format. Without this particular group of participants, we would not have had as successful of a meeting.

We want to thank the Upham Hotel for providing an environment conducive to the exchange of ideas.

We want to thank the National Science Foundation for their generous financial support.

Lastly, we want to thank Barbara Tversky and David Mark for their incredible support. Their faith in us to co-lead this workshop, their many thoughts and ideas, and their senses of humor were appreciated more than they realize. Thank you Barbara and David!

VII. References

Carlson-Radvansky, L. A., & Jiang, Y. (1998). Inhibition accompanies reference-frame selection. *Psychological Science, 9*(5), 386-391.

Levinson, S. C. (1996). Frames of reference and Molyneux's question: Crosslinguistic evidence. In P. Bloom, M. A. Peterson, L. Nadel, & M. F. Garrett (Eds.), *Language and space*, (pp. 109-170). Cambridge, MA: The MIT Press.