Cognitive Engineering for Geographic Information Science

Abstract

Geographic information science provides the foundation for the development of geospatial tools and services that support people in their spatio-temporal decision-making. In order to offer useful and useable solutions, principles of human spatial cognition regarding the representation and processing of spatial and temporal aspects of phenomena must be considered in the design of these tools. Such *cognitively engineered* geospatial services aim for cognitive adequacy and therefore facilitation of user interaction. This article argues for the necessity of cognitive engineering methods in the field of geographic information science by explicating their theoretical foundation and demonstrating practical geospatial applications. It further provides a framework for classifying cognitive user parameters, which can be employed for the personalization of geospatial services.

Introduction

Geographic information science (GIScience) is concerned with the systematic study of all aspects regarding geographic information. Such information is eventually used by people to solve spatial tasks (National Research Council 2006), such as finding one's way around a city or looking for a place to live. It is therefore necessary that the tools, which support us in our spatial decision-making—geographic information systems (GIS) and geographic information services (GIServices)—are designed and engineered by taking into account principles of human cognition (Anderson 2005). This will facilitate people's interaction with these systems and lead to more useful and usable solutions to their spatial problems. *Cognitive engineering for GIScience*—or *spatial cognitive engineering* (Raubal in press)—is an interdisciplinary endeavor, involving the disciplines of geography, cognitive science, computer science, and engineering. A special focus is put on human-computer interaction based on the integration and processing of spatial and temporal aspects of phenomena (Egenhofer and Golledge 1998).

Spatial cognitive engineering has gained importance due to the ongoing evolution of personalized geospatial services. In recent years there has been a paradigm shift in the area of geographic information science and systems (Longley, Goodchild, Maguire and Rhind 2005). In the past, GIS were mainly used by large organizations, such as public utility companies, regional planning offices, and highway departments, to support them in their decision-making processes. Often, these organizations collected the necessary data, managed them in their own database systems, and produced reports and maps for various internal uses. Today, different providers offer services and tools for geospatial problem solving and by that means sell geographic information (GI) to many individual users in small quantities. Various kinds of *location-based services* (LBS), information services that are sensitive to the location of a (mobile) user (Schiller and Voisard 2004, Küpper 2005), serve as examples: they inform clients about the locations of nearby hotels, restaurants, and cultural sites; they support users of public transportation systems; and they help people find a new apartment or house. In other words, we have witnessed a shift from *Big GIS* to *Small GI* (Frank 1999).

This trend to highly specialized geospatial services is intensified by people's increased need to acquire and use spatial information. Formerly, people could find spatial information in the environment when needed and often use it over the course of a lifetime. In today's world of vast mobility and change we frequently face novel situations in unfamiliar environments, such as finding one's way in an unfamiliar city or airport (Raubal 2002). People's information needs depend highly on *situational and personal context* (Schmidt, Beigl and Gellersen 1999). For example, when looking for a place to stay overnight, a business traveler has higher demands with respect to the quality of accommodation than a low-budget traveler. Handicapped people require different route instructions from a navigation service than other wayfinders. These scenarios exemplify the motivation and need for cognitive engineering in GIScience: *Useful and usable solutions to people's geospatial problems can only be found by considering people's cognition, abilities, and strategies brought to the problem-solving process.* It is therefore necessary to employ approaches and methods, which allow for the integration of human concepts into geospatial problem solving in order to bridge the discrepancy between user variables on the one hand and system variables on the other hand. Closing this gap will give users better (in the sense of more personalized) answers to their geospatial queries. For example, users of a navigation service that offers landmark-based wayfinding instructions, will receive directions tied to landmarks that are chosen according to their preferences (e.g., color saliency versus shape) or familiarity with the environment (Winter, Raubal and Nothegger 2005). This will eventually lead the way to enhanced people-based geographic information services (Miller 2007).

This article argues for the importance of cognitive engineering for GIScience, which is an often neglected topic in current GIS and GIScience textbooks. We demonstrate that cognitively engineered geospatial services must consider people's spatio-temporal cognitive strategies and abilities as well as their specific requirements to the services. The next section of this article portrays how the general idea of cognitive engineering is adapted and extended to GIScience. Two examples concerning spatio-temporal concepts and reasoning illustrate the importance of this extension. We then provide a framework for classifying cognitive user parameters to be utilized for the personalization of geospatial tools and services. This proposed categorization into *generic*, *group*, and *individual* is based on research in the cognitive sciences and the field of human-computer interaction (HCI). The next section provides cognitively engineered applications from the spatial domain for each of the categories. The article concludes with directions for future research in the area of spatial cognitive engineering.

From Cognitive Engineering to Spatial Cognitive Engineering

Roots: Cognitive Engineering

The term *cognitive engineering* was coined by Donald Norman in an effort to integrate cognitive and computer science approaches to the design and construction of machines (Norman 1986). According to Norman, cognitive engineering is a type of applied cognitive science. When looking at people's interactions with different everyday things, such as telephones, faucets, and doors, one notices a discrepancy between *psychological user variables* and *physical system variables*. The psychological user variables comprise goals, intentions, concepts, and also spatial and cognitive abilities. During the performance of a task a user must therefore interpret the physical system variables in the context of her psychological goals and translate her psychological intentions into physical actions upon the system. The goal of cognitive engineering is to bridge the so-called *gulf of execution and evaluation* (Figure 1), which results from the differences between user and system states in terms of form and content. This gulf can be bridged from two sides:

1. The system designer can move the system closer to the user in terms of finding better matches to her psychological needs.

2. The user can bridge the gap by approximating the description of goals and intentions to the system's language. Such approximation covers different levels of outcomes and intentions.

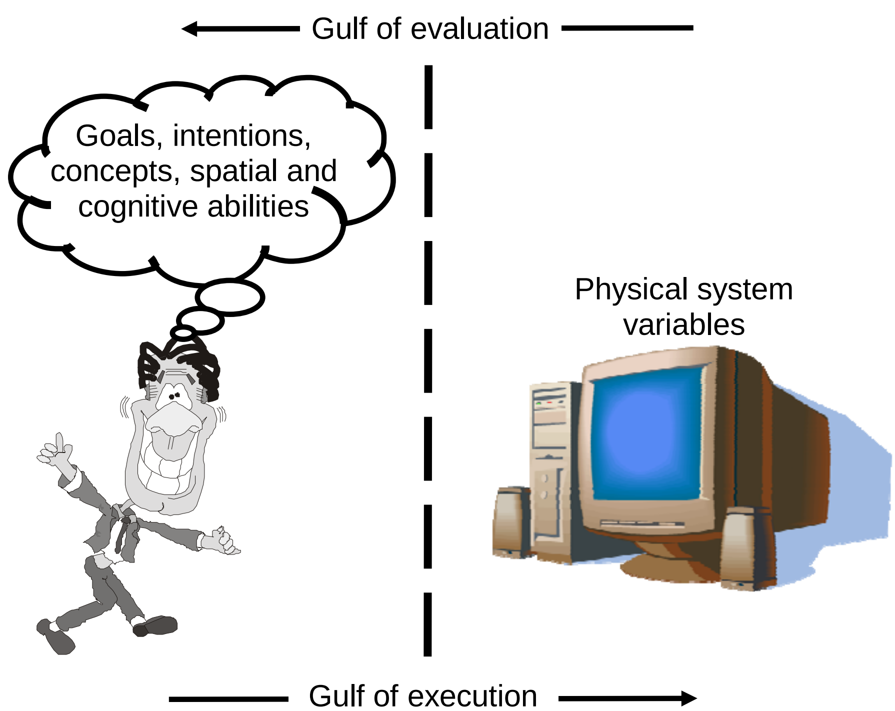

Figure 1: Discrepancy between psychological user variables and physical system variables, adapted from (Norman 1986).

In his account of cognitive engineering as a new discipline, Norman focused on computer design in general and on the design of user interfaces (Shneiderman and Plaisant 2005) in particular. A major aspect in the analysis was that different users may require different interfaces, even when performing the same tasks and working with the same system. He therefore advocated a *user-centered system design*, which starts with the user's needs regarding a particular problem.

Spatial Cognitive Engineering

Spatial cognitive engineering follows the general ideas of cognitive engineering and applies them to the geospatial domain. Such application highlights important aspects, which are integral and characteristic to geospatial problem solving. Spatial cognitive engineering focuses especially on human-computer interaction regarding spatial and temporal aspects of phenomena in the world. Geospatial services and systems are unique in the way that they use data, which are related to locations in space (and time), and the way that processing the data with respect to these spatial locations is possible. The fact that everything is tied to a location in space and time leads to increased complexity regarding reasoning with and analysis of the data. People's questions when using geospatial tools have a spatio-temporal context. One can ask 'where is a certain object' or 'where are all objects with certain properties' at a given time when trying to find the nearest kindergarten for a child, or one can ask 'what are the properties of a certain area in space' at a given time when trying to assess the environment in which to rent a house. Resolving the discrepancy between psychological user variables and physical system variables in the geospatial domain goes beyond the user-interface level, which is illustrated through the following two processes.

- *Matching Spatio-Temporal Concepts.* People use various conceptualizations of *space* and *time*, such as 'continuous versus discrete' or 'absolute versus relative' (Peuquet 2002). The particular spatio-temporal perspective in spatial cognitive engineering implies that spatial and temporal concepts need to be matched between users and systems. Take, for example, the different semantics of spatial terms, such as *location* or *road,* depending on the user and context. In transportation, a road means an open way of travel whereas in a wildlife habitat it represents a potentially dangerous border for various species. Semantic heterogeneity—two contexts leading to different interpretations of the same information (Wache, Vögele, Visser, Stuckenschmidt, Schuster, Neumann and Hübner 2001)—can lead to erroneous decisions made by geospatial services. Results of a spatial analysis may be correct for the data model of the dataset, but do not meet the user's expectations and can therefore lead to false decisions. Figure 2 shows an example by illustrating the use of topographic data for noise abatement planning (Lutz, Riedemann and Probst 2003). To determine which roads have a significant noise effect on residential areas, those roads touching or crossing these areas must be identified. A user might have the mental concepts of roads and residential areas as depicted on the left in Figure 2, whereas the system uses representations of roads and residential areas as shown on the right in Figure 2. If the user is not aware of the system designer's conceptualization she might assume that roads overlap residential areas and will consequently use the dataset as input for an intersect operation to find roads crossing residential areas. However, based on the system's representation the user will not find any roads by doing so.

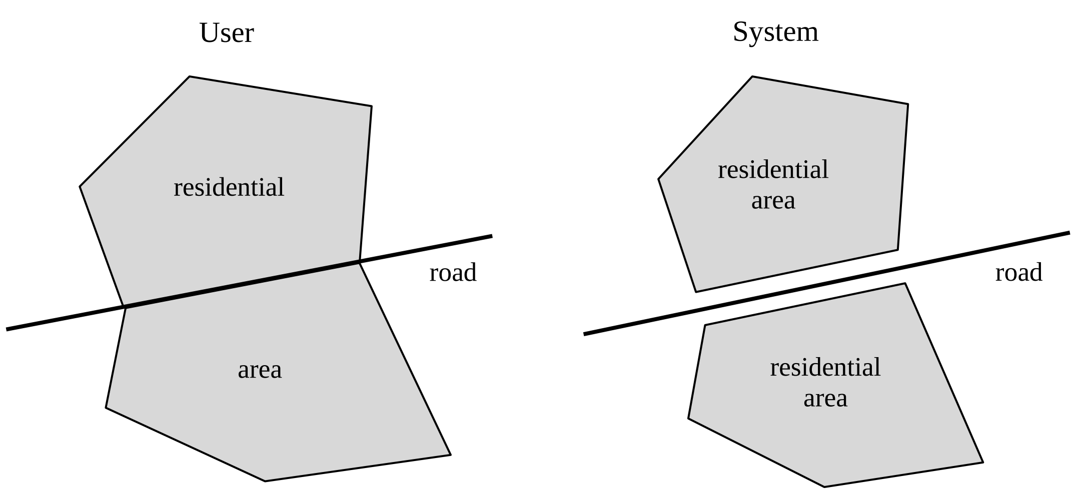

Figure 2: User and system models of roads crossing residential areas.

- *Spatio-Temporal Reasoning*. Spatial reasoning and decision-making in a spatio-temporal context include particularities, which need to be accounted for during HCI. Spatial reasoning is about topology, distance, orientation, and shape with regard to objects and configurations of objects in space and time. Instead of doing exact calculations, people apply qualitative methods of spatial reasoning (Cohn and Hazarika 2001, Guesgen, Ligozat, Renz and Rodriguez 2008) that rely on magnitudes and relative values—see, for example, the differences between wayfinding instructions as given by humans versus machines. When people perceive space through different channels, they arrive at various kinds of information, which are usually qualitative in nature. Spatial reasoning involves a variety of decision-making methods and choice behavior. Decision theory covers a large range of models with different foci on describing how decisions could or should be made and on specifying decisions that are made (Golledge and Stimson 1997). In many cases, human decision-making is not strictly optimizing in an economical and mathematical sense, such as proposed by the algorithms of classical decision-making theories. Several of these aspects are accounted for to various degrees during spatial cognitive engineering.

The goal of applying cognitive engineering methods within GIScience is to design spatial information systems and services based on principles of human communication and reasoning. The field of spatial cognitive engineering is motivated by the belief that useful and usable solutions to people's geospatial problems can only be found by considering the cognitive abilities and strategies people bring to the problem-solving process.

Personalization and Cognitive User Parameters

According to the Oxford English Dictionary (http://www.oed.com/), *personalization* is defined as "the action of making something personal, or focused on or concerned with a certain individual or individuals; emphasis on or attention to individual persons or personal details." From a GIScience perspective this translates to the customization and adaptation of geospatial tools and services to their users. It has been argued that consumers of geographic information differ in their cognitive styles, abilities, and preferences. Cognitive research helps to understand how individuals and groups of people differ in their cognition of GI, and its results can be used to improve the usability and efficiency of geospatial tools and services (Montello and Freundschuh 2005). Much research in the area of information system design and human-computer interaction (Ghaoui 2006) has focused on the problem of designing systems for the average versus the specific user. Here, we argue for a threefold categorization of cognitive user parameters, i.e., *generic*, *group*, and *individual*. This distinction is based on work done in the areas of psychology, spatial cognition, and user interface design.

A View from Psychology

There exist two historical streams of psychology, termed *experimental* and *correlational* (Cronbach 1957). In experimental psychology the conditions in the environment are changed and the resulting consequences of these changes observed. The experimenter is interested in the created variation and therefore brings situational variables under control. Correlational psychology focuses on the already existing variation among individuals, social groups, and species. Yerkes (1913) argued that all correlational psychologies are one and named this branch *comparative* psychology. For the experimenter, individual differences are an irritation because the goal is controlling behavior. The correlational psychologist, on the other hand, considers individual and group variation as important effects of biological and social causes.

In *applied* psychology, the application of psychological principles to practical problems in various domains, the two streams were traditionally seen to be in active conflict. The goal of applied experimental psychology is to modify treatments in such a way that the highest average performance is obtained when all persons are treated the same way. It is a search for the 'one best way.' Applied correlational psychology tries to raise the average performance by treating persons differently. Cronbach (1957) made a case that "it is shortsighted to argue for one science to discover the general laws of mind and behavior and for a separate enterprise concerned with individual minds, ..." and therefore called for an integration of experimental and correlational psychology.

Spatial Cognition

Human spatial cognition belongs to the interdisciplinary and wide-ranging field of cognitive science (Wilson and Keil 1999). Researchers from many academic disciplines, such as psychology, linguistics, anthropology, philosophy, and computer science investigate the mind, reason, experience, and people's conceptualizations of the world in which they live (Lakoff 1987). As a part of cognitive science, it deals with human intelligence in all its forms, from perception and action to language and reasoning (Pinker 1997). Mark *et al.* (1999) presented a hypothetical information flow model for spatial cognition that consists of four stages: acquisition of geographical knowledge, mental representations of geographical knowledge, knowledge use, and communication of geographical information. For all of these stages individual and group differences need to be considered.

Montello and Freundschuh (2005) come to the conclusion that people differ in various ways regarding their cognition of geographic information. They emphasize the importance of research on education, experience, and age differences to design better geospatial tools—see also *applied spatial cognition* (Allen 2007). More specifically, the consequences of age and gender differences, and also the effects of different background and culture need exploration. Further explanatory variables for differences in spatial cognition as part of a comprehensive (but non-exhaustive) list are genetic constitution, physiology and anatomy, sex, education, expertise, socioeconomic status, family membership, and residential environment (Montello 1995). Following a study on people's practices of navigating a ship, Hutchins (1995) made the case that cognition is a fundamentally cultural process and that culture defines the boundaries of a cognizing system. When investigating the significance of cultural differences in spatial cognition, Montello (1995) argued that despite the existence of *cultural groups* there are many cultural universals that people share. Therefore, cultural differences in spatial cognition may not be nearly as substantial as is often assumed. Several case studies involving the cognitive aspects of navigation systems demonstrated the importance of taking into account individual differences among navigators, such as different abilities, preferences, and navigational styles (Montello and Freundschuh 2005).

User Interface Design

User categories and individual user differences are a major topic in the area of user interface design for information systems (Norman 1986, Nielsen 1993, Shneiderman and Plaisant 2005). Nielsen (1993) argues that the users' tasks, and individual characteristics and differences are the most important aspects for usability. Therefore, a key issue in usability engineering is *knowing* *the user*. Several systems come with at least two sets of menus, one for the expert and another for the novice user. Among the most important variables regarding differences between individual users and user groups are age, gender, differences in spatial memory and reasoning abilities, preferred learning style, and attitude differences. Rubin (1994) emphasizes the importance of identifying a user profile describing the range of skills, which constitute the whole universe of end users. Such a profile can then be used to identify groups of users who share many of its characteristics. When classifying groups it is necessary to define them through measurable criteria, i.e., using operational definitions. Maybury and Wahlster (1998) address the design of *intelligent user interfaces* (IUI), which provide additional benefits to their users, such as adaptivity, context sensitivity, and task assistance. Here, it is especially important to represent and exploit models of the user, the domain, tasks, and context. They state that adaptation is required because it is practically impossible to anticipate the needs and necessities of each potential user in an infinite number of presentation situations. An overview of adaptive mobile web applications and mobile guides is presented in (Krüger, Baus, Heckmann, Kruppa and Wasinger 2007).

A similar focus on user differences can be found in the field of GIScience. It has been argued that the design of GIS benefits by considering how individuals understand and represent space (Mark 1989, Medyckyj-Scott and Blades 1992). Kuhn (1996) recommends to *spatialize* user interfaces in order to map the particular spatial experiences of users to various application domains. With regard to using GIS it has been pointed out that, for the user, the user interface is the system (Frank 1993). Further work in this area deals with user models in designing query interfaces for GIS (Lindholm and Sarjakoski 1992) as well as customization and specification of GIS users as part of the design process (Medyckyj-Scott 1993).

Classifying Cognitive User Parameters

The design of cognitively engineered geospatial tools and services requires an initial decision about the level of personalization. Should the tools work for the average user, should differences between specific groups of users be taken into account, should the tools be customizable to individual users? Based on the presented work regarding differences among people in general and users of information systems in particular, a tripartite distinction (Figure 3) is derived here to classify cognitive user parameters. This distinction leads to the three user categories *generic*, *group*, and *individual* with regard to their cognitive parameters, such as strategies, abilities, and concepts.

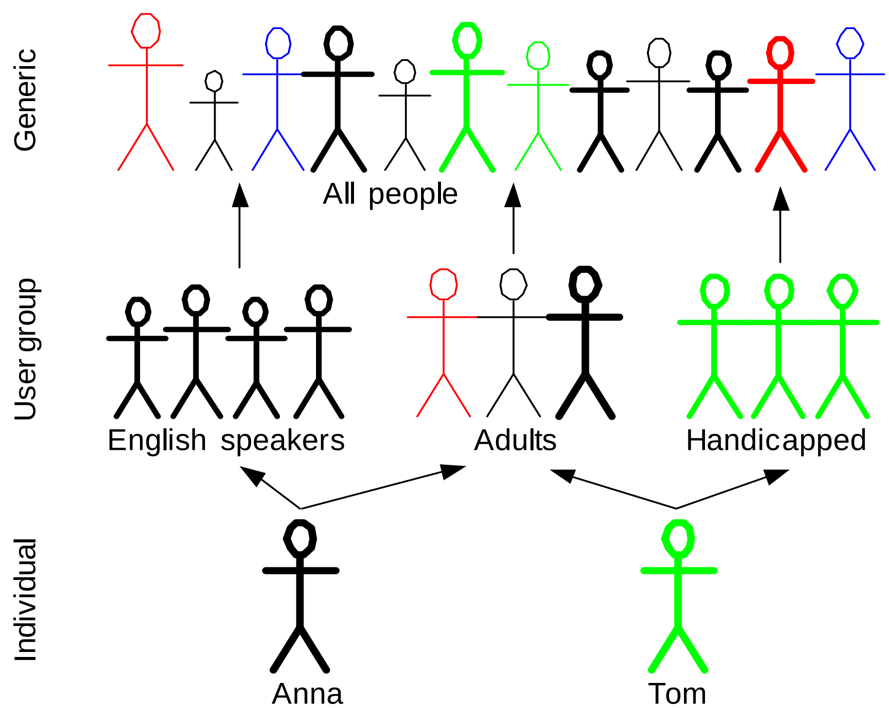

Figure 3: User categorization into generic, group, and individual.

The *generic* level relates to the experimental stream of psychology insofar as it comprises a general set of cognitive parameters assumed to be applicable to all people. For example, in general, people use landmarks for finding their ways and for communicating wayfinding directions to others. The generic category also accounts for the fact that there are numerous cultural universals that people share (Montello 1995) and with regard to these a finer distinction is not required. There are many computer systems, which do not offer any possibilities of customization but are still used by different people, such as information terminals, mobile phones, etc. Although such use occurs in more or less efficient ways, the fact that different people can use these systems at all, provides evidence that people do share important cognitive abilities.

Groups of users are defined by common sets of cognitive parameters. Such definition is intentionally left broad and allows for the formation of user groups based on similar abilities, interests, concerns, goals, beliefs, or behavioral practices. This necessarily results in various overlaps between different groups of users. The *group* level is linked to the comparative stream of psychology. The focus of analysis is on the variation of parameters between different groups. Examples are gender groups, such as all women and all men, and comparatively smaller cultural groups defined, for example, by sharing a common language. These examples demonstrate that groups of users occur at different hierarchical levels expressed through the number of their members. For example, relative to the group of all students at a particular University, the group of blind students at that University is small. The main question here is what kinds of differences should be taken into account when forming a group of users within a particular spatio-temporal context (see, for example, the distinction between landmark selection at day versus at night in the next section)? The importance of defining user groups for user interface design, e.g., novice versus expert, was previously pointed out. In wayfinding one can, for example, distinguish between different groups of handicapped (e.g., blind and deaf) persons. Wayfinding instructions need to be adapted for specific groups in order to be useful.

Dealing with people as *individuals* relates to comparative psychology with a focus on individual variation. Every single person is treated differently. Personalization can go a long way and the more parameters there are that need to be adapted the more difficult and complex it becomes. An example for location-based services is the representation of individual user preferences, such as ‘I want to go from location X to location Y *by public transport*’ (Raubal, Miller and Bridwell 2004).

It is important to take note that this classification forms a hierarchy with part-of relations (Figure 3). All people share some cognitive parameters but they also fall into various user groups and have their individual preferences. When using cognitive engineering approaches for the design of geospatial tools and services a major question is therefore how far one wants to move down in this hierarchy. The following section provides applications that serve as examples for choices of such movements.

Cognitively Engineered Geospatial Services

In this section we provide two prototypical application areas of *mobile location-based services* (mLBS), a pedestrian navigation service and a hotel-finder service, to demonstrate both the general need for cognitively engineered geospatial services and the different levels of personalization presented in the previous section.

Landmark-Based Wayfinding Instructions

People usually employ landmarks when mentally representing, describing, and communicating routes in their environment (Lynch 1960, Lovelace, Hegarty and Montello 1999, Denis, Michon and Tom 2006). Such use denotes a *generic* cognitive strategy. Over the last decade it has been realized that route instructions from existing navigation services lack cognitive adequacy (Strube 1991), because they rely on quantitative values, such as ‘go straight for 0.5 km, then turn right, go 1.2 km, etc.’, instead of providing landmark-based instructions, such as ‘go straight until you reach the large red building, turn right after the building, etc.’. Researchers have therefore investigated methods for the automatic detection of landmarks to be used in wayfinding instructions (Sadeghian and Kantardzic 2008). Raubal and Winter (2002) addressed the question of how to enrich instructions from a wayfinding service with local landmarks in order to make them compatible with human thinking. A model was developed, which formally specified measures that define the landmark saliency of a feature. These measures fall into the three categories of visual, semantic, and structural attraction (Sorrows and Hirtle 1999). Put together, they form a global measure of saliency for each feature in a dataset. With the use of stochastical tests one can identify the most significant landmark at each decision point for inclusion in the wayfinding instructions. This model was implemented and applied to a concrete wayfinding task in the city of Vienna (Nothegger, Winter and Raubal 2004). A human participants test demonstrated that the automatically identified features correlate highly with human choices of landmarks at these decision points.

This case study on using landmarks in wayfinding instructions was used by Winter, Raubal and Nothegger (2005) in further work to investigate the adaptability of the saliency model to abilities and preferences of *user groups*. A human participants test focusing on people’s landmark selection was conducted to identify differences between user groups with regard to age, gender, and familiarity with the environment. This study also addressed differences in landmark selection between day and night, the relative importance of each salience measure, and whether these differences can be modeled through weights for the criteria. The results suggested significant differences between female and male subjects regarding the selection of landmarks. It was further demonstrated that people select different landmarks by day and night, and that such behavioral variation can be accounted for through different weight sets for the automatic selection of landmarks.

Hotel-Finder Service

A large number of mobile location-based services has been developed and introduced in the literature (Raper, Gartner, Karimi and Rizos 2007). These applications fall into various categories, such as mobile guides, navigation and transportation services, location-based gaming, and other services that support everyday decision-making in a mobile context in different domains (Schiller and Voisard 2004, Küpper 2005). Current LBS are limited in their capacity to consider user preferences for the performance of spatio-temporal tasks (Raubal, Miller and Bridwell 2004). We use a mobile hotel-finder service to demonstrate the influence of different *user groups* and different decision strategies on the outcomes of location-based analyses with the ultimate goal of service personalization for the *individual*. This also shows that the distinction between the hierarchical levels regarding user classification introduced in the previous section is not always clear cut and for several reasons it often makes sense to define user types instead of considering each user as an individual.

The *Hotel Finder* was developed as a location-based decision service (LBDS) and integrates methods of multi-criteria evaluation. The software features multi-criteria decision support for the task of finding suitable hotels in an unfamiliar environment depending on the user's location and preferences. The original application (Raubal and Rinner 2004) was extended in (Rinner and Raubal 2004) by integrating the ordered weighted averaging (OWA) decision rule (Yager 1988). The OWA method allows users to choose a decision strategy as part of their decision-making preferences. This leads to different answers by the LBS depending on people's level of risk-taking. In this way, LBS have the potential to better represent the parameters of user groups and individuals. Decision strategies range from 'optimistic' (i.e., risk-taking) to 'pessimistic' (i.e., cautious), and allow from a full trade-off to no trade-off between the different decision criteria. OWA uses a second set of weights (besides criterion importance weights) to emphasize either high or low standardized criterion outcomes. For example, with a pessimistic strategy, decision-makers focus on the lower outcomes of each decision alternative to avoid the risk of selecting an alternative with poor performance in any criterion. In contrast, with the optimistic strategy, decision-makers focus on the higher outcomes, thus incurring the risk of accepting an alternative with excellent performances in some criteria but possibly poor performances in other criteria. The service was tested by using business traveler and low-budget traveler scenarios, where users run through the steps of an MCE process that includes determining decision alternatives (hotel destinations), selecting decision criteria (e.g., room rate, and checkout time), standardizing the criterion values for all alternatives, determining importance weights for criteria, and using a multi-criteria decision rule to aggregate the weighted standardized criterion values to an evaluation score and rank for each alternative (see Figure 4 for exemplary steps of finding an optimal hotel in the city of Toronto, Canada). The test case demonstrated that different users can and should be offered specific choices by LBS. The usefulness of the *Hotel Finder* was further demonstrated through a comprehensive user test showing that MCE-based decision support can be used for optimizing location-based decision processes (Bäumer, Panov and Raubal 2007). The goal of this test was to focus on the benefits and drawbacks of a personalized mobile LBDS. The results confirmed that applying the multi-criteria decision strategy enhances people's decision support in unfamiliar environments.

Figure 4: Cognitively engineered mobile hotel finder. The screenshots present user standardization and weighting of criteria, selection of a decision strategy, and presentation of the results with the option of calculating the route to the optimal hotel.

Conclusions and Future Research Directions

Geographic information science investigates all aspects of geographic information. It therefore provides the scientific foundation for geospatial tools and services. In order to be useful and usable for people, these tools must be designed and engineered by incorporating principles of human cognition with respect to spatial and temporal aspects of phenomena. Only then will they facilitate human-computer interaction and provide high-quality support for their users' spatio-temporal decision-making. This article argued for the importance of integrating cognitive engineering methods within the field of GIScience. Cognitive engineering is a type of applied cognitive science and has its roots in user-interface design. Geospatial services are unique in the way they incorporate spatial and temporal data, therefore requiring the extended version of *spatial cognitive engineering*. Its major goal is personalization of geospatial services because users of geographic information differ in their cognitive styles, abilities, and preferences. Based on research in the cognitive sciences and human-computer interaction—more specifically in psychology, spatial cognition, and user interface design—we provided a framework for classifying cognitive user parameters into *generic*, *group*, and *individual*. Such parameters concern people's concepts, abilities, and strategies, and must be utilized for the personalization of geospatial tools and services. Two application areas from mobile decision-making were chosen as examples for such cognitively engineered geospatial services. They demonstrated that spatial cognitive engineering supports all three levels of personalization. First, geospatial services must account for universal concepts and strategies in order to come closer to their users' thinking in general and to be based on solid cognitive ground. Second, by taking specific cognitive characteristics of groups into consideration, the systems' solutions can be improved for each individual group. Finally, personalization of geospatial services leads to the highest level of usefulness and usability for the individual user but it is hardest to achieve because of the sometimes unlimited complexity regarding data acquisition, modeling, and representation.

The area of spatial cognitive engineering leads to a series of research directions for future investigation:

- *Formal Conceptual Representations.* People's conceptual representations need to be formalized in order to integrate them into computer systems. The closer the system's view comes to the user's view in terms of conceptualizations and reasoning processes, the higher the likelihood of facilitating human-computer interaction and delivering cognitively adequate answers to the users' spatio-temporal problems. Various formal approaches to cognitive modeling, and the representation and processing of geographic knowledge exist (Barkowsky 2002), resulting from different views on the nature of conceptual representations in the human cognitive system. This leads to the question whether there is a hybrid spatial cognitive model that covers 'the whole ground' and if so, what are its components? Multidisciplinary research in the cognitive sciences, the geosciences, and computer science is required to find answers to this question. Human participants tests may help assess the validity and potential limitations of conceptual representations. Cognitively based spatio-temporal ontologies, such as the Descriptive Ontology for Linguistic and Cognitive Engineering (DOLCE) (Gangemi, Guarino, Masolo, Oltramari and Schneider 2002), can be used as a foundational representational upper-level framework for specifying such conceptualizations.

- *Spatio-Temporal Decision-Making.* Usefulness and usability of cognitively engineered tools depend strongly on how well their underlying theories represent elements of people's spatial and temporal decision-making, including aspects of uncertainty and vagueness in the real world. It is necessary to investigate the various effects of geographic and temporal scales on people's information requirements. Such effects will help to establish different levels of granularity for the represented information. Further research is necessary to explore how time constraints for different types of geographic information and desired activities are constructed and how this process is influenced by cultural differences.
- *Representing Context.* Geospatial information must be understood by different users and in different contexts. The semantics of expressions for objects, actions, and relationships can change significantly depending on the user's background, perspectives, and situation.

Investigations on people's different foci with respect to their activities in space and time will help to establish sets of parameters for focalization, i.e., the adaptation to different decision situations (Raubal and Panov 2009). An example is the modeling of different foci onto urban space during wayfinding. Furthermore, context must be quantified in order to be utilized in geospatial services. One possible way of quantification is to assign weights to measures, depending on the cognitive representation. Human participants tests will help to determine these weights for different context parameters.

- *Applications and Evaluation.* A large number of different models and prototypes for geospatial services exists, in addition to the applications discussed in this article. In order to test their usefulness and usability in a comprehensive way, they have to be fully implemented and further extended. This also concerns architectural and user interface issues. Not only is it important whether such services are technically feasible but with the help of human participants tests one also needs to find out how well they work for their users and whether or not people want to use them in their everyday lives.

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