USER CENTERED TIME GEOGRAPHY FOR LOCATION-BASED SERVICES

by
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ABSTRACT. Location-based services assist people in their decision-making during the performance of tasks in space. They do not consider the user's individual preferences, time constraints and possible subtasks to be performed. In order to account for these important aspects, a user-centred spatio-temporal theory of location-based services is required. We propose such a theory by combining classical time geography with an extended theory of affordances. It assumes that affordances belong to three realms: physical, social-institutional, and mental. In addition to covering the capability, coupling and authority constraints from time geography, this allows for a user-centred perspective because affordances describe action possibilities with regard to a specific person. Furthermore, the integration of mental affordances offers the possibility to account for cognitive time constraints due to the duration of decision-making processes. This new theory for location-based services is closer to the individual user and more plausible with respect to their daily lives. A business traveller scenario is used as a case study to demonstrate this.

Key words: Xxxxxx, xxxx, xxxxxx, xxxxxx

Introduction

Imagine the following situation. A business traveller arrives in a new city at 6 a.m. She is scheduled to have a meeting at 8 a.m. in a local office building. On the way to the meeting – preferably by public transport – she would like to have breakfast – preferably an espresso and a bagel – read a newspaper, and make a phone call. Through her Personal Digital Assistant (PDA) the business traveller connects to a location-based service (LBS), which suggests a way to do all of these tasks considering her time constraints and personal preferences:

1. Take bus no 3 and get off after seven stops. Make your phone call while riding on the bus because the connection is good along this route.
2. Walk five minutes to Café X, where they have espresso, bagels, and various newspapers. You have 45 minutes.
3. Walk three minutes to subway station Y. Take the green line and get off after three stops.
4. Walk two minutes to the office building. You will be there at 7.55 a.m.

These instructions are complemented by additional information, such as wayfinding maps and the names of the bus and subway stops involved.

Receiving such information from LBS is yet a vision. Current LBS neither consider the user's personal preferences nor can they integrate interlinked time constraints and subtasks. In the above scenario the business traveller could only ask separately for the ways to the office building, a café and a newspaper store. What is missing is a *user-centred-spatio-temporal theory*, which allows location-based services to assist users individually during multiple activities within a specific period of time.

This paper presents a general framework for such a theory, which combines the ideas of classical *time geography* (Hägerstrand, 1970) with an extended theory of *affordances* (Gibson, 1979). Time geography has tried to define the time-space mechanics of different constraints, i.e., the capability, coupling, and authority constraint. It does not include cognitive constraints – although see (Kwan and Hong, 1998) – and does not integrate very well the possibility of telepresence and the ability to project one's manifestation beyond one's physical location – although see Hägerstrand, 1970; Adams, 2000. The concept of affordance has its roots in ecological psychology. Affordances describe possibilities for actions with reference to a user. In an effort to extend the original concept with elements of cognition, situational aspects and social constraints, it has been proposed that affordances belong to different realms – physical, social-institutional and mental (Raubal, 2001).

The integration of time geography and extended affordance theory allows for representing a user-specific level including time constraints and possible subtasks to be performed. The capability constraint is expressed through physical affordances for an agent, depending on its capabilities. Physical and social-institutional affordances for agents at various places represent coupling and authority constraints. They also permit us to remove action possibilities from particular locations. In addition, we consider cognitive constraints by integrating mental affordances into the theory. These should be included in a plausible spatio-temporal theory because using mental affordances (e.g. people engaging in decision-making processes) takes time and therefore leaves less time for other actions. Time constraints and tasks are modelled by a hierarchy of space-time prisms. The main task is represented by a fixed space-time prism, which cannot be changed – in the above example the business traveller must be at the meeting at 8 a.m. Subtasks are more adaptable and can therefore be represented by flexible space-time prisms with variable time constraints.

A user-centred theory for LBS must take into account that different people have different preferences for their various activities. Representing these preferences through affordances allows one to focus on the activities themselves instead of conventional categories of places, which are assumed to allow for certain activities. The integration of social-institutional affordances into the preference model also supports the proposed classification of time-geographic communication possibilities (based on a given classification, which is extended by social constraints). This new classification seems to be more plausible with regard to everyday life.

Section 1 gives an overview of location-based services. In section 2 the relevant principles and concepts from time geography are introduced. Section 3 describes the original theory of affordances and explains the ideas behind the extended theory. In section 4 the general framework of combining time geography and affordances is demonstrated. We use a functional approach for representing the extended theory of affordances to model time-geographic constraints and communication modes. Section 5 describes additional elements needed for the new theory of LBS: cognitive time constraints in decision-making processes, user preferences, and hierarchies of space-time prisms representing combinations of tasks. Section 6 shows how this integration leads to a new theory for location-based services, which is demonstrated by using the case study. The final section gives conclusions and presents directions for a future research agenda.

1. Location-based services

Mutual advances in wireless communications and geo-spatial technologies have spurred interest in developing information services that are sensitive to the location of a mobile user. These so-called *location-based services* (LBS) allow users to query their location from a mobile terminal, such as a phone or PDA, and relate it to the surrounding environment. This facilitates the successful completion of tasks such as navigation (Winter *et al.*, 2001). Tremendous benefits may be achieved from the widespread adoption of these services, providing large segments of the population real-time decision support for purposes ranging from trivial (concierge services, location-sensitive games) to critical (emergency response). LBS may also serve as a mechanism for collecting disaggregate activity-travel data from users, providing researchers and planners with more detailed information regarding spatio-temporal patterns of interaction in urban environments (Miller, forthcoming, d). In the longer term, many expect the technology to impact upon our lives in unpredictable ways, similar to the initial development of the Internet (Jensen *et al.*, 2002).

LBS architectures

LBS are available in Japan and Europe, with more rudimentary services such as Vindigo (www.vindigo.com) available in the USA. An important emerging standard is the Open GIS Consortium (OGC) (http://www.opengis.org/) OpenLS initiative. It defines standards and interfaces to foster openness and interoperability in LBS development and deployment. These efforts seek to leverage existing investments in geo-spatial data and processing resources with investments in communication protocols and infrastructures. This is conducted under the philosophy that the spatial processing and data required to support LBS functions are already present, but fragmented among disconnected proprietary systems. Thus interoperable architectures to support LBS may be achieved by defining the core framework of services that can be linked together to provide a functional LBS, and implementing a set of interfaces that wrap the functionality of the core services according to standard specifications.

The core services defined by the OpenLS are: (1) directory services, (2) gateway services, (3) location utility services, (4) route services, and (5) presentation services (Bishr, 2002). *Directory services* provide users with online directories to assist in finding specific places, products or services, or ranges of places defined by a distance threshold. *Gateway services* provide the interface to the location position server. *Location utility services* provide geo-coding functions. *Route services* provide a route between two given points, with options to include specific way-points within the route. Routes can be generated to minimize either distance or time, and specified according to a particular mode of travel. The results to route requests can optionally include route geometry or textual descriptions. *Presentation services* provide the cartographic capabilities for the LBS; these may be tailored for different types of mobile devices.

The core services provide powerful functionality, but are even more powerful when coupled together. Consider the following request: 'Give me a map with the route from here to the closest café.' This query would require each of the core services mentioned above. The service chain might begin with a directory service to find the addresses of cafés in that area. These addresses could then be geo-coded by a location utility service. The gateway service would then query the location of the user and provide this location, along with the café locations, to another directory service to determine which café is closest to the user. A route service would find the fastest route from the user to the café. All of this information would then be summarized into a map that is optimal with regard to the user's device.

In theory, each of the components to this query could be completed by different entities, connected through standard protocols. This is the goal of the OpenLS XML for Location Services (XLS) specification. The XLS provides standard interfaces for requests and responses to the core services discussed above. These interfaces are implemented using XML Schema, allowing for easy reuse of defined elements and attributes. Efforts have also been developed to 'harmonize' the core services with interfaces developed by other specifications. This means that any request or response created under either protocol will validate against the other.

LBS Limitations

Current LBS implementations in Japan and Europe as well as emerging architectures in the USA support only basic locational queries such as location-sensitive maps, route finding and spatial searching capabilities (e.g. finding all cafés within 300 meters of my current location). These services provide support for 'first-order' location queries, (i.e., 'Where should I go from here and how do I get there?'). This represents only a limited scope of the broad spectrum of services that could comprise LBS.

While interoperable architectures will likely promote the widespread adoption of LBS, they fail to account for some of the key properties of activities in space and time. First, the LBS inherit the GIS (Geographic Information System) preoccupation with space and fail to capture the temporal properties. For instance, the directory service considers proximity in space but not availability in time. One café may be closer than another, but it may not be open. The services discussed above would fail to consider this possibility and could provide the user with misinformation. Another limitation is lack of support for activity scheduling. More sophisticated LBS would support *n-order space-time activity queries*: the scheduling and execution of multiple, linked activities and subtasks over longer time frames (daily, weekly) and locations rather than based only on a current location, independent of time.

The possibility of supporting sophisticated LBS queries such as the situation presented at the start of this paper cannot be accomplished by chaining core components together in an *ad-hoc* manner. Rather, services must be configured to reflect an explicit theory about what is possible for an individual in space and time. In addition, there should be some way to select from several possible activity locations and schedules based on user preferences. This paper suggests that integrating time geography with an extended theory of affordances can provide such theory.

Time geography

Time geography focuses on a necessary condition at the core of human existence: 'How does my location in space at a given time affect my ability to be at other locations at other times?' Since people and resources exist at a small number of locations for limited temporal durations, the ability to be present or telepresent at particular locations and times is required for almost every human activity. Conditioning these possibilities are transportation and communication services: they determine the ability of a person to trade time for space (through movement or communication) in order to be present or telepresent at a particular location and time (Hägerstrand 1970). This section reviews major time geographic concepts, particularly as they relate to LBS.

Space-time paths

The *space-time path* highlights the constraints imposed by activities that are finite in space and time as well as the need to trade time for space when

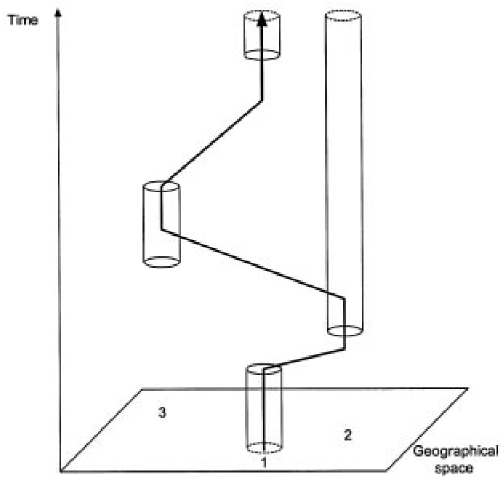

Fig. 1. A space-time path and stations.

moving among activities. Figure 1 illustrates a space-time path representing a person's movement and activity participation at three locations during part of a day.

Space-time stations (depicted as tubes in Fig. 1) are locations containing resources required for activities such as eating, sleeping, work, shopping, obtaining medical services, and so on: in general, any activity that does not involve movement given the scale of analysis. If the path is vertical, the person is conducting a stationary activity. If the path is not vertical, the person is moving between stationary activities. A relatively shallow slope indicates that less time is required per unit space when moving, (i.e. transportation services are more efficient). The path can never be horizontal: this would indicate a perfectly efficient transportation service (Lenntorp, 1976, 1978; Pred, 1981). Time geography traditionally considers movement at the geographic scale, but the increasing spatio-temporal resolution allowed by positioning technologies could push its domain to architectural scales such as shopping in a city center or mall.

Note that the person depicted in Fig. 1 left station 1 but arrived early at station 2 – presumably she had to wait until it was available. Consequently, this person arrived late at station 3 and had to leave when it was no longer available. She subsequently returned to station 1 earlier than necessary. A better choice would have been to conduct the activity at station 3 first: although station 3 is relatively distant from station 1, station 2 was available later and for a longer duration. However, if transportation services were more efficient, the shallower slopes of the space-time path during movement episodes could have made the original activity schedule feasible.

Constraints and the space-time prism

There are three major classes of constraints that limit an individual's ability to participate in activities in space and time. *Capability constraints* limit activity participation through their inherent abilities and available resources. Having to be at home for at least six to eight hours per day for sleep is a fundamental physical limitation. Owning a car is a resource that allows more efficient trading of time for space in movement. Having broadband Internet connections allows more efficient communication. *Coupling constraints* require a person to occupy a certain location for a fixed duration in order to conduct some activity. Attending a meeting, dinner with your family, having a coffee and surfing the web at an Internet café all reflect coupling constraints. *Authority constraints* are fiat restrictions on activities in space and time; these may include private property restrictions such as a shopping mall being open from only 9 a.m. to 9 p.m.

Coupling constraints lead to another fundamental distinction in time geography: the partitioning of activities into fixed and flexible activities. *Fixed activities* are those that cannot be easily relocated and rescheduled in space and time, at least in the short run. Examples include many home activities (particularly when children are involved), work, and scheduled meetings with other people. *Flexible activities* are those that are relatively easy to relocate or reschedule. Examples include shopping and dining. Although the boundary between fixed and flexible activities can be indistinct (e.g. a film versus a live performance), this is a powerful concept that allows the analyst to link accessibility to individual activity schedules.

An individual's physical reach in space and time has a geometric expression; namely, the *space-time prism* (STP). The STP delimits the possible locations for the path based on the ability to trade time for space when moving and participating in flexible activities in the limited durations between fixed activities during a given time horizon (hourly, daily, weekly and so on). Figure 2 illustrates a STP for the case where two fixed activities occur at different locations (say, home and work) and frame a flexible activity (say, shopping). The STP can be constructed if we know the times when the fixed activities

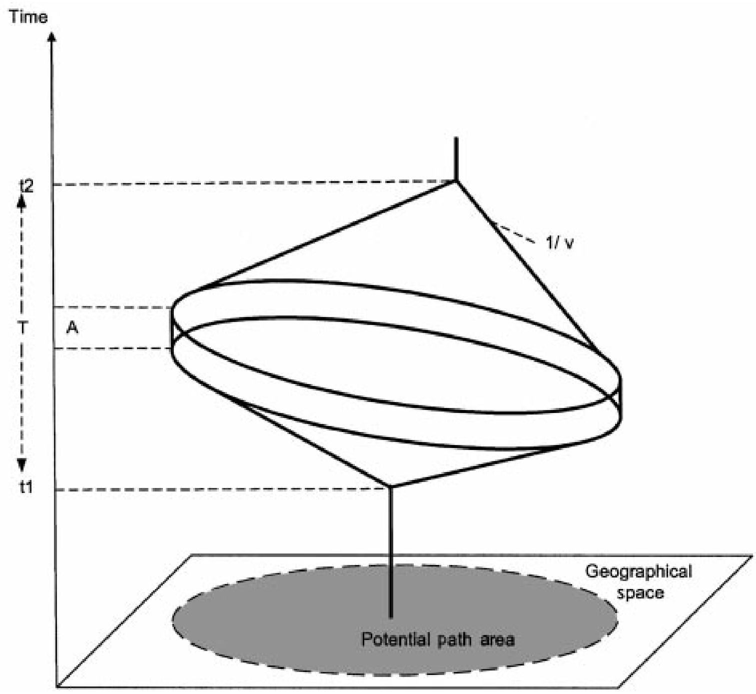

Fig. 2. A space-time prism and potential path area.

must occur (t1 and t2), the minimum time required for the flexible activity (A) and the average maximum travel velocity in the area (v). An activity or person is accessible only if its station or path intersects the STP to a sufficient degree (i.e. a minimum temporal duration, determined by the type of activity). The projection of the STP to geo-space defines a *potential path area* (PPA): this shows all locations in space that are accessible to the individual. Ignoring their temporal durations, an activity or person is accessible only if its location intersects the PPA (Miller, forthcoming, a).

Figure 2 shows only one type of STP. We can also construct STPs for cases where the second fixed activity is unspecified, the two fixed activities occur at the same location, and the minimum required flexible activity time is unspecified. See (Burns, 1979) and (Lenntorp, 1976) for examples and analytical calculations. It is also possible to construct these entities within multi-modal transportation networks, accounting for spatial and temporal variations in travel velocities. This allows more realistic space-time prisms that are more useful directly in applications such as LBS (see Miller, 1991, 1999; Miller and Wu, 2000; O'Sullivan, *et al.*, 2000; Wu and Miller, 2001).

The STP can serve as a theoretical foundation for space-time queries. Queries supported by a space-time prism include (Miller and Shaw, 2001):

- What locations can I reach in 15 minutes? (What is the volume of the STP at my location and time?)
- How long can I stay at this café? What about another café? (What is the degree of overlap between a space-time station and my STP?)
- Where and when can I meet my friends this evening? (Where and when do our STPs intersect?)

STP queries can only capture capability and coupling constraints; authority constraints do not factor into the STP directly. Authority constraints can be incorporated indirectly by eliminating the STP locations that intersect with a restricted region in space and time.

Cognitive constraints have received less attention in time geography since the framework explicitly avoids questions concerning individual preference and choice behaviour. However, incomplete information and locational preferences can limit a person's accessibility as well as the usefulness of

Table 1. Spatial and temporal constraints on communications.

Temporal	Spatial Physical presence	Telepresence
Synchronous	*SP* Face to face (F2F)	*ST* Telephone Instant messaging Television Radio Teleconferencing
Asynchronous	*AP* Refrigerator notes Hospital charts	*AT* Mail Email Fax machines Printed media Webpages

Source: Based on Janelle (1995); Harvey and Macnab (2000).

activity possibilities obtained from a STP (Hall, 1983; Kwan and Hong, 1998). This can be solved in an indirect manner similar to incorporating authority constraints into the STP. The set of preferred locations may be derived through behavioural analysis of locational and activity attributes using multidimensional projection and grouping techniques (Kwan and Hong, 1998). Intelligent agent and machine learning techniques could also analyze the attributes of location queries versus those actually visited by an LBS client.

Presence and telepresence

Classical time geography recognizes the possibility of telepresence or the ability to project one's manifestation using electronic communication. However, telepresence is greatly downplayed relative to physical presence. For example, coupling constraints traditionally require physical proximity in space and time. This leads to the emergence of *space-time bundles*, or clustering of space-time paths in order to conduct a shared activity (usually at stations). Although Hägerstrand and others recognize the possibility of sharing activities without physical bundling, this has only recently received explicit attention by researchers. Time geography's focus on time as a resource enabling activity participation fits naturally to emerging perspectives that view time as the major scarce resource in information economies and accelerated modern lifestyles (Miller, forthcoming, d).

Janelle (1995) classifies communication modes from a time-geographic perspective. Table 1 summarizes classes based on their spatial and temporal constraints. Spatial constraints are either physical presence or telepresence, while temporal constraints are either synchronous or asynchronous. *Synchronous presence* (SP) is the time-honoured communication mode of face-to-face (F2F) interaction. F2F requires coincidence both in time and space. *Synchronous telepresence* (ST) requires only coincidence in time: telephones, radio and TV allow individuals to communicate among different places at the same time. *Asynchronous presence* (AP) requires coincidence in space but not time: examples include Post-It® notes and hospital charts. *Asynchronous telepresence* (AT) does not require coincidence in space and time. Printed media, e-mail and webpages are popular examples of AT.

Figure 3 characterizes the communication modes in Table 1 using the space-time path. Two people conduct a ST communication (say, a phone call) early in the day and then conduct SP communication at an agreed location (say, a café). Later, one person initiates an AP communication at an appropriate location (say, by leaving a note on an office door). The other person receives the AP communication at that location later and then conducts an AT communication (say, by sending an e-mail).

Affordances

This section introduces Gibson's theory of affordances and describes an extended theory, which is more suitable for a spatio-temporal theory of location-based services.

Gibson's theory of affordances

The term *affordance* was coined by James J. Gibson who investigated how people visually perceive their environment (Gibson, 1977, 1979). His theory is based on *ecological psychology*, which suggests that knowing is a direct process and therefore the perceptual system extracts invariants embodying the ecologically significant properties of the perceiver's world. An important point in Gibson's theory is that animal and environment are an inseparable pair. This complementarity is implied by Gibson's use of *ecological physics*. Such physics considers functions of the environment at an ecological size level in contrast to a description in terms of space, time, matter, and so on within classical physics.

Affordances have to be described relative to the person. For example, a chair's affordance 'to sit' results from a bundle of attributes, such as 'flat and hard surface' and 'height', many of which are relative to the size of an individual. Later work with affordances builds on this so-called *agent-environment mutuality* (Gibson, 1979; Zaff, 1995). According to Zaff (1995) affordances are measurable aspects of the environment, but to be measured only in relation to the individual. It is particularly important to understand the *action-relevant* properties of the environment in terms of values intrinsic to the agent. Warren (1995) shows that the 'climbability' affordance of stairs is specified more effectively as a ratio of riser height to leg length. Experimentally, subjects of different heights perceived stairs as climbable depending on their own leg length, as opposed to some extrinsically quantified value. In addition, dynamic or task-specific conditions must be considered (Warren, 1995).

Norman (1988) investigated affordances of everyday items, such as doors, telephones, and radios, and argued that they provide strong clues to their operation. He recast affordances as the results from the mental interpretation of objects, based on people's past knowledge and experiences, which are applied to the perception of these objects. Gaver (1991) stated that a person's culture, social setting, experience and intentions also determine her perception of affordances. Affordances therefore play a key role in an *experiential* view of space (Lakoff, 1988; Kuhn, 1996), because they offer a user-centered perspective. Similarly, Rasmussen and Pejtersen (1995) pointed out that modelling the physical aspects of the environment provides only a part of the picture. 'The framework must serve to represent both the physical work environment and the "situational" interpretation of this environment by the actors involved, depending on their skills and values' (Rasmussen and Pejtersen 1995, p. 122). This may be broken down into three relevant parts: the mental strategies and capabilities of the agents, the tasks involved, and the material properties of the environment.

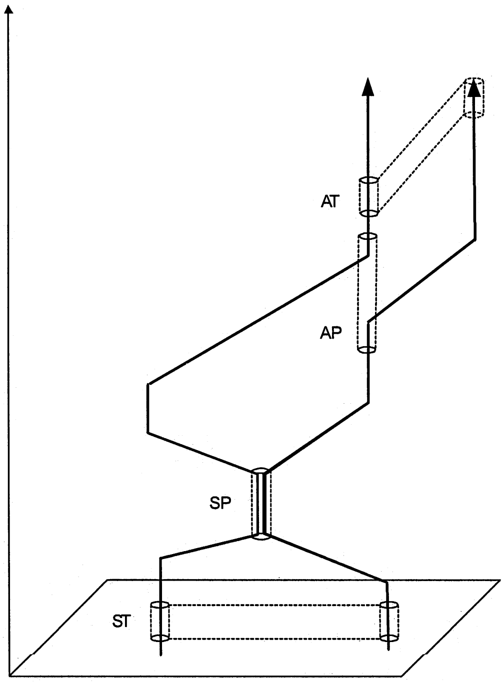

Fig. 3. Presence and telepresence in space-time paths.
Source: Miller (forthcoming, c).

Extended theory of affordances

In this work we use an extended theory of affordances and integrate it with time geography in order to develop a new theory for location-based services. It supplements Gibson's theory of perception with elements of cognition, situational aspects and social constraints. This extended theory of affordances proposes that affordances belong to three different realms: physical, social-institutional and mental (Raubal, 2001).

Physical affordances require bundles of physical substance properties that match the agent's capabilities and properties – and therefore its interac-

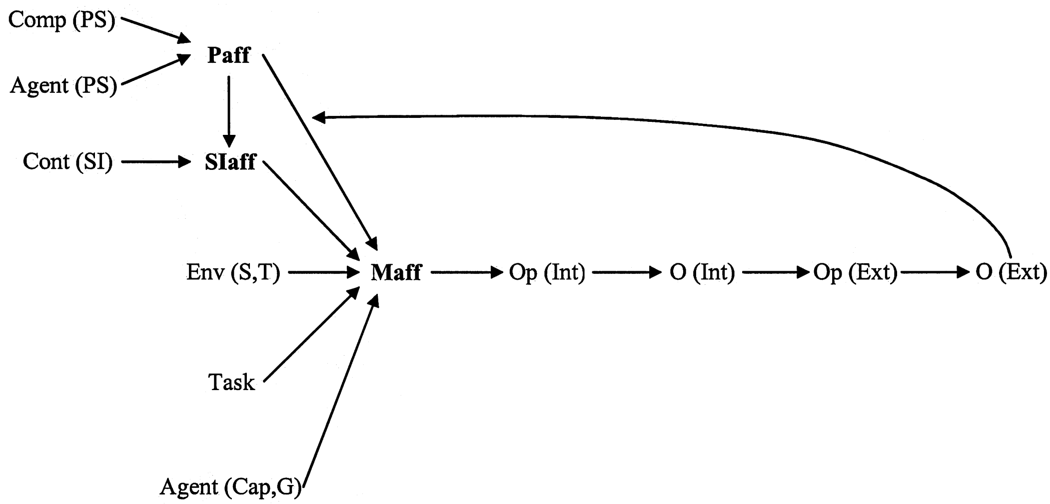

Fig. 4. Functional representation of affordances within activity process of an agent.

tion possibilities. One can only place objects on stable and horizontal surfaces, one can only drink from objects that have a brim or orifice of an appropriate size and can be manipulated and so on. Common interaction possibilities are grasping things of a certain size with one's hands, walking on different surfaces, and moving one's eyes to perceive things. Physical affordances such as the 'sittability' affordance of a chair depend on body-scaled ratios, doorways afford going through if the agent fits through the opening, and monitors afford viewing depending on lighting conditions, surface properties and the agent's viewpoint.

Many times it is not sufficient to derive affordances from physical properties alone because people act in environments and contexts with social and institutional rules (Smith 1999). The use of perceived affordances, although physically possible, is often socially unacceptable or even illegal. The physical properties of an open entrance to a subway station afford for a person to move through. In the context of public transportation regulations it affords moving through only when the person has a valid ticket. The physical properties of a highway afford for a person to drive a car as fast as possible. In the context of a specific traffic code it affords driving only as fast as allowed by the speed limit. Situations such as these include both physical constraints and social forces. Furthermore, the whole realm of social interaction between people is based on social-institutional affordances: other people afford talking to, asking, and behaving in a certain way. Many of these affordances are not tied to particular locations (e.g. people can also talk to other people over the phone).

Physical and social-institutional affordances are the sources of *mental affordances*. During the performance of a task a person finds herself in different situation, where she perceives various physical and social-institutional affordances. For example, a public transportation terminal affords for a person to enter different buses and trains. It also affords to buy tickets or to make a phone call. A path affords remembering and selecting, a decision point affords orienting and deciding and so on. In general, such situations offer to the person the mental affordance of deciding which of the perceived affordances to use according to her goal.

Combining time geography with affordances

This section describes how to represent elements of time geography with affordances. By integrating time geography and affordance theory we propose a conceptual framework, which serves as the basis for a new theory of LBS. This new theory should focus on the user and must explain what is possible for an individual in space and time. We first introduce a functional framework of representing the extended theory of affordances. In the following, the time-geographic constraints are modeled with affordances. Affordances are further used to represent an enriched model of spatio-temporal communication.

Representing affordances

The proposed formal framework of affordances uses an adjusted version of the HIPE theory, of function, which explains how functional knowledge is represented and processed (Barsalou *et al.*, forthcoming). According to the HIPE theory function representations integrate four types of conceptual knowledge: history, intentional perspective, physical environment, and events. This theory seems to be well suited for the formalization of affordances because of their functional character. Similar to functions, affordances are complex relational constructs, which depend on the agent, its goal and personal history, and the setting. The HIPE theory allows for representing what causes an affordance and therefore supports reasoning about affordances. More specifically, it is possible to specify which components are necessary and sufficient to produce a specific affordance for a specific agent.

Figure 4 shows the abstract functional representation of the relation between the three affordance categories during the process of an agent performing a task. The agent is represented through a physical structure (*PS*), spatial and cognitive capabilities (*Cap*), and a goal (*G*). Physical affordances (*Paff*) for the agent result from invariant compounds (*Comp*) – unique combinations of physical, chemical and geometrical properties, which together form a physical structure – and the physical structure of the agent. This essentially represents Gibson's concept of affordance: a specific combination of (physical) properties of an environment taken with reference to an observer.

Social-institutional affordances (*SIaff*) are created through the imposition of social and institutional constraints on physical affordances (i.e. when physical affordances are perceived in a social-institutional context *Cont (SI))*. While performing a task the agent perceives various physical and social-institutional affordances in a spatio-temporal environment represented through *Env (S,T)*. This allows for localizing the perception of affordances in space and time. Otherwise it would be impossible to determine where and when the agent perceives a specific affordance.

Mental affordances (*Maff*) arise for the agent when perceiving a set of physical and social-institutional affordances in an environment at a specific location and time. Affordances offer possibilities for action as well as possibilities for the agent to think about them and decide whether to use them or not (i.e. mental affordances). The agent needs to perform an internal operation *Op (Int)* to use a mental affordance. Internal operations are carried out on the agent's beliefs and lead to an internal outcome *O (Int)*. In order to transfer such an outcome to the world, the agent has to perform an external operation *Op (Ext)*, which then leads to an external outcome *O (Ext)* (i.e. some change of the external world). This external change, in turn, leads to new physical affordances, situated in social-institutional and spatio-temporal contexts. The following scenario from a navigation task illustrates the functional framework.

Imagine a person finds herself in the negotiating situation while following a route. The person wants to cross a river by car and has two options to do so, either driving over a bridge or using a ferry. Translated to the formal model this means that a *driving agent* perceives the physical affordances *drive over* from the compound *bridge* and *drive on to* from the compound *ferry*. Notice the importance of integrating spatio-temporal constraints: the bridge always affords driving over whereas the ferry affords the agent to drive on to it only when it is there (i.e. connected to the road network). The social-institutional contexts of the applicable traffic code and the ferry business create social-institutional affordances for the agent. For example, while driving over a bridge the agent is not allowed to exceed a certain speed limit and driving on to a ferry is allowed only for paying passengers. These social-institutional affordances are imposed on the physical affordances. The mental affordance for the agent is then to decide which of the perceived affordances to use according to the goal of crossing the river. The agent performs an internal operation, (e.g. a utility function), which might result in the outcome that the agent wants to drive over the bridge because it is cheaper. The external operation is *driving over the bridge*, which leads to the external outcome that the river has been crossed. At this point, new affordances may appear in the environment, such as a restaurant affording to eat.

Modelling constraints with affordances

The three classes of constraints in time geography limit a person's ability to participate in spatio-temporal activities. Positively formulated, they offer a

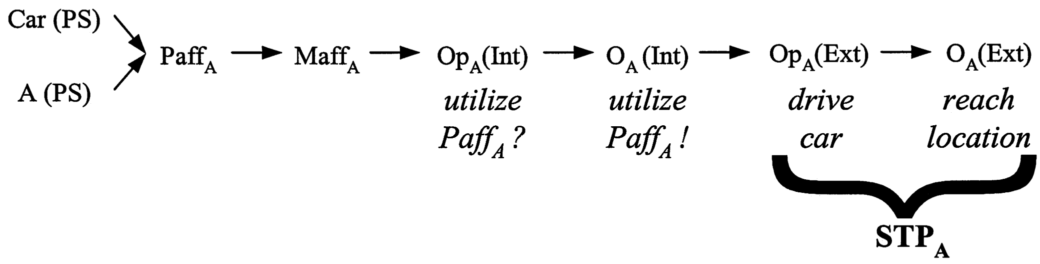

Fig. 5. Functional activity process for person A.

specific set of possible actions for an individual. Affordances are such action possibilities; therefore they may be used to represent the time-geographic constraints.

Capability constraints result from an individual's biological and physical structure, its various abilities, and the environment's resources. This relates strongly to the roles of the physical agent structure and its surrounding environmental structure represented in the functional framework of affordances. Capability constraints lead to specific sets of *Paff* for a person. For example, a bed at home affords sleeping for an individual; a car affords driving for particular individuals only, (i.e. when the physical structure of the car can be used by the person). Figure 5 gives an example of the corresponding functional activity process. The $Paff_A$ 'car affords moving around for person A' offers to the person to think about this action possibility ($Maff_A$). The person then performs an internal operation, deciding whether to drive the car or not. The outcome of this operation could be that the person wants to drive the car. Driving the car is an external operation and after some time the person could reach a certain location. Given a fixed activity at this location, the final two steps may be ideally represented geometrically through the corresponding STP_A. It is the spatio-temporal consequence of using $Paff_A$ with regard to person A's physical reach. Figure 6 demonstrates the consequences of two different *Paff* for a given time interval (t1, t2) by showing the corresponding STPs. STP_A results from the $Paff_A$ 'car affords moving around for person A' whereas STP_B results from the $Paff_B$ 'public bus affords moving around for handicapped person B' (who cannot drive a car).

Coupling constraints fall into two categories,

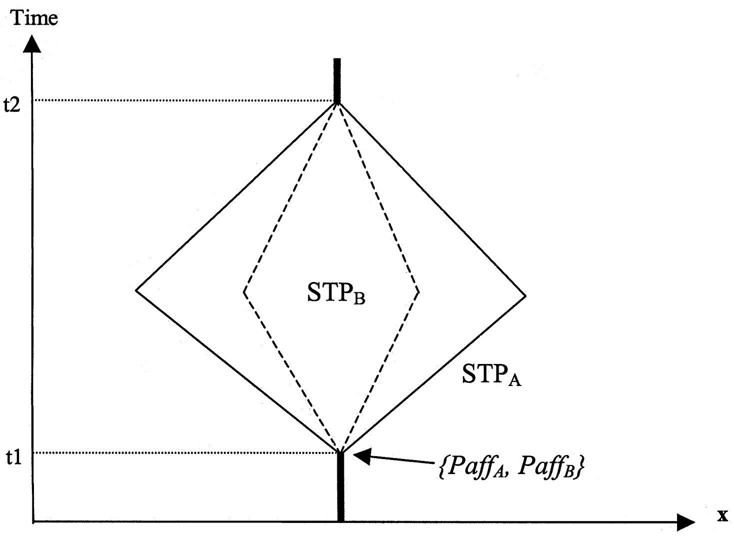

Fig. 6. Space-time prisms resulting from different affordances.

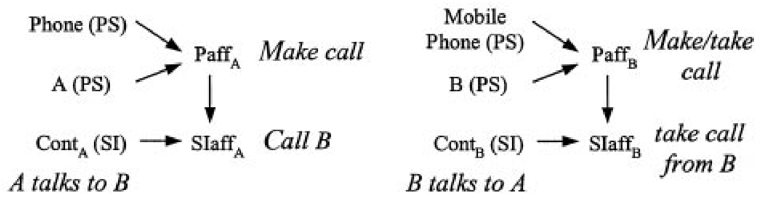

Fig. 7. Functional activity processes for persons A and B.

depending on whether other individuals are involved or not. For example, surfing the web at an Internet café does not require another person and therefore the activity's possibility may be represented by a *Paff* only, (i.e. 'computer at Internet café affords surfing the web for person A'). In cases where other individuals are involved, combinations of *Paff* and *SIaff* are required for representing the coupling constraints because the *Paff* are embedded in a social-institutional context. Take, for example, the situation of a person A making a phone call to a person B. Figure 7 illustrates parts of the functional activity processes, assuming that person B uses a mobile phone. The space-time path of person A (Fig. 8) shows two space-time stations containing the resources of making a phone call (i.e. a telephone) and therefore offering the *Paff* 'telephone affords calling person B for person A'. On the other hand, the space-time path of person B shows a continuous offering of the *Paff* 'mobile phone affords calling and being called for person B'. In addition, we need to consider the *SIaff* because although physically possible, person B may not want to talk to person A, or the two individuals may speak a different language, which makes communication impossible. The geometric representation of Fig. 8 is based on the functional framework, but in addition we can now identify the two time intervals where communication is possible, (i.e. T_1 and T_2). It is important to note that coupling constraints also involve capability constraints (in the sense of *Paff*) because the coupling has to be both physically possible as well as socially.

Certain domains in everyday life are controlled, leading to *authority constraints*. In some cases, such as a private property restriction of a shopping mall, these constraints can be represented by neg-

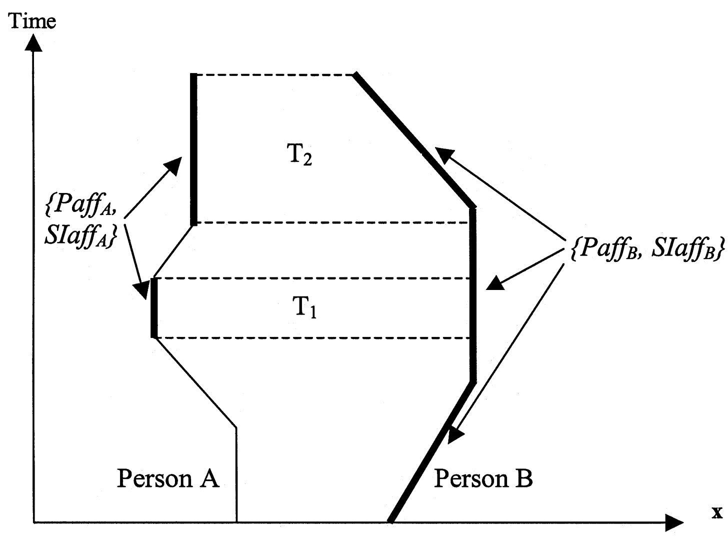

Fig. 8. Coupling constraints for person A calling person B.

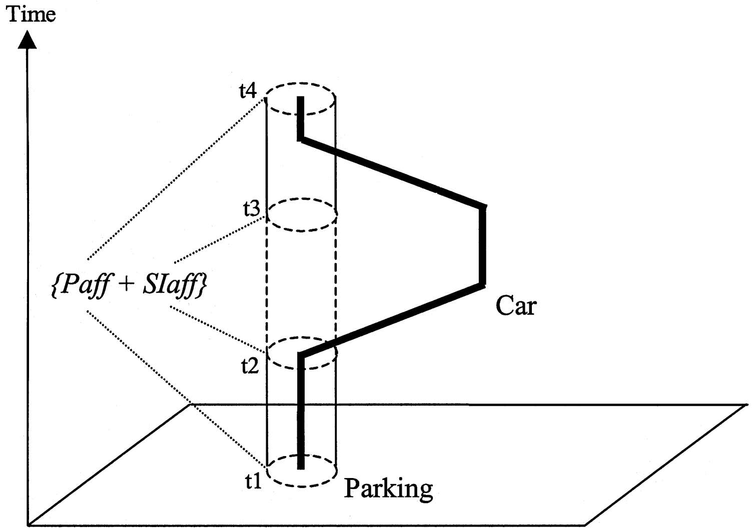

Fig. 9. Space-time stations are represented through sets of affordances.

ative physical affordances, (e.g. 'shopping mall's entrance is locked and does not afford entering for person A'). By representing authority constraints with affordances it is also possible to model activities that are physically possible but not allowed due to social-institutional rules, (e.g. legal regulations). For instance, at certain parking spots along busy streets parking is allowed only during night hours. Figure 9 shows the geometric representation of such a situation: Although parking is physically afforded for a car (driver) C between t1 and t4, this *Paff* is restricted by the negative *SIaff* 'parking spot does not afford parking for car (driver) C' between t2 and t3.

In general, space-time stations are represented by sets of affordances for specific locations and time intervals. Such sets may be used to analyse the action possibilities for an individual. Again, there are consequences for the respective STPs. The STP for a person following the speed limit with her car is smaller (STP_B in Fig. 6) than the STP for a person exceeding the speed limit and therefore violating the *SIaff* (STP_A in Fig. 6).

Modelling communication modes with affordances

Section 2 highlighted the importance of communication-related time geography. The extended theory of affordances allows for representing the different modes of spatio-temporal communication in a plausible way. For user-centered time geography however it is necessary to extend the given classification (Janelle 1995) based on spatial and temporal constraints by a third dimension, (i.e. *social constraint)*. Figure 10 shows the possibilities for communication. The social constraints are thereby represented through *SIaff*. It is through these affordances that communication finally becomes possible or not. Spatial and temporal coupling is not sufficient if one of the individuals cannot or does not want to communicate for social reasons (e.g. speaking a different language).

Communication between two persons through *synchronous physical presence* or *synchronous telepresence* is achieved when the relevant *Paff* and *SIaff* for both of them match. The first case requires that the *Paff* 'place X affords being there for person A' and 'place X affords being there for person B' both exist for a point in time t. Furthermore, the respective *SIaff* need to correspond: 'person A affords talking to person B' and 'person B affords talking to person A' (see also Fig. 8 for the case of telepresence).

Communication based on *asynchronous physical presence* is made possible through the creation of a new *Paff*, such as 'note on office door affords picking up for person A'. Creating a new affordance in our framework means adding it to the existing set of affordances at a space-time station. Again, we need to consider the corresponding *SIaff* for person A to evaluate whether actual communication is possible. Illegibility of the note might be an obstacle.

In the case of *asynchronous telepresence* a new *Paff* is created at different places (i.e. space-time stations). For example, by sending an email one creates the same new *Paff* 'e-mail affords receiving for person A' at different places with access to the Internet at the same time. In addition, these places must be accessible (afford being there) for person A at some later date.

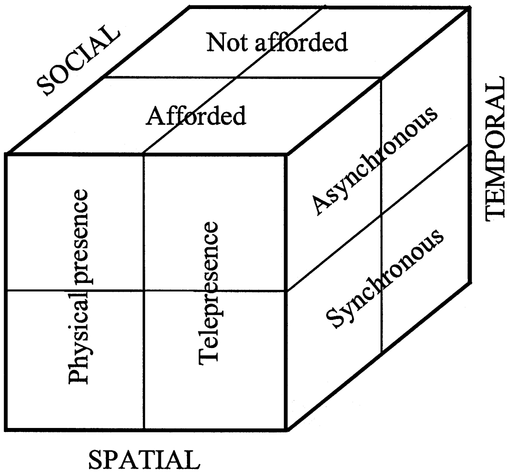

Fig. 10. Communication possibilities from a user-centered time-geographic perspective.

Decision-making and user preferences

In this section we describe the additional elements needed for a user-centered spatio-temporal theory of location-based services. Individual decision-making processes take time, which can be taken into account by considering mental affordances. The modelling of user preferences through affordances allows for representing an individual's preferred activities. Finally, we demonstrate the modelling of tasks and subtasks through hierarchies of STPs.

Decision-making processes

Spatial reasoning involves a variety of decision-making methods and choice behavior. Decision theory covers a wide 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). Mathematically, a *decision rule* is a function that assigns a value to each alternative, showing what will happen when a particular strategy is adopted. *Decision-making criteria* are a set of procedural rules that oversee the evaluation of the outcome when decision rules are applied to a task situation. A *strategy* contains decision rules that seek a result from all possible ways of making a relevant decision.

Classical decision-making theories may be classified into the categories of riskless decision-making, risky decision-making, transitivity in decision-making, and game theory and statistical decision functions. Golledge and Stimson (1997) argue that 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 – and therefore emphasize *behavioral decision theory.* In this respect they refer to Timmermans' (1991) typology of decision-making according to spatial choice. It includes models accounting for:

– *variety-seeking behavior* such as in recreational choice;
– *uncomplicated choice among limited alternatives* such as choice of travel mode;
– *complex choice situations* including preference and attitude;
– *temporal choice* involving stochastic models;
– *simulation of complicated choice outcomes*.

The decision-making process of an LBS user, such as the business traveller in our case study, typically involves uncomplicated choice among limited alternatives (e.g. going by car or taking the bus), complex choice situations involving a preference (e.g. having an espresso and bagel for breakfast), and temporal choice (e.g. be at the meeting at 8 a.m.).

It takes time for an individual to make a decision about what to do next – think of a tourist on her way through an unfamiliar city. These time constraints are essentially cognitive constraints, which differ from person to person. The availability of *Paff* and *SIaff* at space-time stations leads to *Maff* for an individual. The time used for utilizing the mental affordances may be represented and has an influence on how much time is left for other activities, (i.e. the longer people need to make decisions, the less time they have for doing other things). Figure 11 illustrates the situation: At time t1 a person faces a *Maff* whose utilization takes until t2. By then the person has decided on which of

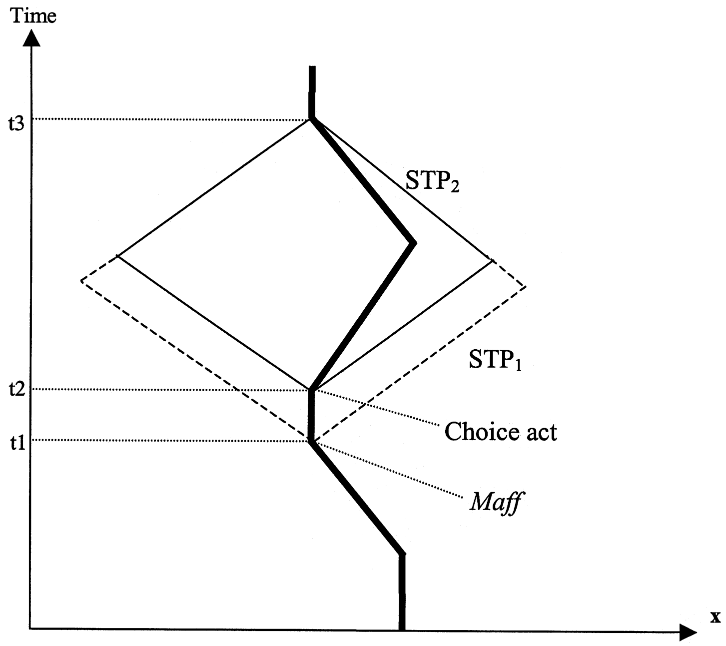

Fig. 11. Cognitive time constraint due to decision-making.

the available *Paff* and *SIaff* to use, (i.e. the choice act). One needs to distinguish between the *choice act* – the outcome of a decision-making process – and a *preference* – an activity within the decision-making process expressing what is desirable. Note that due to the time loss, the size of the original space-time prism at this decision point (STP_1) shrinks in size (STP_2), therefore leading to a reduction of accessible places considering a future fixed activity at t3.

Modelling of user preferences

Representing what is desirable for an individual is a major aspect for a user-centered time geography. One benefit lies in the support of spatio-temporal queries for a particular person (Miller, forthcoming, d): A general query such as 'Which locations can I reach in 15 minutes?' results in a different answer whether the person prefers to walk or go by public transport. User preferences are strongly linked to capability, coupling and authority constraints (and also cognitive constraints) because what people desire is not always achievable. The constraints are generally intervening between preference and choice (Golledge and Stimson 1997).

Our model of user preferences is strongly focused on activities (i.e. what people want *to do* in certain situations and places). This has the advantage of correlating with the action potential of the agent–environment duality represented through the extended theory of affordances and also of searching for places where an individual can engage in a particular activity (Jordan *et al.*, 1998). It allows for questions such as 'find me a place where I can eat pizza for lunch' instead of asking for a restaurant with 'type = pizzeria'. The latter would result in a list of pizzerias whereas the answer to the first question might also include a café with pizza on the menu.

User preferences are therefore desired activities, which have the effect of reducing the sets of affordances at various space-time stations to subsets of these (see Fig. 12). Figure 13 gives an example: The capability, coupling, and authority constraints for a café and person A within a particular spatio-temporal context result in a set of four *Paff* (drink coffee, smoke cigarette, eat pizza, eat bagel) and two *SIaff* (talk to person B, talk to person C). All of these represent action possibilities for person A at the given space-time station. By considering the general (e.g. never talk to person C) and time-specific (e.g. drink coffee only before noon) preferences of person A this set is reduced to the subset of

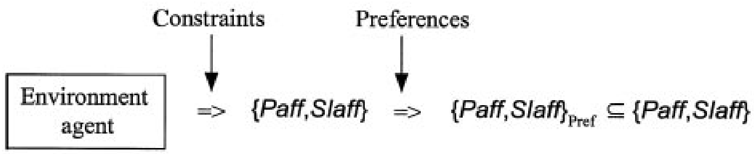

Fig. 12. Preferences lead to a subset of *Paff* and *SIaff*.

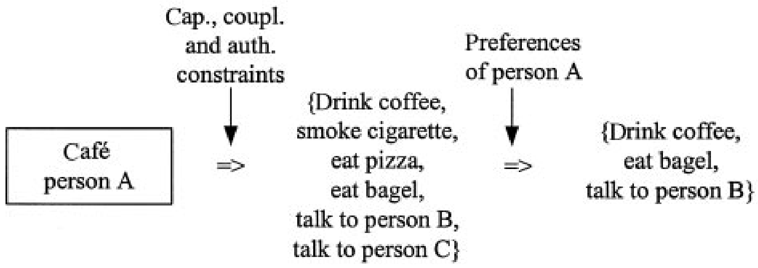

Fig. 13. Example for reducing set of affordances through user preferences.

two *Paff* and one *SIaff*. In general, user preferences need to be specified for various domains and spatio-temporal contexts in order to be applied to different situations.

Tasks and subtasks

People often combine different tasks and divide complex tasks into smaller subtasks. Such combinations and divisions of tasks can be represented through hierarchies of space-time prisms. These hierarchies form the basis for analyzing people's performance of various tasks in a spatio-temporal environment and also for finding optimal solutions to their efficient spatio-temporal combination.

An optimal solution under time constraints is required when a person needs to participate in a future fixed activity and has time beforehand to engage in some flexible activity. The main task of moving to the place of the fixed activity is thereby represented by a fixed STP. The respective STPs concerning the flexible activity are contained

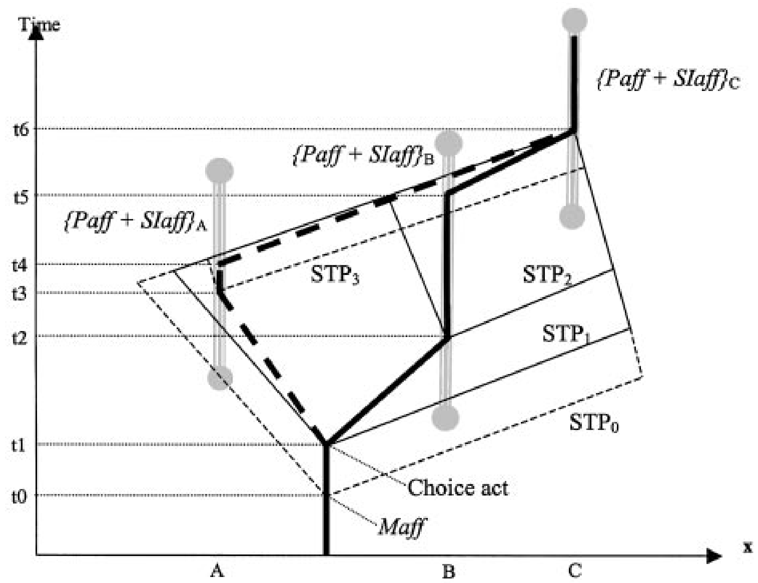

Fig. 14. Optimal solution for flexible activity before fixed activity.

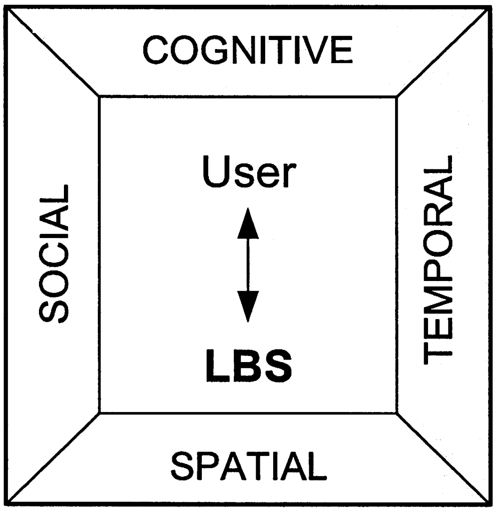

Fig. 15. User-centered theory of LBS.

within the fixed STP. Figure 14 illustrates this case: The fixed activity (e.g. participating in a meeting) starts at t6 at space-time station C (represented through a set of *Paff* and *SIaff*). STP_1 represents the spatio-temporal possibilities for an individual to move there. Engagement in the flexible activity (e.g. spending time at a café) must therefore occur within STP_1 but there are two places to choose from. Notice that the original STP_0 shrinks in size due to the time spent on using the *Maff* – which comprises the three sets of *Paff* and *SIaff* – (i.e. (t1-t0)). In the case of conducting the activity at space-time station A and then moving to space-time station C (dashed space-time path), the time loss due to movement would be (t3-t1) + (t6-t4), leaving (t4-t3) for the activity. Engaging in the activity at space-time station B would minimize the time loss and leave more time for the activity, (i.e. (t5-t2)). The latter is therefore optimal with regard to the preference of spending time on the activity. The respective space-time prisms (STP_2 and STP_3) limit the amount of time which may be spent on the flexible activity, keeping in mind the future fixed activity.

Every subtask performed within a fixed STP leads to a new smaller fixed STP, which can again be analyzed for action possibilities at space-time stations. The optimal solution for the combination of various tasks and subtasks may be found by searching through possible STP hierarchies.

Towards a user centered theory for location-based services

This section presents an overview of the conceptual framework developed above, and explains why it will lead towards a more plausible and effective theory for LBS. The application to our case study demonstrates how this theory should help in solving complex problems.

Overview

Current location-based services do not support a majority of tasks, which people perform in their daily lives (see also section 1). In particular, they are not tuned to the individual users, therefore ignoring the users' preferences. The conceptual framework of integrating time geography and affordance theory presented in the above sections is intended to serve as the basis for a user-centered theory of LBS, which can explain user-specific possibilities in space and time. By taking into account not only spatial but also temporal, social and cognitive aspects (Fig. 15), this theory allows for assisting people in tasks, such as activity scheduling based on individual preferences and time constraints, which current services fail to support.

Current LBS focus primarily on the *spatial* aspect, which is manifested through geo-coding functions, spatial search capabilities and route services. The latter calculate an optimal route and provide a sequence of instructions for this route. These instructions are always the same for the same route – they are not tailored to the user. For example, many people want route instructions to include landmarks (Raubal and Winter, 2002), while others prefer survey information. Considering the user's preferences (section 5) allows for making LBS more adaptive to the individual in various contexts. Spatial activities occur in time but the *temporal* aspects are mainly neglected by existing implementations of LBS – estimations of how long it takes to follow a calculated route being an exception to the rule. The proposed framework allows for a theory of LBS, which explicitly captures the temporal properties. Affordances correspond to spatio-temporal sets, (i.e. they are available at certain locations and for given time intervals (section 4)). The model considers temporal availability of possible activities, which makes the scheduling of multiple tasks over longer time frames achievable (section 5). *Social* aspects, including institutional and legal characteristics, affect our daily lives and need to be integrated into a plausible user-centered theory for LBS. So far, only a few social services, such as friends finder services, are supported. The new theory allows not only for integrating institutional and legal facts, but also for calculating their spatio-temporal consequences (section 4). This is a direct result of representing social-institutional affordances in a time-geographic context. Furthermore, it becomes possible to model the various communication modes, including telepresence, in a socially plausible way, i.e., by taking into account an individual's willingness or unwillingness to communicate with other individuals (section 4). A user-centered LBS theory must include *cognitive* aspects regarding its users. In combination with user preferences, the new theory accounts for individual decision-making processes through the integration of mental affordances and their spatio-temporal consequences, (i.e. spatial accessibility and temporal availability (section 5)).

Application to the case study

LBS that are based on the new user-centered theory support sophisticated queries, including task scheduling and time constraints. As an example, we show its application to our case study, described at the beginning of this paper. The case study covers most of the concepts presented, such as time-geographic constraints in the form of affordances, telepresence, user preferences and subtasks.

Figure 16 demonstrates the LBS reasoning process based on a user-centered spatio-temporal theory, which allows for solving the business traveller 's task scheduling problem. The numbers refer to the affordances in Table 2, which also shows the user's fixed and flexible activities and preferences. In order to keep the figure simple, the specific instructions for using public transport and wayfinding are not considered. Answering the user's query may be visualized through geometric intersections of spatio-temporal sets. The following steps are applied:

1. mark fixed activities;
2. create STPs for possible transportation modes;
3. mark affordance sets at space-time stations;
4. intersect STPs and affordance sets;
5. intersect previous results with set of user preferences;
6. calculate space-time paths and analyze them;
7. show result.

This approach is similar to Kwan and Hong's (1998) GIS-based method of restrictive spatial choice set formation, which results in the cognitive feasible opportunity set (CFOS). There are important differences however: First, we consider all feasible activity locations for the individual, whereas a CFOS does not consider unknown locations as alternatives but only those present in the user's cognitive map. Such an approach does not work for users of LBS in unfamiliar environments, however. Second, a CFOS is based on locational preference, whereas here we focus on activities, which allows for a more comprehensive search (see section 5).

For the case study, the method works as follows. The business traveller has two fixed activities: arriving in the city at 6 a.m. (at train station TS) and being at a meeting, which starts at 8 a.m. (at office building OB). She has two possibilities of going to the meeting, either by car or by public transport (represented through *Paffs* 7 and 8). The LBS now derives two different STPs depending on the mode of travel – STP_{car} and STP_{pub}. Next, the spatio-temporal affordance sets for relevant space-time stations are being marked (i.e. for locations A, B, C, D, and E). These sets are then intersected with the STPs, reducing the number of relevant space-time stations to four (B is eliminated because it does not fit into the time constraints). The result of this intersection are sets of possible activities for the business traveller within her available time interval. These sets are then intersected with the set of the user's preferences (Table 2) with the result of eliminating A because it falls completely into STP_{car} (which is eliminated because of the preference 'go by public transport'). The resulting three sets C, D and E are highlighted in dark grey. Based on these sets, two possible space-time paths are calculated by the service. The first path (dashed line) leads from TS to newspaper store E, where the business traveller would arrive early. After waiting for 20 minutes (the store opens at 7 a.m) she could buy a newspaper and go by public transport to café C. At C the traveller would have 15 minutes to enjoy breakfast (espresso and bagel) and make a phone call before heading off to the office building. The second path (solid line) leads from TS directly to bistro D. During this journey the business traveller is telepresent (represented through $\{6\}_{pub}$) and could therefore make her phone call. At D she would have 45 minutes for breakfast (again, espresso and bagel) and reading a newspaper (various newspapers are available at this place). Based on the user's preference of 'spending time for breakfast', the LBS suggests the latter result to the business traveller for scheduling her desired spatio-

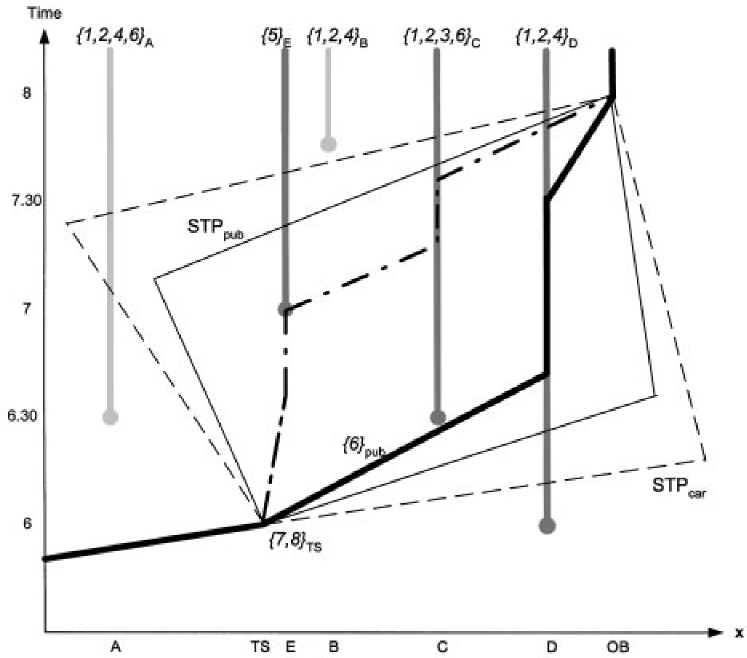

Fig. 16. LBS theory applied to the case study.

temporal activities. This example does not involve cognitive time constraints due to decision-making because the user is presented with only one result. Cognitive time constraints need to be represented when more than one possible space-time path is suggested to the user, leaving the final decision to her (i.e. creating a mental affordance for her). *SIaff* such as for communication can be taken into account only when the person to be called is also represented by the LBS.

Conclusions and research agenda

In this paper we proposed a conceptual framework based on the integration of time geography and affordance theory for a user-centered theory of LBS. This integration allows space-time mechanics and human interactions to be expressed as user-specific action possibilities. A case study was presented to demonstrate the benefits of this approach in answering sophisticated spatio-temporal queries in-

Table 2. Activities, preferences, and affordances for the case study (depending on the level of granularity – which is being ignored here, but see research agenda – activities comprise one or more actions; preferences are *desired* activities/actions; and affordances are *possibilities* for actions).

	User	Affordances
Fixed activities	Arrive in city	1 Drink espresso
	Be at meeting	2 Eat bagel
Flexible activities	Go to meeting	3 Eat sandwich
	Have breakfast	4 Read newspaper
	Read newspaper	5 Buy newspaper
	Make phone call	6 Make phone call
Preferences	Go by public transport	7 Go by car
	Drink espresso (for breakfast)	8 Go by public transport
	Eat bagel (for breakfast)	
	Spend time for breakfast	

volving time constraints, subtasks and user preferences. However, implementing this framework as a theoretical foundation for LBS development will require coordination among several research directions.

Enhanced knowledge regarding the decision-making process of individuals is one potentially vital research direction. Particularly intriguing questions involve the time constraints imposed by necessary decision-making activities. Future research should attempt to gain insights into how these constraints are constructed and how variations occur among different people and cultures, in different geographical and temporal contexts, and for different types of desired activities. This knowledge will facilitate more realistic derivations of the space-time prism that will in turn provide users with more appropriate action possibilities. Understanding these decision-making processes may also assist in developing methods for deriving personal preferences. In order for LBS to realize its true potential, it must account for user preferences and past experiences. These advances may then allow scheduling or activity planning to occur without an explicit user request. Work in this area may benefit from frameworks that store histories of previous user requests using multidimensional database designs (Smyth, 2001; Jensen *et al.*, 2002) which are analyzed to determine trends in time and across space. An understanding of these trends may then be used in our spatio-temporal theory to weight action possibilities represented through a user's mental affordance. It should be noted that methods involving the analysis of stored behavior raise serious questions with regard to personal privacy and surveillance. The usefulness of these techniques must also be measured in relation to their potential invasive practices (Smyth, 2001). Methods for doing so are open research questions.

Decision support for mobile users should also consider the effects of geographic and temporal scales on an individual's information requirements. The current framework incorporates the extended theory of affordances with an assumed uniform scale. However, it seems likely that the information required when traversing street networks in an automobile is very different from that when walking in a shopping mall, as perception is largely a function of situational context. These considerations are equally valid at different temporal scales. Users may require different assistance when scheduling activities within a day as opposed to throughout the week. These considerations affect how users will query a LBS, what information should be provided, and how it should be presented. Accommodations for this may be directly incorporated into our theory by applying body-scaled ratios (section 3) at different scales to physical and mental affordances. The results from this work will no doubt have direct impacts on user interface designs and human–system interaction.

Attention must also be given to the implementation specifics of measuring affordances in real time for mobile users. The framework presented here fails to consider the difficulties inherent in measuring user locations, as well as measuring the space-time locations in the environment that afford action possibilities. Concrete implementations will need to consider the uncertainties occurring among both. With regard to user locations this will require an understanding of how user tracking affects the real-time calculation of space-time prisms. Work in this area is currently ongoing, and may benefit from existing research on moving objects databases – see Sistla *et al.*, 1998; Moreira *et al.*, 1999; Pfoser and Jensen, 1999; Leonhardi and Rothermel, 2002 – and measurement theories for time geography (Miller, forthcoming, b).

Work must also be conducted in the area of formal representations and implementations. Much of this work will require the representation of spatio-temporal sets and perhaps formulating a multi-agent system that would allow for using the framework's asynchronous communication possibilities. These works could be augmented by a direct interface with the OpenLS specification to make the services more dynamic and central to the user needs. Representations of moving space-time stations are also required to provide the communication possibilities of users with mobile phones or wireless communications. The underpinning of this work will then be the synthesis of all these areas of research into a formal theory of LBS.

At the present time, researchers have yet to consider LBS as anything more than a location-dependent wireless extension of the current GIS application framework. This is particularly apparent in the lack of attention given to the temporal properties of activities and the unique situational contexts of individual users. Current applications also fail to consider activities with unique spatial dependencies, such as those provided through telecommunications and asynchronous interaction. The integration of time geography and affordance theory addresses some of these issues, but future work is required before a functional theory may realistically be implemented.

Acknowledgements

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References

ADAMS, P. (2000): 'Application of a CAD-based accessibility model', in JANELLE, D. and HODGE, D. (eds): *Information, Place and Cyberspace: Issues in Accessibility.* pp. 217–239. Springer, Berlin.

BARSALOU, L., SLOMAN, S. and CHAIGNEAU, S. (forthcoming): 'The HIPE theory of function', in CARLSON, L. and VAN DER ZEE, E. (eds): *Representing Functional Features for Language and Space: Insights from Perception, Categorization and Development.* Oxford University Press, New York.

BISHR, Y. (2002): 'OGC's open location services initiative and location interoperability forum': Putting them together. http://www.jlocationservices.com/EducationalResources.

BURNS, L. (1979): *Transportation, Temporal and Spatial Components of Accessibility*. Lexington Books, Lexington, MA.

GAVER, W. (1991): 'Technology affordances', in *Human Factors in Computing Systems, CHI'91 Conference Proceedings.* pp. 79–84. ACM Press, New York.

GIBSON, J. (1977): 'The theory of affordances', in SHAW, R. and BRANSFORD, J. (eds): *Perceiving, Acting, and Knowing – Toward an Ecological Psychology.* pp. 67–82. Lawrence Erlbaum., Hillsdale, NJ.

GIBSON, J. (1979): *The Ecological Approach to Visual Perception*. Houghton Mifflin, Boston, MA.

GOLLEDGE, R. and STIMSON, R. (1997): *Spatial Behavior: A Geographic Perspective.* Guilford Press, New York.

HÄGERSTRAND, T. (1970): 'What about people in regional science?' *Papers of the Regional Science Association,* 24: 7–21.

HALL, R. (1983): 'Travel outcome and performance: the effect of uncertainty on accessibility'. *Transportation Research B,* 17B: 275–290.

HARVEY, A. and MACNAB, P. (2000): 'Who's up? Global interpersonal accessibility', in JANELLE, D. and HODGE, D. (eds): *Information, Place and Cyberspace: Issues in Accessibility*. pp. 147–170. Springer, Berlin.

JANELLE, D. (1995): 'Metropolitan expansion, telecommuting and transportation,' in HANSON, S. (ed.): *The Geography of Urban Transportation,* pp. 407–434. Guilford Press, New York.

JENSEN, C., KLIGYS, A., PEDERSEN, T. and TIMKO, I. (2002): 'Multidimensional data modelling for location-based services', in *Proceedings of the Tenth ACM International Symposium on Advances in Geographic Information Systems.* pp. 55–61, McLean, VA.

JORDAN, T., RAUBAL, M., GARTRELL, B. and EGENHOFER, M. (1998): 'An affordance-based model of place in GIS', in POIKER, T. and CHRISMAN, N. (eds): *8th Int. Symposium on Spatial Data Handling, SDH'98,* pp. 98–109. Vancouver, Canada.

KUHN, W. (1996): 'Handling data spatially: spatializing user interfaces', in KRAAK, M. and MOLENAAR, M. (eds): *SDH'96, Advances in GIS Research II, Proceedings.* 2, pp. 13B.1–13B.23. International Geographical Union, Delft.

KWAN, M.-P. and HONG, X.-D. (1998): 'Network-based constraints-oriented choice set formation using GIS'. *Geographical Systems,* 5: 139–162.

LAKOFF, G. (1988): 'Cognitive semantics', in ECO, U., SANTAMBROGIO, M. and VIOLI, P. (eds): *Meaning and Mental Representations.* pp. 119–154, Indiana University Press, Bloomington.

LENNTORP, B. (1976): 'Paths in space-time environments: a time-geographic study of the movement possibilities of individuals'. *Lund Studies in Geography, Series B*, 44.

LENNTORP, B. (1978): 'A time geographic simulation model of individual activity programmes', in CARLSTEIN, T., PARKES, D. and THRIFT, N. (eds): *Timing Space and Spacing Time, Volume 2: Human Activity and Time Geography.* Edward Arnold, London.

LEONHARDI, A. and ROTHERMEL, K. (2002): 'Protocols for updating highly accurate location information', in SARIKAYA, B. (ed.): *Geographic Location in the Internet.* pp. 111–141, Kluwer Academic, Norwell, MA.

MILLER, H. (1991): 'Modelling accessibility using space-time prism concepts within geographical information systems'. *International Journal of Geographical Information Systems*, 5: 287–301.

MILLER, H. (1999): 'Measuring space-time accessibility benefits within transportation networks: Basic theory and computational methods'. *Geographical Analysis,* 31: 187–212.

MILLER, H. (forthcoming, a): 'Activities in space and time', in *Handbook of Transport 5: Transport Geography and Spatial Systems*. Pergamon/Elsevier Science.

MILLER, H. (forthcoming, b): 'A measurement theory for time geography'. *Geographical Analysis.*

MILLER, H. (forthcoming, c): 'Tobler's First Law and spatial analysis,' *Annals of the Association of American Geographers*.

MILLER, H. (forthcoming, d): 'What about people in geographic information science?' in: FISHER, P. and UNWIN, D. (eds): *Re-presenting Geographical Information Systems.* John Wiley, New York.

MILLER, H. and SHAW, S.-L. (2001): *Geographic Information*

Systems for Transportation: Principles and Applications. Oxford University Press, New York.

MILLER, H. and WU, Y.-H. (2000): 'GIS software for measuring space-time accessibility in transportation planning and analysis'. *GeoInformatica*, 4: 141–159.

MOREIRA, J., RIBEIRO, C. and SAGLIO, J-M. (1999): 'Representation and manipulation of moving points: an extended data model for location estimation'. *Cartography and Geographic Information Science,* 26: 109–123.

NORMAN, D. (1988): *The Design of Everyday Things.* Doubleday, New York.

O'SULLIVAN, D., MORRISON, A. and SHEARER, J. (2000): 'Using desktop GIS for the investigation of accessibility by public transport: An isochrone approach'. *International Journal of Geographical Information Science* 14: 85–104.

PFOSER, D. and JENSEN, C. (1999): 'Capturing the uncertainty of moving-object representations', in *Proceedings of the Sixth International Symposium on Spatial Databases.* pp. 111–132. Hong Kong.

PRED, A. (1981): 'Of paths and projects: individual behavior and its societal context', in COX, K. and GOLLEDGE, R. (eds): *Behavioral Problems in Geography Revisited.* pp. 231–255, Methuen, New York.

RASMUSSEN, J. and PEJTERSEN, A. (1995): 'Virtual ecology of work*, in FLACK, J., HANCOCK, P., CAIRD, J. and VICENTE, K. (eds): *Global Perspectives on the Ecology of Human-Machine Systems*. Vol. 1, pp. 121–156, Lawrence Erlbaum Associates, Hillsdale, NJ.

RAUBAL, M. (2001): 'Ontology and epistemology for agent-based wayfinding simulation'. *International Journal of Geographical Information Science*, 15: 653–665.

RAUBAL, M. and WINTER, S. (2002): 'Enriching Wayfinding Instructions with Local Landmarks', in EGENHOFER, M. and MARK, D. (eds): *Geographic Information Science – Second International Conference, GIScience 2002, Boulder, CO, USA, September 2002. Lecture Notes in Computer Science*, 2478, pp. 243–259. Springer, Berlin.

SISTLA, P., WOLFSON, O., CHAMBERLAIN, S. and DAO, S. (1998): 'Querying the uncertain position of moving objects', in ETZION, O., JAJODIA, S. and SRIPADA, S. (eds): *Temporal Database: Research and Practice.* pp. 310–337, Springer, Berlin.

SMITH, B. (1999): 'Les objets sociaux'. *Philosophiques*, 26: 315–347.

SMYTH, C. (2001): 'Mining mobile trajectories', in MILLER, H. and HAN, J. (eds): *Geographic Data Mining and Knowledge Discovery*. pp. 337–367, Taylor & Francis, London.

TIMMERMANS, H. (1991): *Retail Environments and Spatial Shopping Behavior*. Department of Architecture, Building, and Planning, University of Technology, Eindhoven, The Netherlands, Technical Report.

WARREN, W. (1995): 'Constructing an econiche', in FLACK, J., HANCOCK, P., CAIRD, J. and VICENTE, K. (eds): *Global Perspectives on the Ecology of Human-Machine Systems.* Vol. 1, pp. 121–156, Lawrence Erlbaum Associates, Hillsdale, N.J.

WINTER, S., PONTIKAKIS, E. and RAUBAL, M. (2001): 'LBS for Real-Time Navigation – A Scenario'. *GeoInformatics*, 4: 6–9.

WU, Y.-H. and MILLER, H. (2001): 'Computational tools for measuring space-time accessibility within dynamic flow transportation networks'. *Journal of Transportation and Statistics,* 4: 1–14.

ZAFF, B. (1995): 'Designing with affordances in mind', in FLACK, J., HANCOCK, P., CAIRD, J. and VICENTE, K. (eds): *Global Perspectives on the Ecology of Human-Machine Systems*. 1, pp. 121–156, Lawrence Erlbaum Associates, Hillsdale, N.J.