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Knowledge-based wayfinding maps for small display cartography

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Small displays are currently gaining importance as interfaces for geographic information. More specifically, mobile position-aware devices, such as mobile phones equipped with globally positioning system, are increasingly used for mobile wayfinding assistance. But their constrained displays are too small to reproduce conventional maps without an increasing effort for the user. For example, they have to zoom in and out, and to scroll through the map to understand the details and configurational relationships of the involved entities of a route. This fragmentation of the information is not just inconvenient, but actually affects the cognitive processing of the given information and lowers the effectiveness of the assistance. One way to attack this problem is to tailor maps to the individual knowledge of a user. If an assistance system knows about the places and paths a user knows, it can generate maps according to this information: those parts of a route, which the user has good knowledge of, can be displayed with less detail and parts with no or little knowledge can be emphasised. However, the transformation of maps with respect to previous knowledge is a yet unexplored field and requires new and basic considerations about map generation. In this work, we analyse prototypical spatial configurations, geographic veridicality and assistance scenarios. We demonstrate first prototypes of personalised maps for small display cartography.

Keywords: maps; personalisation; wayfinding assistance; navigation assistance; mobile cartography; schematisation

1. Introduction: wayfinding with maps in the age of turn-by-turn instructions

Wayfinding is a significant task in our lives. Recurrently, we have to find our way to an unknown destination. In such a case we typically consult a form of wayfinding assistance, like a map or a turn-by-turn navigation application (wayfinding decisions, like turning at a junction, are announced just before their execution is required). The first case, namely wayfinding maps are the subject of this article. There is a prominent question we (researchers on wayfinding maps) are regularly confronted with: why do we still focus on maps as wayfinding aids, especially as turn-by-turn navigation assistance is on the edge of ubiquity? Most people who have experienced the ease and effectiveness of a turn-by-turn navigation system are convinced by the contemporarity of the application: one has just to type in a destination and they will be guided effectively, fast and conveniently always with

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respect to one’s current position. These systems usually react to navigation errors, blocked roads and traffic conditions and re-route the driver if required; the driver just has to mentally lean back and follow the instructions. In contrast to that, maps appear as an inopportune relict. Even if they are generated with respect to a particular query, this means that they only cover the requested geographic area and already contain a pre-computed and highlighted route, they still require close examination: what course does the route take, which elements along the route are significant or already known, and so forth. During navigation, the map has to be matched against the environment and vice versa to ensure successful wayfinding. But there is a huge positive side-effect which does not develop with turn-by-turn assistance: people collateralise learn the environment beyond the route and are, as a result, more independent from assistance (Richardson et al. 1999). There are observations that people do not learn the environment similarly well when they use turn-by-turn assistance instead of maps (Ishikawa et al. 2008). A possible explanation is that this kind of representation does not require a close examination of the environment anymore, and even navigation errors are immediately corrected (Burnett and Lee 2005, Parush et al. 2007). This means, if we want people to learn an environment and to navigate independently in large parts of it, maps seem to be indispensable. We believe that maps can be further improved to facilitate their successful parsing, understanding and use for wayfinding, especially in the context of mobile devices and mobile navigation support.

Today, wayfinding assistance is no longer limited to either paper maps or computers with comparable large displays. We can find wayfinding support in many mobile and semi-mobile devices, like mobile phones or PDAs or car navigation systems. The visual interfaces of all these devices are small displays. The actual sizes and resolutions of the displays differ from very small (as usually found on mobile phones) to a more moderate size and resolution (e.g. car navigation systems). Dillemuth (2007) has shown in her experiments that traditional interaction (like scrolling) with large visual information (the map) on small displays does affect knowledge processing of the information significantly. As geographic information usually requires space to be displayed properly, we have a need to develop different forms of representation for the required geographic information (usually in the form of maps) for these kinds of devices.

A key concept can be the schematisation of the required map. Schematisation is usually understood as the intentional distortion of a representation beyond technical needs to achieve cognitive adequacy (Klippel et al. 2005). In the following, we will have a look at some prominent schematisation approaches and highlight their essential cognitive concepts.

2. Wayfinding maps: selected schematisation techniques

Agrawala and Stolte (2001) introduce an activity-based schematisation for driving routes. It is based on the observation that driving routes often incorporate long parts where no decision activity (like turning or changing a road) is required during wayfinding. An example is driving for a long time on highways without leaving it or changing roads. When we visualise the geographic region in according scale on a map, these parts can require a significant amount of the available limited interface space. This is contrary to the actual activity and cognitive load related to these parts. As Agrawala and Stolte show in their pictorial examples, this can lead to situations where the important parts of a route will be literally suppressed while uncritical parts are dominant. They propose to adapt the
scale of the particular route elements to the corresponding wayfinding activity: a high degree of required activity (and corresponding cognitive load) will lead to a more detailed view of the involved entities; a low degree of required activity will lead to a highly schematised view. As a result the distance information is no longer in a uniform scale, but relates to the activity required by the route. The result is a route strip map which requires significantly less display area if the route incorporates big parts with no required wayfinding activity.

Zipf and Richter (2002) introduce a different form of schematisation. They do not primarily aim at the compression of the visual representation of a route, but to improve the extraction and processing of the actual route and its context within a rich map, thus a map which contains significantly more information than required. They highlight the route by schematising and fading out map features depending on their proximity to the route. That is, the closer a feature of the map is to the actual route the higher is its level of detail and the intensity of its colouring; the more distant a feature is the more schematised and uncoloured is its appearance. This concept is based on the observation that a larger spatial context is helpful during wayfinding (in contrast to strip maps), but not all spatial regions are of equal interest for the given task. This idea was further extended by Klippel and Richter (2004) with the introduction of chromatic focus maps, which further improve map understanding. Junctions and turns of the route are represented by means of choremes (Klippel 2003), reflecting the prototypical mental representations of turns.

A promising approach to information reduction that at the same time preserves the meaning and the accessibility of geographic information is to generate maps according to the spatial knowledge of a user. Although they present no explicit mapping, the concept of Srinivas and Hirtle (2007) is important to this end. They introduce the concept of knowledge-based route chunking. Srinivas and Hirtle assume a path network encoded with a familiarity measure for certain locations. If a specific route incorporates two or more subsequent known segments, these are combined to one semantic unit. In their paper, Srinivas and Hirtle show how routes and their conceptual representations can be tailored to the knowledge of an individual by applying these chunking rules.

In Patel et al. (2006), the authors introduce a similar concept but focus more on the pictorial representation in forms of maps. Patel and co-authors refer to complete existing known routes between landmarks and introduce a cost function to select not only the fastest route but the route with the most well-known parts. As long as the cost for the route does not exceed a certain ratio, the longer route is assumed to be equivalent to the route choice that does not consider prior knowledge. An informal study shows that users are willing to accept longer routes if they incorporate well-known parts. Using this known sub-route, Patel and co-authors compress route directions and render personalised strip maps. They indicate prior knowledge by schematising the known parts of the route: the original street course is replaced with a straight line (space needle). The space needle does not attempt to reduce the required size for the route and the map, since it covers the same space. But it indicates the presence of previous knowledge.

3. Personalising wayfinding assistance with individual spatial knowledge

Personalised wayfinding assistance is not a new invention but a very natural form of support produced by humans for humans. If we ask somebody for directions, we usually get involved in a dialog (Tomko and Winter 2006). During this conversation the
participants discuss familiar, unfamiliar and salient features of the route and consider the situation and the type of transportation of the wayfinder. Resulting from this process are directions tailored to knowledge and needs of the wayfinder (which is a subset of the knowledge of the assistant). Usually, the result leaves out descriptions that are unnecessary for the wayfinder, i.e. those parts of the route the wayfinder knows do not need to be explained in detail (e.g. Schmid and Richter 2006). This has two effects: first, the directions can be significantly shorter but still contain all relevant information; second, the remaining parts and elements of the route are related to already known elements, which helps to integrate the new facts into the existent mental map. If maps reflect this process, we can expect them to be efficient in terms of size (as parts of the environment do not need to be depicted in detail while other parts can be emphasised) and efficient in terms of mental processing, as the information is related to existing previous knowledge.

If we want to transfer this process to an application, namely the personalisation of maps under the consideration of individual knowledge of an environment, then the application will require access to this knowledge. To enable an application to access this particular knowledge, it needs to be developed and represented beforehand in an effective way. Patel et al. (2006), and Srinivas and Hirtle (2007) propose to enter the required knowledge manually: i.e. users have to enter exactly those places and routes that between them they actually know via a proper interface. The advantage of this approach is the availability of verified and fully labelled data. But this method only reflects the part of the knowledge an individual can recall and label at that given moment. We can expect that the resulting data will not reflect what a person really knows about the environment. Especially all the small and apparently insignificant places like junctions, the post office, the grocery, etc., will not be considered although they can play an important role in an individual’s segmentation of space as discussed in Schmid (2007). Furthermore, it is clear if the data are not maintained regularly, it will soon become obsolete.

One promising way to resolve this problem is the maintenance of a spatial user profile based on the trajectories of an individual. Some years ago the recording of everyday trajectories was only possible either under laboratory conditions in specially modified test environments or with additional hardware, like GPS (Global Positioning System) handhelds. Currently we can record GPS-based trajectories with many everyday devices like mobile phones, wristwatches, or car navigation systems. These trajectories can be analysed according to inherent patterns: the visited places and travelled paths (Ashbrook and Starner 2003, Hightower et al. 2005, Schmid and Richter 2006). This information can be used as an input for a spatial user model which is constantly updated and maintained. The drawback in relying solely on a built-in GPS module as an input for a spatial user profile is the potentially highly fragmented and noisy datasets we will obtain. A major problem is the handling of personal mobile devices, because their use is contrary to the requirements of a GPS device: they are usually not carried at places where the signal reception is optimal (e.g. on the top of the head or at the window of the tram), but in jackets, trouser pockets or bags. This massively downgrades the quality of the received signals; they are only occasionally outside of pockets or bags and on account of this rarely in optimal receiving mode. A further error source lies in the mobility of the devices: they can be turned off, forgotten, stolen, lost, shared or lent. This means, they are not necessarily there where the user is and the user is not necessarily the ‘owner’ of the user profile. Additionally, all these devices operate with batteries and GPS is still an energy intense technology. Weak batteries are often a source for bad signals; empty batteries will result in signal loss. Another problem with GPS is the general visibility of the satellites.
The quality is usually good in open areas with no extreme topography such as parks, rural areas, etc. In densely built urban areas, the signals get reflected and distorted by the surfaces of walls of buildings and water bodies. The signals can usually not be received in a satisfying quality within buildings and vehicles. Especially during transportation this has implications: if a person moves with a car, bus, tram, train... or subway the trajectories are usually of unacceptable quality or simply not available. As a result we only obtain the transitions from one place to another, but we will miss out on the actual travelled route.

For real life applications, this means that a reliable spatial user profile cannot be solely obtained by manually entering spatial data or by GPS trajectory analysis. We will require the integration of multiple spatial sensors, non-spatial sensors and manual data. Future applications will have to communicate with the ticketing system of the public transportation to identify the travelled, untrackable routes, they will have to be able to receive positioning information from car navigation systems, and of course they have to be able to include external spatial sources, like internet route planner queries or manually entered spatial data. We have to enable the plausible interweaving of all possible sources of verifiable individual spatial knowledge to receive a clear and expressive spatial user model. Such a model should not only minimise the errors and inaccuracies introduced by sensors, but should also be able to express the mode of transportation (such as walking, car, active or passive navigation), environmental influences (e.g. daytime dependent illumination, weather conditions, viewpoint analysis) and individual conditions (stress level, emotional state) related to the learning of particular spatial layouts. All these factors can massively influence the perception and, consequently, the conceptualisation of an environment.

It is important to note that spatial knowledge is built up and fed by different sources and senses. Knowledge is not only assembled from direct perception during locomotion, but also from external sources, like maps, from videos, photos or information gained from conversations with other people. We can build concepts of the environment before we actually perceive it (Richardson et al. 1999). In order to give meaningful assistance, a personalised wayfinding assistance application must rely on verified data, i.e. prior knowledge for which it is assured that a user indeed possesses it. This means, personalised wayfinding assistance is mainly interested in physically perceived knowledge, which contains all forms of perceptual knowledge acquisition of the surrounding environment during locomotion (Golledge 1992).

The utilisation of physically perceived knowledge does still not guarantee the reflection of the actual knowledge of a user. First of all, we have to consider memory effects. Although (to the knowledge of the author) there exists no long-term study on spatial memory, we can assume that spatial knowledge – as any learned fact – is subject to fading, forgetting, systematic and individual errors. Places and routes we have not visited and travelled for a long time will most probably lack details when we recall them. Due to missing evidentiary functions, we are currently not able to state which parts of the knowledge will fade to which degree. Or, vice versa, we are not able to say which elements will be preserved to which level of detail.

Cognitive models of long-term memory usually include functionality to model loss of memory (which is usually equivalent to the reduced activation of neurons over time). These models are usually context specific, and once again, to the knowledge of the author, there exists no empirically supported model explicitly for spatial knowledge (e.g. Anderson et al. 2004, Schultheis et al. 2006).

We know from other areas of cognitive research that human memory is no veridical storage for experienced facts (e.g. Baddeley et al. 2001), and the same holds for spatial
knowledge as well. Research on spatial memory unfolded a range of systematic errors related to spatial knowledge (see Tversky (1993), for an overview of prominent examples). A further critical influence on spatial knowledge acquisition is the level of involvement during navigation and transportation. One can travel passively by public transportation and at the same time read a book. Doubtlessly, the acquisition of knowledge will be very limited. As another extreme, one can navigate by paper map and instructions and potentially learn the environment beyond physical experienced space.

The observations and particularities of human spatial knowledge acquisition raise the question of the validity of trajectory-based user modelling. On the one hand we have a bunch of potential problem sources and effects, on the other hand we have pragmatic experiences with places and paths we travel and visit frequently. This question and its implication cannot be answered easily and will clearly require user-centred and, ideally, long-term studies.

3.1. Conceptual elements of personalised wayfinding assistance

Two key units of human conceptualisation of space are places and paths. The term place has no clear definition and is used ambiguously over a variety of publications and in different contexts (see Agarwal (2004) for an elaborative overview; see also Bennett and Agarwal (2007)). Observing commonsense and empirical studies lead to the interpretation that places are regions obtained as the result of structuring the world individually into semantic, perceptual or functional units for the purpose of spatial communication (as discussed in Montello (2003), Agarwal (2004), Wiener (2004), and Edwards (2007)). From the perspective of an individual, places are connected to activities and vice versa most activities are connected to places. It is hard to identify activities beside those grounded in travelling as their main purpose (like hiking or driving over large distances), which are not directly connected to a kind of place. This means, in the majority of cases whenever we perform any kind of activity, we visit a place in the course of doing so. And as activities usually need time to be performed, we can say that a place is a conceptualised geographical region where an individual spends more time than in other regions. The ‘other’ regions are the remaining parts of the physical presence, the travelled routes between the places. Consequently, there is no ‘placelessness’ since we are always physically present and ultimately have to perform at least basic activities (eating, resting, sleeping, etc.) which are covered by the concept of place. In the following, we will differentiate between a ‘route’ and a ‘path’: a route is the result of the query for a way between two places A and B, a path describes a known and, therefore, previously travelled route between two known places A and B. Whenever we refer to the term ‘route’, we mean the result of a route planning process, a path will always describe a previously travelled route as part of the previous spatial knowledge of a person. Routes and paths can intersect each other in any possible configuration.

3.1.1. Major, minor and inferred places

The question is now whether all places qualify in the same way as references in personalised wayfinding assistance. It is easy to see that this is not the case: there are places we know very well, places we can hardly remember and there are many places we are not aware of without pointing to a larger context. If we only take the perceived environment into account, we can differentiate between major places and minor places. Major places are purposefully visited places, they are characterised by relatively long duration stays,
and people usually have an explicit name for them (home, work place, etc.). There are indications that people remember these places without frequent repetition, since the learning usually takes place in advance: people plan their activities and visit previously chosen places to exercise them. People usually do not visit places randomly to perform unconscious activities. This means, a major place is a place with a distinct and specifiable meaning to an individual. A major place can be labelled with respect to a particular experience, activity, salience or function. In contrast to that, minor places are ‘collateral’ places and they are not intentionally visited. Due to spatial particularities like junctions or construction sites, people are forced to spend time in some regions without explicit intention. If people are regularly at such a place, they start to learn it due to the inherent recurring activity and experience. But people usually do not have an explicit name for them. The names typically reflect the local spatial configurations (‘the junction at the pharmacy’), landmark-like particularities (‘at the crossover’) or the involved destination (‘the large junction on the way to the Uni’). A third, but not directly operational category of places is inferred places. Inferred places are places inferred from the structure or naming of the environment, like street names or street block conventions. For example, if a person knows that ‘Peter’s place’ is in XYZ-Street 15 and the new unknown destination is in XYZ-Street 19, they are most likely close to each other. Although the wayfinder has never been to the place before, he can directly infer the relationship with existing knowledge without the consultation of wayfinding assistance.

Personally meaningful places are inline with the anchor-point hypothesis of Couclelis et al. (1987). According to the authors, ‘anchor-points are the most important elements in a person’s cognitive map’, thus, personally experienced places which serve as structural fix points in the cognitive map, organisational ‘top nodes’ within each individual cognitive map. Major, minor and inferred places can be viewed as a refinement of the term anchor point. Couclelis and co-authors state that ‘there appears no obvious method for identifying individual anchor points’, which is still true for the complete set of possible places of a person. But due to the activity-driven definition of places and by means of trajectory analysis, we can identify the set of personally meaningful places which is grounded in recurring activity. As stated above, this set will obviously not cover all possible meaningful places, but a verifiable and utilisable subset.

3.1.2. Familiar, partially familiar and unknown environments

When we use the term environment in the context of knowledge-based wayfinding assistance, we mean the regions which are geographically relevant for an individual. An environment does not have to be limited to regions around the person’s centre of life. The understanding of environment must be driven by the knowledge corresponding to it: each region a user has knowledge on is a possible environment for him. We can say that the environment of an individual is the vista-space (Montello 2003) around all locations the individual has physically ever been to. Additionally, in the context of personalised wayfinding assistance, we will have to answer the question how well the environment is known. Basically there are three categories of environments, independently from the actual level of knowledge: there are regions which an individual has full knowledge of, regions where he does not know all relationships between all features and regions in which he knows nothing. In other words, we can say that a familiar environment (FE) is the environment where an individual knows at a particular point in time all possible places and at least one route between each of them (full knowledge). A partially familiar
environment (PFE) is the environment where an individual does not know at a particular point of time all possible places and routes between each of them (partial knowledge). And finally, an unknown environment (UE) is the space where an individual has never physically been to, and which is not covered by the vista-space of the historical trajectories of the individual (no physically perceived knowledge is present at all). Figure 1 illustrates the relationships between the three types of environments: the FE is embedded within the PFE which is embedded in the UE.

Spatial familiarity is hard to express and even harder to measure. Couclelis et al. (1987) suggest a recognition- and labelling-based multidimensional measure to express familiarity. The basic idea is, if people recognise a place and can label it properly, they must have a high level of familiarity with this place (this anchor point).

3.1.3. Labelling places – attaching individual semantics

The communication of places for personalised wayfinding assistance has to rely on individually assigned labels. A large set of places in the user profile will not be public places or landmarks, but places such as ‘home’ or ‘work’. In order to address the name or the concept of an identified place, an application has to know this name. In the prototype of our application, when a user visits a previously identified (major) place again, we pop up a window and ask the user to enter a description of the place. If a place is labelled, we assume this as a verification of the identified place, similar to Couclelis et al. (1987). In order to reduce the required manual entering of names (which is always a critical usability point), we are currently working on collaborative labelling techniques, the application of media based (e.g. photos taken at a place – personally or collaboratively), and phone-based activity detection (recurring calls at the same place). Collaborative labelling has the advantage of generating hierarchically meaningful conceptual regions with only small effort to the individual. Especially public places, like a university campus, only have to be labelled by a small group of people. Other people can either reuse already assigned labels or refine existing concepts (university vs. building name). Combined with geographic analysis we can expect further insights in human conceptualisation of semantic regions – what elements belong to concepts and where the borders run.

By applying the mentioned techniques, we expect more convenient data acquisition, and at the same time additional questions about the validity and quality of labels. Naming and recognising of places is no longer solely the responsibility of the addressed user, but in charge of a ‘community’. This means, that the acceptance of labels will require a different familiarity measure: accepting a predefined label is clearly not as expressive as generating a new label. A key to this problem can be the enforcement of the selection of a finer or
coarser concept or the refinement of an existing concept. An intended selection of a label expresses the familiarity with a place and the desired granularity connected with this place.

4. Personalised wayfinding maps – maps built around individually meaningful places

If we want to generate personalised wayfinding maps, we have to consider the basic requirements and elements of wayfinding maps. We have to examine which elements of the previous knowledge can replace elements of traditional maps, and how elements of the unknown parts of the environment can be integrated in a personal frame of reference.

First of all, let us have a look at the basic demands of a wayfinding map: for self-localisation a wayfinder has to identify the surrounding environment with the map at hand. For the unknown parts of the environment, we can rely on either established or experimental mapping (as illustrated in Section 2). But for the known parts of the environment and especially the transition points, i.e. those areas where familiarity ends and unfamiliarity starts, we will have to think about a suitable form of visual communication. This is necessary because the reference systems of the information changes: the unknown parts of the environment are expressed by means of geographic mapping, whereby the known parts directly refer to mental concepts of the user. We will have to make this change clear to avoid misinterpretations. Additionally, we will have to consider how the actual spatial relations between the elements of the PFE and the UE can be clarified and which information is required for successful map understanding.

During navigation, a wayfinder has to identify his physical location on the map and the surrounding environment on the map. When maps are used for pre-trip planning, i.e. the consultation of the map before the actual travelling, a wayfinder benefits from the meaningful integration of the route within the environment he will cross. This will help him to integrate the queried places and the route into his prior knowledge. For both scenarios the initial orientation, i.e. the alignment of the map with the environment is of crucial importance for the wayfinding success. A good map selects features that resolve local ambiguities with carefully selected landmarks and/or structural configurations and helps the wayfinder to identify the local configuration (‘if you see the park on your left and the river to your right, you are oriented correctly’). For the UE, we can rely on any available method, for the PFE and the transition areas we will need a suitable bridge between the two frames of reference. The strongest pointers we have at hand are the major places of the prior knowledge. As these places have a very distinct meaning for an individual, we have very good anchor points for the indication of global and local orientation of a route. As soon as we incorporate prior spatial knowledge we can rely on places as references, even if no place is covered by the actual route. If we just refer to a part of a path, we can indicate at the transition points how the route enters the path and how the places are related to this location. If a route starts at a place, we can rely on the knowledge about the local configuration at the place; we only have to indicate in which direction a wayfinder has to follow the path (‘go from here as you usually go to the university’). To foster the integration of new knowledge in existing knowledge, we have to make sure how the route and the new place(s) are related to existing entities of the spatial knowledge. We have to consider two basic cases: either the new place(s) and well known parts of the environment are in the same geographic region or they are in a distance such that references to well-known elements are not really helpful. Of course, different areas in the world have different concepts of scale: in dense urban areas ‘far’
means something else than in rural areas with a very low density of population and larger distances between places. The selection of known references must be driven by their closeness to a UE and the established level of knowledge connected to them. If a person is close to well established knowledge (e.g. where they live), we can clearly indicate the location or direction by nearby places. If the person is far from ‘everyday knowledge’, e.g. in a holiday resort, instead of pointing to the usual surroundings we can integrate the prominent patterns of the latest trajectories, like the way to the hotel or the church visited 1 h ago.

5. Knowledge-based schematisation of wayfinding maps: route-path configurations, assistance types and schematisation techniques

According to the definitions of the different kinds of environments, namely that FE and PFE are developed by trajectories, all known parts of the environment are connected to each other. An extreme interpretation can be that we only have three possible configurations of routes and paths in the FE/PFE and UE (in the following we will only refer to PFE instead of FE and PFE, as in the important properties they share the same concepts):

- **Route is contained in PFE**: This means that the start and endpoint of a route is completely contained in a combination of paths in the PFE (Figure 2).

- **Route overlaps PFE**: This describes the scenario depicted in Figure 3. A part of the route is addressable with a path; the other part of the route is in the UE. The part in the PFE can, but does not have to be a known place.

- **Route contains PFE**: A known path can be fully integrated within a route but both ends of the route are members of the UE (Figure 4).

In reality, of course, we can expect highly fragmented records of the real trajectories due to the particularities of the positioning devices used (like mobile phones equipped with GPS sensors). When we feed the knowledge presentation with this data, the resulting user model

![Figure 2. Elements contained in PFE.](image)

![Figure 3. Elements overlap PFE.](image)
will be fragmented as well. Under realistic conditions, we will have fragmented data and cannot expect a completely connected PFE. As a consequence, we will have to deal with complex configurations of UE and PFE (as illustrated in Figure 5). However, the three basic configurations are important for the identification of suitable schematisation principles. In the following, we will focus on the particularities of each configuration and propose suitable schematisation methods.

5.1. Optimal route detection

In this article, we assume a coherent PFE and just allow the three basic configurations discussed previously. As we want to generate a map for a particular route with respect to particular knowledge, the most basic step is the selection of a route from the desired point A to point B. There are several route selection strategies, but we will only focus on the shortest path with maximised known parts. In Patel et al. (2006), the authors only allow complex routes between landmarks, which can result in suboptimal routes in terms of length and time. We developed an algorithm which allows us to identify the path with maximised familiar parts and is shortest within the PFE. This means we can identify the shortest route with the minimal unknown elements. In this work we do not aim to compare it with results of other route selection strategies, as we primarily aim at the treatment of previous knowledge for map generation.

At this point we do not aim to identify a plausible tradeoff between an optimal route (under the fastest or shortest route assumption) and one integrating previous spatial knowledge. But it is clear as soon as we spread a personalised assistance system beyond the walls of our lab and encourage people to use the system in their real life settings, we will require an operational measure for the route selection. People will only use a new system if it is at least as effective as the old system it aims to replace and if they obtain an additional feature (which can also have a better interface or easier to extract information). Consequently, a personalised wayfinding system must be able to offer effective routes in

Figure 4. Elements contain PFE.

Figure 5. Fragmented PFE/UE configuration.
terms of quantitative measures, like distance or time. This will require further empirical
analysis of the travel behaviour of people within their familiar environments and their
natural route selection strategies when leaving them. A good starting point is the analysis
of trajectories in unassisted travel: we can classify the different modes of transportation on
a path and compute the distance difference between the actual travelled route and an
‘optimal’ route for each mode. If we can identify significant differences (e.g. a user accepts
14% longer routes), we could use this ratio as a clue for an individual operational measure.
Besides the operational measure for the route choice, we will have to ensure that the
selected route will be coherent and plausible while integrating the previous knowledge:
it would be hard to understand why a user should leave a main road he would just have to
follow just to find his way through small and winding side streets. This means, we will have
to find measures and algorithms which ensure the integration of previous knowledge
plausibly with respect to distance and coherence of the involved elements.

The algorithm FIND-OPTIMAL-KNOWLEDGE-PATH (Algorithm 1) works as
follows: it requires two graphs, the street network graph G and the graph containing the
previous knowledge KG (which is required to be a proper subset of G). Furthermore we
require two nodes, which define the start- and endpoint of the route (S, D). The shortest
path computation (in this context it should be interpreted as a graph search) can be
performed with any algorithm, such as the Dijkstra algorithm. First of all, we compile
a list of all nodes of KG and pass it on to the function FIND-N-SHORTEST-PATH
(Algorithm 2) together with one of the nodes S, D. Here we compute the Euclidean
distance of every pair of the two nodes S, D and all the nodes of the list KN (Steps 1–3).
In the next step (Step 4), we sort the list according to the distances and compute the
shortest path from S, D to the prior knowledge starting with the smallest Euclidean
distance. The shortest so far identified path is stored and only replaced if a shorter one can
be found (Steps 6–10). We can use the shortest path as a break condition for the shortest
path algorithm. When we reach the point that the Euclidean distance is longer than the
path distance, we can finally stop the search at this point, as it will not be possible to find
a shorter path.

Back in the main algorithm, we now have to compile the three pieces (entrance part,
known part, exit part) whereby we still have to find the shortest path within the PFE
(a shortest path search from the entrance point to the exit point does just this). As a result,
the presented algorithm will neither identify the shortest path, nor the shortest well known,
but the path with the shortest parts within the UE and the shortest path within the PFE.

The result of a query for a route between a location A and B consists of three elements:

- The starting point and a certain area around this place
- The destination and a certain area around it
- The known path which shares exactly one node with the area around the starting point and one with the area around the destination.

All three elements are represented as graphs. If one of these areas is contained in the PFE, they are only represented as one node.

5.2. Linearisation and μ-mizing depending on route-path configurations and assistance types

In the next step we are interested in visualising the resulting path conveniently. A straightforward schematisation for a known path is its linearisation, i.e. the complete abstraction from the geometric layout as proposed by Patel and colleagues. This works fine if the addressed path is fully contained by a route, i.e. its two places are completely integrated. But as soon as we only refer to parts of the path (which we explicitly allow), we face the problem that we will have to make clear where a required wayfinding action has to be performed. A straightforward approach is the segmentation of the known path into suitable sections, determined by cognitively plausible elements (such as landmarks, major junctions or places). The elements can be plotted along the linearised path with respect to their relative distance. This involves some tricky representational problems. Let us consider the situation depicted in Figure 6: A and B are known places and connected by the known path illustrated with the bold line. The user usually turns left from the main road into the street leading to B, the new place is at the extension of the main road. If we linearise the path as described above, we will introduce spatial (and most likely cognitive) artifacts. Figure 7 illustrates one possible arrangement of the schematised path. It indicates to turn right which is not required in the real environment, as the user only has to follow the main road straight on. In Figure 8, we can see how this schematisation

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**Algorithm 2.** The function to identify the shortest route from the UE to the PFE.

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Function: FIND-N-SHORTEST-PATH (G, KN, N)
Input: A network graph G, a list of nodes KN of previous knowledge, a node N
Output: Returns the shortest path between N and a node of KN, N will be the first node of the path.
1. for all KNi ∈ KN
2. d ← compute Euclidean distances between N and KNi ∈ KN
3. SN ← add (KNi, d)
4. SN ← sort SN with respect to d
5. SKP ← compute shortest Path for N, KNi ∈ (KNi, d) in G
6. for all (KNi, d)i ∈ SN
7. temp ← compute shortest Path for N, KNi ∈ (KNi, d)i in G
8. if (temp < SKP)
9. SKP ← temp
10. if (SKP < d ∈ (KNi, d)i+1)
11. return SKP
12. return SKP
```
introduces wrong spatial constraints. In terms of cardinal directions, it seems like the unknown place is west of A and B (instead of south). Furthermore, we can find the false activity indicator as in Figure 7. Figure 9 seems to work best in terms of spatial configuration of the known places, but still fails with the configuration of the unknown place as well as with the activity indication.

We require this veridicality, because in contrast to fully contained paths, we have to perform a different activity than usual on this path. The location of this decision point has to be inferred from the map which requires self localisation. Self-localisation in unknown
environments requires a certain degree of veridicality, as the wayfinder has to identify the decision point in the environment. If the information on the map is misleading, especially at the critical decision point, the potential of navigation errors increases. We can conclude that linearisation is not a proper schematisation method for all spatial configurations. Especially when we refer only to parts of a path, we can easily identify configurations which will lead to problematic externalisations. The possible misinterpretation of potential wayfinding activities and/or the wrong interpretation of the spatial configuration can be attacked by abstractions which inherently contain the required information and/or will foster the understanding of the relationships of the addressed entities. We know from our own experience that people, while giving route directions, tend to de-emphasise elements which are known to the receiver. We can now carry these observations forward to the schematisation of complex route configurations. The primary element of the desired map is the route with its known and unknown parts. Especially the spatial layout of the known path has, due to its intrinsic configurational properties, a supporting role; if we preserve the layout properties of the known path and arrange the unknown elements with respect to their position relative to the path, we introduce a natural allocentric reference frame for the spatial relations and are able to preserve the correct interpretation of the locations of the new decision points. To preserve the spatial layout and at the same time achieve schematisation, we now have to apply two basic steps: generalisation and minimising. We will call the result of these two operations $\mu$-mizing.

Generalisation describes the simplification of a polyline and is a widely applied technique in geographic visualisations. One well-known algorithm is the Douglas–Peucker algorithm, a cognitively motivated one is the Discrete Curve Evolution (Barkowsky et al. 2004). In our actual implementation, we apply discrete curve evolution to generalise the known path. A comprehensive overview of further approaches and their properties are offered in Stein (2003).

In Figure 10, we can see the basic steps involved in $\mu$-mizing: the left image contains two unknown regions A and B connected by a part of the path between X and Y. In the first step we generalise the path; in the second step we minimise the schematised path such that the regions A and B do not touch. The algorithm sketch $\mu$-MIZE-GRAph (Algorithm 3) illustrates the functionality in more detail. The regions A and B and the path are a partition of a street network part. We split it up into three graphs: the regions A, B and the path P (Figure 10). P has to be chosen such that it exactly shares one node with A and with B. In the first step, we will generalise P. In the next two steps, we compute the convex hulls of A and B. In Step 3, we compute the shortest distance between the two hulls. From the distance and the two points we can immediately receive the

Figure 10. $\mu$-Mizing of a route.
transition vector, which will be applied to all nodes in A in Step 6. The displacement vector will be shortened by a certain value to guarantee that the two regions do not touch (which would be the case if we would directly apply the displacement vector). In Step 8, after the translation of A, we just have to minimise P with the according scale factor. The minimised path now serves as the constraining link to the global configuration of the involved elements. The layout of the path ensures that the unknown and known elements are in a mutually correct configuration.

The linearisation of routes is still a promising option for knowledge-based schematisation. Patel and colleagues propose the 'space needle', a geographically veridical linearisation of the known path. In Figure 11, we can see different linearisation possibilities of the path between the places A, B and route alignment options for different assistance scenarios. Let us assume a wayfinder travels from \(x\) to \(y\) via the path between A and B. We now have several possibilities to arrange the involved elements. Illustration 1 depicts the original configuration of the elements, i.e. their topological relationships in a cardinal reference frame. Illustration 2 follows the concept of Patel and colleagues: the path is schematised, but the cardinal directions and the topological relations are preserved; we also applied an additional minimisation of the Euclidean distance between A and B. By de-emphasising the path, the unknown parts of the route are clearly emphasised and the wayfinder is not distracted by the elements of the path. Illustration 3 shows an allocentric route perspective, where the linearised path is horizontally aligned and the unknown parts are veridically organised at the transition points. In illustration 4, we can see a typical navigation perspective: the starting point (\(x\)) is at the bottom of the map and the destination (\(y\)) is on the top. It is important to notice that this configuration does not correctly depict the exit/entrance angles at the transition points, but the

$$\text{Algorithm: } \mu\text{-MIZE-GRAH (A, B, P)}$$

| Input: | Two graphs A, B (the two unknown regions) and a graph P (the known path) connecting both graphs (they share a node) |
| Output: | Will return a \(\mu\)-mized graph of A, B, P |

1. \(P \leftarrow\) generalize P
2. \(CA \leftarrow\) compute convex hull of A
3. \(CB \leftarrow\) compute convex hull of B
4. \(v \leftarrow\) get displacement vector between the two closest points of CA and CB
5. \(\text{distVecs} \leftarrow\) get vectors between any node of P and refPoint
6. \(A \leftarrow\) translate every node in A with \(v\-\varepsilon\)
7. \(P \leftarrow\) scale/minimize P
8. return A+B+C

Algorithm 3. \(\mu\)-MIZE-PATH.

**Figure 11.** Eight possible linearisations of the route depicted in 1; see text for details.
geographic configuration. In illustration 5 we can see the navigationally veridical counterpart. In this illustration, the environments are aligned from an egocentric perspective. Illustrations 6 and 7 consider the conceptualisation of turns as identified in Tversky and Lee (1999) and Klippel (2003): when people draw sketch maps, they usually replace angles between streets with 90° prototypes, the choremes. In 6 and 7, we arrange the unknown part by a chorematised angle between the path and the remaining unknown part. Note that this linearisation is able to preserve the geographic relationships of the unknown areas before A and after B. Illustrations 8 and 9 show another possible linearisation: in contrast to the previous illustrations, they imply the identification of the correct orientation at the transition points A and B. This schematisation does not consider the geographic relationship between the unknown area and the path. This projection can be problematic if the situation at the transition points A and B is configurationally complex.

We decided to implement the schematisation corresponding to illustrations 2 and 5, as all other schematisations can be easily derived from them. The linearisation algorithm is based on the μ-mizing procedure. As in the μ-mizing procedure, we work on three key elements: the starting point area X, the path P and the destination area Y. We move X towards Y, but instead of minimising P, we replace it with a straight line. Scenario 4, which is the linearised navigation scenario, can be computed as illustrated in Figure 12. We select the angle \( \alpha \) between the first junction on the path (starting at X travelling towards Y), that is, after the first place in travelling direction, and the angle \( \beta \) between the last junction before the second place in travelling direction (1). In the next step (2), we align both angles, such that the outgoing edges are in line. In the last step, we rotate the two parts in the desired position (here a navigation/egocentric perspective, i.e. the start environment X is aligned bottom-up).

5.3. Navigation versus pre-trip planning

We have to differentiate between maps for assistance during navigation and pre-trip planning situations (e.g. internet-based route planners), because they require a potential different presentation of the spatial information (in a pre-trip planning scenario a survey perspective is more helpful; the navigation scenario requires a map which is aligned with the current heading of the wayfinder). Of particular importance is the queried start place (‘from here’), as it can be part of the PFE, but might not be a known place. However, this does not mean that the wayfinder requires a pointer to where he is, as it can be his

![Figure 12. Illustration of the alignment steps for the linearised navigation perspective. X is the starting area and Y is the destination area.](image)
current position. He probably is just interested in the transition from the PFE to the UE. The other way around, if the current position is in the UE and the queried destination is in the PFE, the user most probably wants to know where the place is located with respect to his known places and landmarks. In the following, we will differentiate between those cases and illustrate different visualisations for the different assistance scenarios.

5.4. Route partially integrates path

If a route enters and exits a path not at places, it only partially integrates a path (Figure 21, configuration 4). The algorithm FIND-OPTIMAL-KNOWLEDGE-PATH allows the integration of only parts of a known path. In Figure 13, we can see a map with known paths (bold lines) and a route (thin dark line) between two queried places (solid circles). The places are assumed to be at the endpoints of the paths. The transition points are indicated with white circles. Note that the route in our cases always goes via the PFE. In Figure 14, we can see an extraction of this map: only the PFE (bold lines), the route (thin line) and the four relevant places are depicted. The thin black line shows the

![Figure 13. Survey map with prior knowledge and partially integrated path.](image1)

![Figure 14. Extracted prior knowledge from Figure 13 and partially integrated path.](image2)
generalised part of the PFE of the route. Figures 15–17 show maps generated from the situation illustrated in Figures 13 and 14, respectively. Like in all other cases where no explicit reference point is addressed, we will have to clarify the spatial relations of the known and unknown elements. In the maps, the arrows point to the usually travelled path to the known places which serve as a reference for the particular query. We have chosen arrows because of the absence of established cartographic symbols for individually known elements like places. In Figure 15 we can see a \( \mu \)-mized map, in Figure 16 we can see a linearised map (as in illustration 2 in Figure 21) and finally in Figure 17 we can see a linearised navigation map (illustration 5, Figure 21) with the start environment at the bottom.

5.5. Route contains path

We say a route contains a path, if both places of a path are part of the route, thus the whole path is a sub-route of the queried route (Figure 21, illustration 3). In this case we can assume that a wayfinder will recall the path and its entities correctly in the sense that he will find his way from the addressed point A to point B. There have been

![Figure 15. \( \mu \)-Map.](image1)

![Figure 16. Linearised map.](image2)
investigations on how people describe a known way to unfamiliar travellers by means of sketch maps (e.g. Tversky and Lee (1998, 1999)). These investigations show that surprisingly people remember the paths accurately. We aim at another type of support: instead of addressing an unfamiliar wayfinder, we want to address a familiar wayfinder that has the same knowledge as the assistant. This has particular consequences for the schematisation: we can interpret the results of the mentioned studies in a way that the assistant has good knowledge of the route; there is no indication that this knowledge will be affected by schematisation, especially if the frame of reference is clear. The key elements are the places addressed by the path, and not the layout, which in this case is irrelevant for the wayfinder. Figure 18 illustrates the relation of UE/PFE, Figure 19 shows the generated $\mu$-map and Figure 20 depicts the linearised navigation map with the start environment at the bottom. In both maps the places are indicated with solid dots, the circles indicate the start point and the destination of the route.

5.6. Route is contained by path

Strict linearisation has a huge drawback: due to its abstraction from the actual layout, it will not provide the spatial configuration within the environment. In the case when the route is completely covered by a path (or multiple paths), we have to make clear where the queried places are located within the PFE (Figure 21, illustration 1). Waller et al. (2001) showed that the relative distance between landmarks is an important property for people
during wayfinding. Note that these findings could be interpreted as to disprove our
corcepts. But we have to consider that the experimental setup was designed not to tell the
subjects about the intentionally distorted distances. Agrawala and Stolte’s (2001) usability
results show that people can use LineDrive maps properly, since they know about the
schematisation and are able to interpret the map correctly. Furthermore, we can interpret
both findings constructively: people can still use a highly schematised map (e.g. strictly
linearised) if the relative distances between the required entities are met. This means, if we
make clear where the queried places are located within the path in terms of relative
distance to significant entities like places, landmarks or major structural elements (like main roads,
junctions, etc.) we can use a linearised representation.
5.7. **Route overlaps path**

In this case one queried place is within the PFE, the other is located in the UE (see Figure 21, illustration 2 and Figure 22). This constellation requires the consideration of the different assistance types and configurations: in case the user navigates, and the start place is within the PFE, and the user is currently within the PFE, we can assume that he will be aware of it. This means, we only have to indicate the direction ('go to the university') and, starting at the transition area, we have to generate a map for UE (see Figure 23, the start environment at the bottom). In the converse case, when the wayfinder is in the UE and queries an unknown location within the PFE, we will have to assist him in the UE, and we have to indicate the location of the queried place within the PFE. If the user is not navigating and queries a place within the PFE, we can infer that he is not aware of this fact and have to indicate its respective location (see the μ-map in Figure 24). The direction of the other place in the path is indicated with the black arrow. In both maps, the start place and destination of the route are depicted with the solid circles.

6. **Discussion and further work**

In this article, we showed how different maps of the same geographic space can be generated with respect to the configuration of the previous knowledge and the route,

![Figure 22. Route overlaps path.](#)

![Figure 23. μ-Map with start place in the UE.](#)
as well as the assistance scenario. The consideration of these relationships is important for the selection of the introduced schematisation principles linearisation and \( \mu \)-mizing. We have seen that the resulting maps contain significantly less information than the corresponding survey maps and it is clear that this is a valuable property for mobile mapping. However, we did not consider how these maps can be optimised for different layouts and sizes of displays. Depending on the actual size of the target display we can, for instance, determine the size of the level of detail for the \( \mu \)-mizing process, which includes not only the size of the path but also the size of the environment of the start and target region. Furthermore, we can optimise the route selection according to the route which results in the smallest map.

But will users be able to navigate with these maps? As any complex symbolic representation, people will have to learn the meaning of the depicted elements. To test whether the proposed schematisation will be interpreted as intended can only be shown by a usability study. The implementation of a user study under realistic conditions is an extensive task. If we want to test \( \mu \)-maps partially incorporating known paths, we will have to collect the trajectories of multiple persons for several weeks or months, and to label and analyse them. After the data acquisition phase, we will have to conduct individual wayfinding tasks to test the performance of the maps. Obviously, this is a major task, raising questions of general feasibility and privacy. On the other hand, simplified tests, with prior negotiation about familiar and unfamiliar parts of the environment, can have massive influence on the results: the user profile is not built-up successively, which means that an examination of paths and places does not occur as intended. Additionally, by means of the negotiation, the subjects are clearly biased to the identified entities.

A third option is testing in virtual reality. In a virtual world, we have ideal training and test conditions: we can ensure that every user is a novice to the virtual environment. This means, we can ensure the absence of a prior knowledge-based bias. Virtual worlds offer full control over tracking, learning conditions, labelling, and finally tests with maps covering the acquired knowledge for all possible scenarios. Besides all positive properties of a virtual environment, we have to face their problems as well: the navigation performance is usually affected by the involved controllers, the learning of virtual worlds is assumed to be different – and the most important point – long-term studies are not

Figure 24. Linearised navigation map with start place in the PFE.
possible due to ‘simulation sickness’. This sickness occurs after a comparable short time in virtual worlds and is explained by the missing interaction of the visual and vestibular system. To sum up, testing of personalised maps is difficult due to required individual knowledge. However, we believe that testing is important and will help to sharpen the externalisations of personalised maps. We propose an open evaluation similar to the testing of LineDrive Maps (Agrawala and Stolte 2001). With the increasing availability of position aware mobile phones and personal GPS trackers, people now have the possibility to integrate user profiling and assistance within their daily routines. Tests under real life conditions will clearly show whether personalised wayfinding assistance is desired by people or not. And by means of channelled feedback prototypes can be further improved towards general applicability.

So far it is not clear if the transition between the two frames of reference, namely the frame of individual knowledge and the geographic frame require either a strict separation or tight integration. These areas can be the crux for successful map understanding. Furthermore, so far it is unclear whether there exist conceptual primitives for the transition areas, such as wayfinding choremes (Klippel 2003) for turns. Such regularities in spatial conceptualisation would clearly foster an intuitive understanding of the information.

Wayfinding assistance based on the integration of previous knowledge has to be as effective as traditional wayfinding assistance. This especially means that it has to be based on routes which are accepted by the intended users. The acceptance will largely depend on the direct comparison between the ease of the cognitive load and quantitative measures, like distance and time. If we can identify the (most probably individual) border between these two extremes, we will have made a huge step towards the applicability of knowledge-based wayfinding assistance.

Knowledge-based strategies can also play a role in meeting the problem of ‘mindless’ wayfinders as described by Parush et al. (2007). They assume that the problem with turn-by-turn navigation assistance is the low level of required examination of the environment during the navigation. This causes the weak learning observed with subjects. They propose to actively involve the user in the wayfinding process. The level of granularity given by navigation devices does not have to be fixed at the finest level of granularity as offered by today’s devices (every required turn is announced). This means, the level of granularity can be connected to the assumed level of knowledge of the user: if a route contains a sub-route a user has travelled in the past, the system can adjust the instructions to only relevant elements (either the major points of reference or the critical parts of a route). In order to generate suitable assistance, this system needs an individual user profile (which is able to differentiate between possible users, in case the device is shared) and it will need to access and communicate contextual information related to a known route.

7. Summary

Due to the positional awareness of mobile devices (like mobile phones), mobile map-based wayfinding assistance is gaining significant importance. But mobile devices have small and constrained display possibilities. However, the visualisation of geographic information, such as routes within an environment, can require a comparable large space.
This problem cannot only be attacked by scaling the information to the matching size or to segment the information to a high degree. It has been shown that these methods substantially affect the cognitive processing of the spatial information.

One possible solution to this problem is the transformation of the geographic space according to the knowledge a user has of this environment. In this article, we demonstrated how prior knowledge can be used to reduce the size of maps and at the same time to preserve the meaning for a particular user.

We discussed that there is no ‘schematisation that fits all’, as the different basic relations of the route with known and unknown parts of the environment require different mutual referencing. Additionally, it is beneficial to adapt the schematisation to the assistance type, like navigation or pre-trip planning. By differentiating between these two scenarios, we were able to further simplify and compress the visual output. We discussed the requirements of most combinations of relations between the possible relations between familiar/unfamiliar parts and the type of assistance. Following on from these considerations, we sketched the algorithmic basis to generate knowledge-based maps. The integration of individual previous knowledge with the route planning process requires the consideration of the intended strategy. We introduced an algorithm which is able to identify a route with minimised parts within the unknown parts of the environment and an optimal route incorporating familiar paths.

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