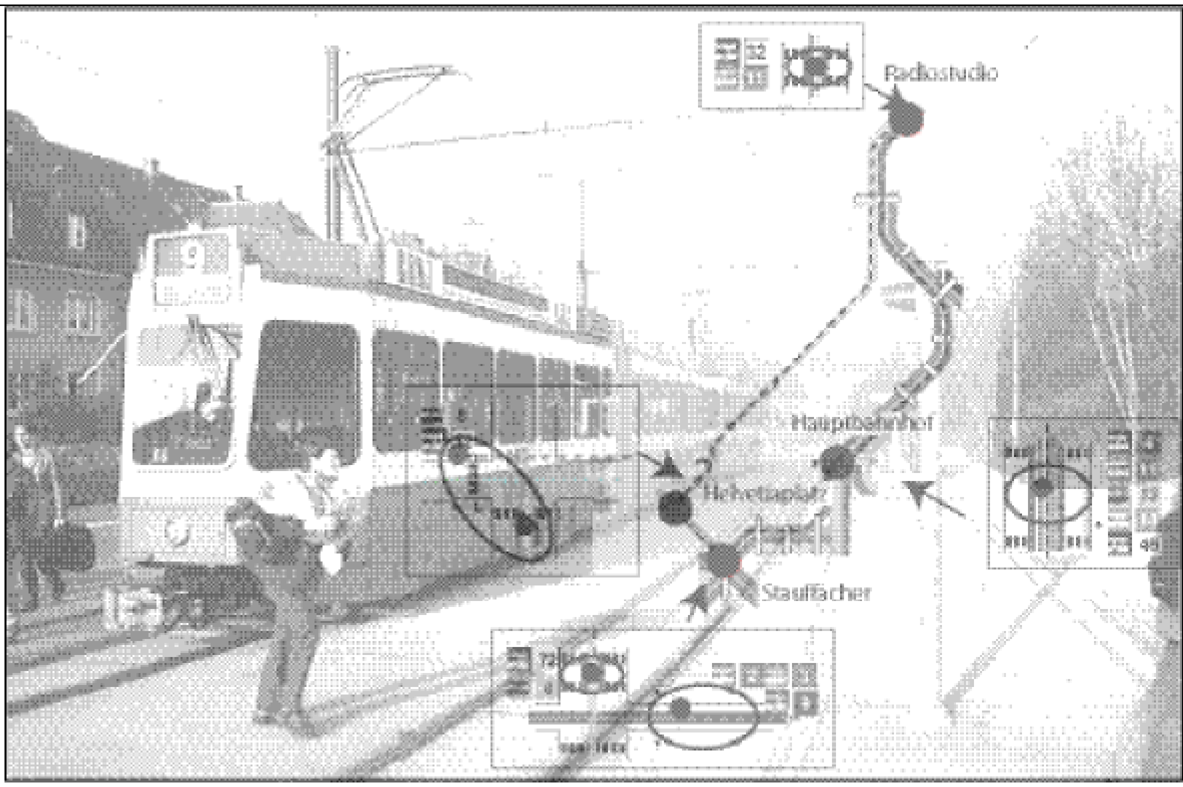

Factors influencing the physical complexity of routes in public transportation networks

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Title: Factors influencing the physical complexity of routes in public transportation networks

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Abstract

Routing decisions by humans are often made based on other criteria than minimum distance, time or cost. We are interested in determining criteria that influence individual travel behavior. The criterion we study in detail in this paper is the perceived complexity of routes, i.e. the perception of how difficult a chosen route will be. For this paper we focus on the physical complexity of routes as opposed to personal or temporal complexity. The physical complexity relates to the visual access and the spatial layout of the built environment. We report on empirical studies that determine the factors influencing route complexity within the public transportation system of Zurich. We then derive a measure for the physical complexity of routes from these factors.

Keywords

route complexity, route choice, way finding, spatial cognition, public transportation, International Conference on Travel Behaviour Research, IATBR

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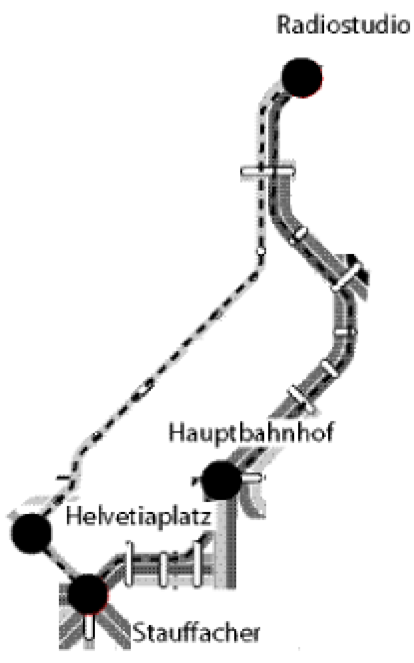
1. Motivation

Routing decisions by humans are often made based on other criteria than minimum distance, time or cost. In figure 1 the route from Radiostudio to Stauffacher via Helvetiaplatz needs the same time and costs the same as the one via Hauptbahnhof. A traveler might not be able to choose between these two routes unless another criterion is introduced into the decision-making process.

The criterion we study in detail in this paper is the perceived complexity of routes, i.e. the perception of how difficult a chosen route will be. This difficulty has an impact on the choice a traveler makes when discriminating between several alternatives.

Figure 1 Example in the public transportation network of Zurich



The research problem is of interest in the context of location-based services, i.e. services that provide information to the traveler based on her[1] current location through the medium of a mobile assistive device. The least complex route would be desirable in order to be able to easily explain routes to travelers. The simplest route may not be the fastest and the traveler might need to make the final decision as to the trade-offs she might be willing to make.

This research is part of a project that models human wayfinding in urban public transportation and proposes a mobile system that can assist the wayfinding process. Thus, we deal with urban navigation, i.e. navigation taking place in a citywide transportation network. For travelers, the most important feature in Public Transportation (PT) is the location at which she can enter or leave the PT system. We are concerned with the perception of these locations, since they play an important role in route choice and route description.

We are interested in determining factors that influence individual travel behavior. Bovy and Stern (1990) describe three objective factors: the physical environment, the socio-demographic environment and normative environment factors. In addition, a subjective factor influences the perception of the three objective factors. In route choice, the physical environment has the largest influence. The same is true for route descriptions or route instructions: the physical environment in the form of landmarks plays the most important role in giving good route instructions (Denis 1997).

In this paper we distinguish between three different aspects of navigation complexity: physical, personal and temporal complexity. Physical complexity refers to potential problems while wayfinding along the designated route. Thus, it refers to the problems inherent in the route that are due to spatial layout and visual access. The second aspect of navigation complexity is personal difficulty, which refers to the strains that are imposed onto the person and depends very much on the fitness of the person. This measure can be used to express special needs (such as walking sticks, handicapped people, person with children, etc.). This measure requires a user model to be developed. The third aspect of navigation complexity is temporal difficulty, which refers to temporal aspects while navigating a specific route (such as rush hour, weather, construction work, etc.). In this paper we will deal with physical factors in a measure for the complexity of routes.

The aim of this study is threefold:

1. derive the physical characteristics of the environment that play a role in the perceived

[1] The use of a single gender is simply for convenience and should be taken as a stand in for both genders.

complexity of a route using a web survey,

2. determine how to conceptually model and represent these physical characteristics for our purposes,

3. and derive a measure for the complexity of the physical environment based on our findings in the survey and on the conceptual model.

In this paper, we are not interested in deriving a measure for the complete network, since this would defy our purpose of determining a human's most likely perception of a specific route. However, we could imagine that a complexity measure for the complete network could be derived as an extension from this work and could be one of the optimization criteria for designers of transportation networks.

The term complexity as used here must be differentiated from the term complexity as used in complexity theory. Complexity theory classifies problems based on how difficult they are to solve. It is thus a measure of computational tractability and does not relate to the cognitively motivated complexity measure we are discussing in this paper.

The paper is structured as follows: section 2 discusses previous work in this area; section 3 presents the empirical study we carried out to determine the factors influencing complexity. Section 4 explains how we represent the important factors of the environment, section 5 derives the complexity measure for routes and transfer points, and section 6 concludes with stating the results and discussing future work.

2. Wayfinding in public spaces

We build on research of Gärling (1986), who proposed a system for classifying environments to predict the extent of wayfinding problems. Weismann (1981) recommended similar classes of environmental variables that influence wayfinding performance (meant for buildings). According to Gärling, the following facets of the environment are important for successful wayfinding:

- degree of architectural differentiation,
- degree of visual access,
- complexity of spatial layout.

The degree of architectural differentiation is less relevant for the public transportation environment than it is for the building literature, except for underground environments. Travelers need to differentiate between different transfer points, but this is usually made easy with signs stating the name of the station. By design those names are unambiguous within a specific transportation system. For our specific case study each station differs from others by the environment in which they are set.

Visual access is important for the traveler. The start and end node of a route within a city are usually not visually accessible from a single vantage point, because the space we are dealing with is at a geographic or environmental scale (Montello 1993). Visual access is important anywhere along the route, however it is especially important within transfer points. Travelers need to be able to see the stop where they are supposed to board the transportation means. We expect this factor to be prominent in the results of the user survey.

The complexity of spatial layout refers to the environmental size and the number of possible destinations and routes. “A simple layout should facilitate both the formation and execution of travel plans by making it easier to choose destinations and routes, to maintain orientation, and to learn about the environment “(Gärling 1986). The complexity of spatial layout and visual access are linked: a complex layout may mean a visually cluttered environment; conversely a visually legible environment may not mean a simple layout.

Lynch (1960) has emphasized the importance of the legibility of the environment, of which visual access is one part and maybe the complexity of spatial layout another. Good legibility of the environment improves spatial orientation and thus wayfinding.

Raubal (1998) determines the complexity of wayfinding tasks in built environments (i.e. airports) using image schemata found in the physical structure of the environment. Our approach is different from his in that we describe the physical structure of the environment in order to derive a measure for complexity that is independent from the human person actually perceiving the environment. However, we take into account those physical structures that are known to have an impact on human wayfinding and orientation abilities (Gärling, 1980) without using image schemata. It would be beneficial to compare our results with the results from a wayfinding model as proposed by Raubal.

In Raubal and Worboys (1999), image schemata are augmented with action and information affordances (Gibson 1986) to describe the physical environment as perceived by a human. This results in a wayfinding graph. The nodes of the wayfinding graph represent states of knowledge and the current location, whereas links represent transition between those. The notion of visual access might be represented with the wayfinding graph. We may investigate the derivation of a simple measure for visual access via the wayfinding graph in the future.

3. Empirical Study on factors influencing route complexity

The aim of this paper is to derive a measure of how difficult or complex a given route will be under present circumstances. We are looking for a method of assessing the physical complexity while planning and optimizing a route. The route runs from a start stop to a goal stop, this means that the traveler is already inside the public transportation system. In this study we will not deal with the problem of getting to and from locations outside of the system.

We assume that in public transportation systems, complexity arises only at transfer points. Once a transportation means has been boarded, the complexity is reduced to zero, since no other action can be taken other than getting off. In this survey, we will thus focus on the factors that determine the perceived complexity of a transfer point.

Each physical characteristic of a transfer point may have a different impact on the complexity of a transfer process. We need to elaborate which physical characteristics have an impact at all and how great their contribution is to the complexity of the transfer process. We performed a *web survey* to analyze the influence from each characteristic of a transfer point to the transfer process and the influence of the transfer itself for the complexity of a route. The most important advantage of a web survey is that a great number of persons can be reached with a low budget. We targeted experts on the public transportation system in Zurich, which are able to assess the transfer process at the different transfer points.

The web survey was carried out on the main web site of the Public Transportation Authority Zurich (VBZ), where travelers may look for actual timetable information. A pretest took place on the website of the Department of Geography half a year before the main survey. 164 members and students from the Department of Geography at the University of Zurich participated.

The questionnaire is divided into two main parts: the first and most important part deals with the analysis of the transfer process in public transportation systems and the second part contains questions characterizing the participants (for more detailed information and the complete survey see Heye 2002).

A few notes on the survey: We tried hard to generate information that can be generalized. However the participants live and work in Zurich and some of the answers may be due to particularities of the Zurich public transportation system. We are aware of this and will take it into account in our treatment of the complexity measure. We also plan to calibrate the measure using Zurich as an example and then apply the measure to other PT systems, such as Munich and London.

3.1 Design of the survey

Before participating in the survey most participants had never thought about the criteria that make a transfer point more complicated than another. So our first task was to sensitize the participants for the objective without manipulating them in one direction or another. After two introductory questions we let them choose the more complicated one from seven pairs of transfer points (question no. 3). The pretest showed that it is rather important to choose transfer points that are well known. So we chose mainly transfer points that are located in the centre of Zurich. There were two different kinds of pairs. Either transfer points were equal in all physical characteristics except one, or they had at least two great differences, e.g., one with much more incoming and outgoing lines versus the second with longer distances. The idea of question (no. 3) was only to sensitize, it was not planned to evaluate it directly. After thinking which transfer point could be more complicated than another, the participants answered the open question (no. 4) about the main criteria they used for the decision-making. The majority of the participants of the pretest answered quite precisely and detailed. So we were encouraged to adopt these proceedings for the main survey.

The next question (no. 5) contained 14 statements about the transfer process, e.g., “It bothers me to make a transfer”, and of the most important characteristics of a transfer point, e.g., “I avoid steps”. To force the participants to take an unequivocal stand, they had to choose between four different categories of agreement. Then another open question (no. 6) followed, which asked participants suggest how to make the transfer process more comfortable for the travelers.

3.2 Results of the survey

The answers on the first open question (no. 4) show that the physical characteristics have in fact a decisive influence on the complexity of a transfer point. 80% of the participants mentioned physical characteristics; two thirds even mentioned physical characteristics exclusively. Not even a tenth mentioned personal or temporal variable factors (Table 1). With circa 120 answers each the most important criteria are the *distance between two stops* and *streets to cross*. Only 45 participants named distance as well as streets to cross. The number of lines and the signage is much less important. Interesting is also that 32 participants mentioned that the existence of a transfer from bus to tram makes transfer points more complicated. So the multimodal wayfinding seems to be in fact a greater challenge.

Table 1 Important criteria for the classification of the transfer points, open question (22 missing values)

		number of answers
physical	transfer between the stops within a transfer point	125
	streets to cross	113
	signage	55
	number of lines	33
	change between bus and tram	32
	compactness	25
	number of directions	21
	roundabout way	16
		6
	clear arrangement	104
personal	security	27
	connections	25
	knowledge about the transfer point	13
	many persons / stress	8
	others	13

The risk of an open question is always that many participants choose not to answer at all or answer in a universally valid manner. But in this case only 22 participants preferred not to answer. 105 participants mentioned a *clear and open transfer point*. There remains the question what makes a transfer point clear and open. Fortunately only 7 persons mentioned this criterion without any other criteria. Mentioning "overview about the transfer point" is significantly depending[2] on mentioning "streets to cross as transfer" and not depending on "longer distances", whereas the last two are depending on each other. So the conclusion is obvious, that longer distances have only a great impact on the complexity, if there are also streets or other barriers to cross.

[2] The distribution was tested by a Chi square test (significance level: 95%).

The importance of the physical characteristics for the complexity becomes affirmed by the results of the given statements concerning the transfer (question no. 5). Two thirds of the participants perceive the physical barriers as discommoding. More than three fourths of the participants do not like longer distances between the stops or that they cannot see the point where they need to go to (Table 2).

Table 2 Percentage of agreement of the statements concerning the change

	statements concerning the transfer procedure	agree [%]
physical	I avoid steps	68
	Longer distances disturb me.	85
	During the transfer I don't like to cross streets.	60
	It bothers me if I am not able to see where to enter the next transportation means.	74
	I like it better to cross a street at a traffic light than using an underpass or a bridge.	75
	It makes no difference to me how a transfer point is constructed.	11
	The signage at the transfer points in Zurich is sufficiently informative.	73
	I don't like underpasses at any time of the day or night.	60
	Underpasses are unpleasant for me at night.	81
general	It bothers me to change transportation means.	49
	Changing a transportation means is stressful for me.	30
	Transferring two times is too much.	56
	I would accept a roundabout way or longer traveling time, if I wouldn't have to transfer at all.	37

The criterion "an open area" is more or less the same as "I would prefer to overview the whole transfer point". Ninety percent of the participants agree with this statement. The mention of an open area and the agreement of this statement are significantly depending on each other. Both depend again on agreeing with the statement that non-visible points in a stop disturb the transfer process. If a stop is well known, the number of lines and the non-visible stops in a transfer point become significantly less important.

For more than half of the participants the transfer process represents a disturbing factor in using public transportation systems. The survey results show clearly that time is an important factor within the routing algorithm to develop. Only one third of the participants are willing to accept a roundabout way to avoid a transfer.

Overall a transfer point with short paths represents one type of ideal transfer point. In the next open question (no. 6, asking for improvement suggestions) there are many mentions of shorter paths (Table 2). This attracts attention, because most improvement suggestions concern better information. More than half of the participants ask for better signage or electronic boards. Only one third call for construction measures. Better connections seem to be of vital importance. So the average waiting time is a factor that adds to route complexity.

3.3 Characterization of the participants

The second main part contained strongly standardized questions for the age, sex and the state of health respectively the existence of disabilities to characterize the participants. Furthermore we wanted to know how frequently the participants use public transportation. It is also important to know if the participants are using public transportation only on the way to work or also additionally during their spare time.

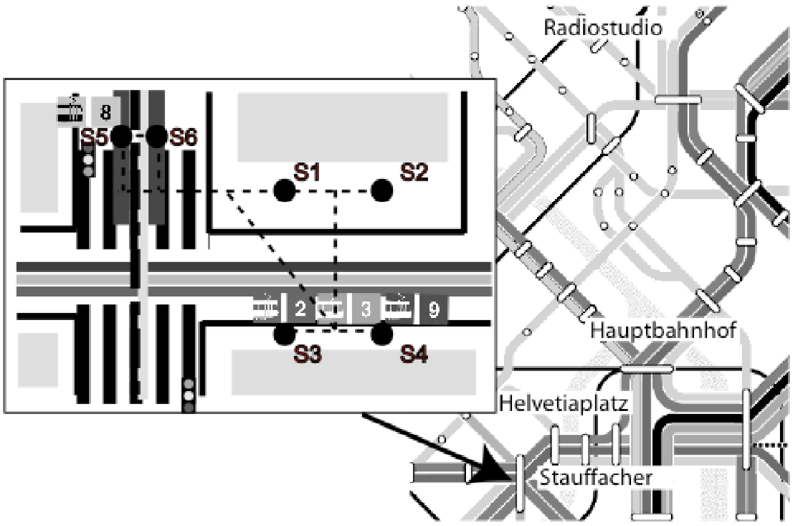
Altogether 298 persons participated. As expected, there was an above-average quota of younger males because of the web survey. Nearly two thirds of the participants were younger than 36 years and more than three quarters were male. The majority of the participants lives (69%) and works (82%) in Zurich. So the knowledge about the location Zurich is quite high. Nearly 90% of the participants were familiar with Zurich. More than two thirds commute to work with public transportation in wintertime as well as in summertime. Also during the spare time the major part of the participants uses the public transportation system quite often. There were only a few persons with special requirements. Only very few persons stated that they were traveling with baby buggies or others bulky goods and had disabilities. The composition of the participants is quite homogeneous. Therefore the impact of different personal attributes is rather small. So we have a homogeneous group using public transportation in Zurich. After the complete analysis it would be very interesting to evaluate the influence of personal attributes on the perception of physical characteristics at transfer points.

This survey did not need to be representative of the population or of the user of public transportation in Zurich, because the target group was a group of experts on the public transportation, which was able to assess the transfer processes at the different stops in Zurich. So the main disadvantage of a web survey, i.e. that the majority of web users are younger and male, does not influence the results of our survey.

4. Representation of the physical environment

For the computation of the complexity measure we need to represent the needed features of the physical environment in a database. As is customary, the network of the public transportations system can be represented as a directed multi-graph. The nodes represent the transfer points and the edges represent the lines between the transfer points. However, we need to represent more detail within the transfer points. This detailed information can also be represented as a directed multi-graph with the stops represented as nodes and the footpaths represented as links. Therefore the network of the urban public transportation system in our study is a two-stage hierarchical graph (Figure 2) as already discussed in Timpf (2002). This hierarchical structure has been recognized in the form of local views and paths between views in Kuipers TOUR model (1977).

Figure 2 Hierarchical graph



The additional information that we need at the detailed level, such as crossings, visibility, and distances, can be added as attributes to the links of the graph, similar to a topological map. In addition the information on the number of stops and the number of incoming and outgoing lines for each stop needs to be recorded within the transfer point.

5. A measure of route complexity

The third aim of this paper is to derive a measure for the complexity of the physical environment based on our findings in the survey and on the conceptual model. According to our survey, the physical complexity is influenced by the number of possibilities to change a transportation means, by the number of stops within the transfer point, by the visibility of the stops, by the distances between the stops, and by the number of barriers between stops. Thus, the route complexity is mostly influenced by the complexities of the transfer points along the route.

The measure of accessibility in graph theory gives us a way to deal with the complexity measure. The accessibility index of a node or vertex is measured as the sum of the number of links connecting this node to every other node in the network. Each additional link adds to the accessibility. The complexity of a transfer point is linked to the accessibility of the corresponding node in the network. Complexity also deals with the accessibility of the transfer point, but solely from the next neighbors. This corresponds to the degree of the node in the graph. In addition, what goes on inside the transfer point needs to be added to this measure. This is our motivation for calculating the route complexity as a sum of the complexities of the transfer points along the route:

Route Complexity $CR = \sum_{j=1}^{r} CS_j$

with CS: complexity of a single transfer point,

CR: complexity of the route,

r: number of concerning transfer points.

This decision gives us the freedom to add weights to each additional factor to account for personal preferences in a latter stage of the research.

5.1 Transfer point complexity

In the survey the following factors were identified as influencing transfer point complexity:

1. the number of stops within the transfer point
2. the number of potential changes of transportation means, i.e., the number of incoming and outgoing lines at each stop within the transfer point,

3. the visibility of the stops,
4. the number of barriers between stops, i.e., the street crossings, and
5. the distances between the stops.

We can incorporate these factors into our measure in the following way: the number of stops (point 1) plus the degree of each stop (point 2) plus the complexity of each link (points 3 and 4). In our measure we include the two strongest influences on the perception of transfer point complexity, i.e., the number of street crossings and the number of invisible stops. Distance alone (point 5) does not have a big influence on complexity, unless in conjunction with street crossings, which is the reason we left it out. This results in the following measure of complexity of a transfer point:

$$CS \approx n + \sum_{i=1}^{n} CP_i + \sum_{j=1}^{m} CW_j$$

with: n: number of stops
m: number of links
CP: complexity of a single stop
CW: complexity of link between two stops.

5.2 Route dependent transfer point complexity

The previous section defined the transfer point complexity from all stops and links that exist in the transfer point. However, some of the stops and links of a transfer point are irrelevant for the process of transferring from one line to another. In order to account for this, the measure needs to be calculated from those stops and links being touched by the route:

$$CS^r \approx n^r + \sum_{i=1}^{n^r} CP_i + \sum_{j=1}^{m^r} CW_j$$

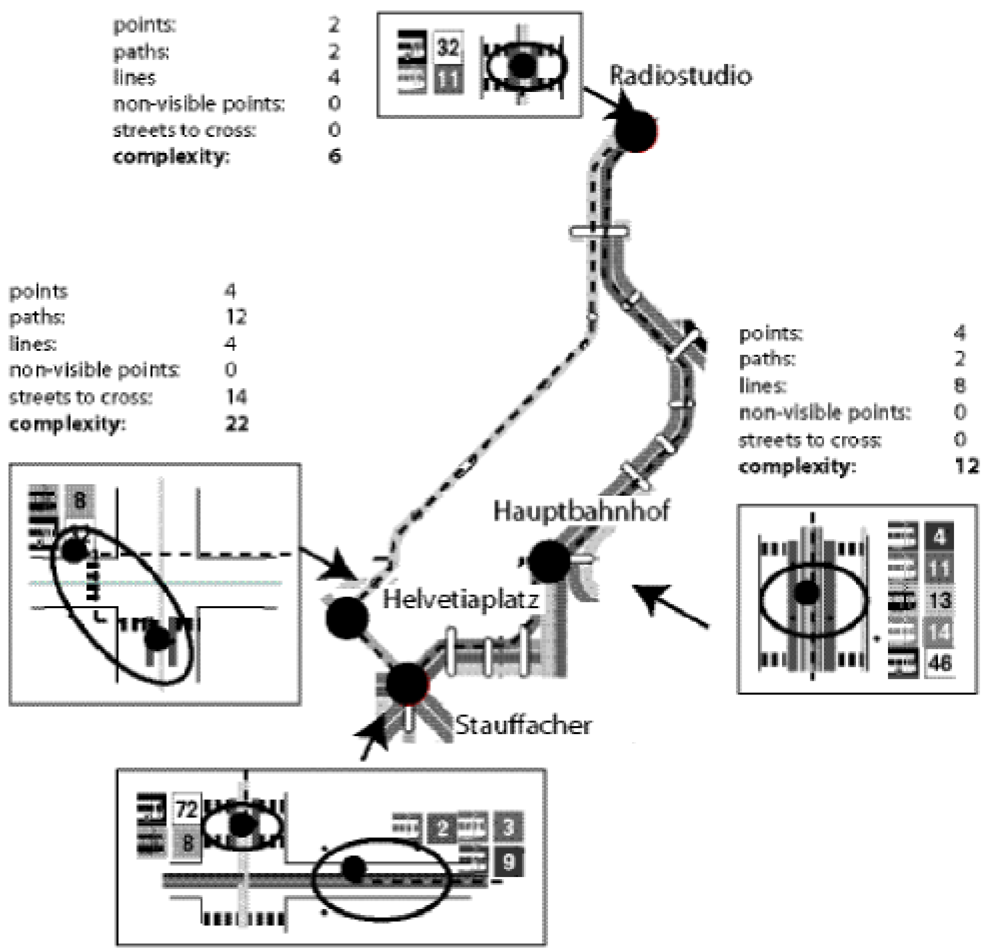
with: n^r: number of stops being part of the route
m^r: number of links within the route
CP: complexity of a single stop
CW: complexity of link between two stops.

In the case of large transfer stations, this reduces the number of stops and links dramatically.

5.3 Application of the complexity measure to a route choice situation

Figure 3 shows an example in the public transportation system of Zurich, where a user needs to travel from the transfer point “Radiostudio” to the transfer point “Stauffacher”. The route finder on the web (www.vbz.ch) provides two alternatives. Both routes take 22 minutes and contain one transfer process. The starting point is a simple transfer point. The other three are more complicated.

Figure 3 complexity of a transfer point for specific route



According to our *route independent complexity measure*, the route via “Hauptbahnhof” is the less complex route of the two. The route complexity of route 1 is 38 and the route complexity of route 2 is 28.

According to our *route dependent complexity measure*, the routes are virtually indistinguishable. The route complexity of route 1 is 15 and the route complexity of route 2 is 16. Route 1 runs via the transfer point “Helvetiaplatz”. Helvetiaplatz is a relatively complex transfer point, because two streets are crossing and on both bus and tram lines run. The route runs such that the whole transfer point must be crossed. Route 2 goes through the transfer point “Hauptbahnhof”, where many lines depart. However within this transfer point only a small part is relevant for the route. So this transfer point becomes relatively easy, because there are no streets to cross and the whole transfer point can be overviewed immediately. The final station does not add to the complexity if we assume that we will stay within the transportation network.

6. Results, conclusions, and future work

We have shown how a complexity measure for physical complexity of routes can be calculated based on information on the environment at transfer points and on information on the network structure. We have also shown that for a meaningful complexity measure for routes, two different levels of detail need to be considered, especially within the transfer points of the route.

The complexity measure incorporates the following results of our user survey for the public transportation system in Zurich. The physical characteristics of a transfer point play a greater role than anticipated; about 80% of the information mentioned refers to physical features. The physical complexity is influenced by the number of possibilities to change a transportation means, by the number of stops within the transfer point, by the visibility of the stops, by the distances between the stops, and by the number of barriers between stops.

Our first approximation of physical complexity of transfer points includes among others the two strongest influences on the perception of complexity: the number of street crossings and the number of invisible stops. Distance alone does not have a big influence on complexity, which is the reason we left it out.

For each route the complexity of a transfer point changes depending on the stops and links used for calculation. This requires that information on all physical factors be represented explicitly in the database. For our route search algorithm, this means that a pre-calculation of complexity weights for nodes and links is not possible. However the route independent complexity measure might be used for the reduction of the complexity in the whole network.

We have made the assumption that in public transportation systems, complexity arises only at transfer points. Once a transportation means has been boarded, the complexity is reduced to zero, since no other action can be taken other than getting off. One could argue that the number of in-between-stops adds to the complexity. It would be simple to add the number of stops along a line to the complexity measure.

We developed a complexity measure that has the form of a sum. The sum is a good approximation of the perceived complexity. We expect to be able to weigh each factor to account for personal preferences. This concurs with the framework of Bovy and Stern (1990), where the physical characteristics are influenced by personal perception. To determine the weights more research is necessary in the area of user modeling or user profiling.

In the past months we have been collecting data for 50 transfer points in the central area of Zurich to build up a database. With this database we will be able to calculate the different complexities of routes. We can also explore what weight each physical characteristic has within the sum in order to correspond to humans rating of a route (e.g., we already know that the influence of distances is dependent on the street crossings, the type of crossing might make a difference to the influence, etc.). In addition, we will be able to adapt the formula according to personal preferences.

As an add on study we would like to survey the role of the frequency of service of the different lines, i.e. the average waiting time per transfer. Many of the answers in the survey included some reference to temporal reasoning. We believe that the waiting time and offered services at a transfer station may play an important role in route choice.

7. References

Bovy, P.H.L., and Stern, E. 1990. Route Choice: Wayfinding in Transport Networks. Studies in Operational Regional Science. Dordrecht: Kluwer Academic Publishers.

Denis, M. "The Description of Routes: A Cognitive Approach to the Production of Spatial Discourse." *Current Psychology of Cognition* 16 (1997): 409-458.

Gärling, T., Laitila, T., and Westin, K., eds. 1998. *Theoretical Foundations of Travel Choice Modeling*. Amsterdam: Elsevier.

Gärling, T., Böök, A., & Lindberg, E. (1986). Spatial orientation and wayfinding in the designed environment: A conceptual analysis and some suggestions for postoccupancy evaluations. Journal of Architectural and Planning Research, 3, 55-64.

Gibson, J. J. (1986). The ecological approach to visual perception. London, Lawrence Erlbaum Associates.

Gluck, M. (1991). Making Sense of Human Wayfinding: Review of Cognitive and Linguistic Knowledge for Personal Navigation with a New Research Direction. In: Cognitive and

Linguistic Aspects of Geographic Space. D. M. Mark and A. U. Frank. Dordrecht, The Netherlands, Kluwer Academic Publishers: 117-135.

Golledge, R., ed. 1999. *Wayfinding Behavior: Cognitive Mapping and Other Spatial Processes*. Baltimore: John Hopkins University Press.

Golledge, R. G. (1995). Path Selection and Route Preference in Human Navigation: A Progress Report. In: Spatial Information Theory-A Theoretical Basis for GIS. A. U. Frank and W. Kuhn. Berlin-Heidelberg-New York, Springer. 988: 207-222.

Heye, C. (2002). Deskriptive Beschreibung der Ergebnisse der Internetbefragung: Umsteigen an Haltestellen der VBZ. Bericht an die VBZ. URL: http://www.geo.unizh.ch/~cheye/

Kuipers, B.J. (1977), "Representing Knowledge of Large-Scale Space."

Montello, D. R. (1993). „Scale and Multiple Psychologies of Space“. In: Spatial Information Theory: Theoretical Basis for GIS. A. U. Frank and I. Campari. Heidelberg-Berlin, Springer Verlag. 716: 312-321.

Raubal, M. and M. Worboys (1999). „A formal model of the process of wayfinding in built environments“. In: Spatial Information Theory - cognitive and computational foundations of geographic information science, Stade, Germany, Springer-Verlag, LNCS 1661.

Raubal, M. and M. Egenhofer (1998). "Comparing the complexity of wayfinding tasks in built environments." Environment & Planning B 25(6): 895-913.

Timpf, S. (2002). "Ontologies of Wayfinding: a traveler's perspective." Networks and Spatial Economics 2(1): 9-33.

Winter, S. (2002). „Modeling Costs of Turns in Route Planning“. Technical Report. Vienna, Institute for Geoinformation, Technical University Vienna.