Judging Spatial Relations from Memory

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Abstract. Representations and processes involved in judgments of spatial relations after route learning are investigated. The main objective is to decide which relations are explicitly represented and which are implicitly stored. Participants learned maps of fictitious cities by moving along streets on a computer screen. After learning, they estimated distances and bearings from memory. Response times were measured. Experiments 1 and 2 address the question of how distances along a route are represented in spatial memory. Reaction times increased with increasing number of objects along the paths, but not with increasing length of the paths. This supports the hypothesis that only distances between neighboring objects are explicitly encoded. Experiment 3 tested whether survey knowledge can emerge after route learning. Participants judged Euclidean distances and bearings. Reaction times for distance estimates support the hypotheses that survey knowledge has been developed in route learning. However, reaction times for bearing estimates did not conform with any of the predictions.

1 Introduction

Psychological research on spatial memory has used a number of different methods. One particular method is the judgment of distances between locations. The present chapter reports results from three experiments. These experiments tested specific hypotheses about how subjects perform distance estimates from memory in the context of route learning. Before turning to the experiments we briefly discuss the logic behind the use of distance estimation in research on spatial memory.

In a general sense, space consists of objects and distances in between. In mathematics a *metric space* is defined as a set of objects (i.e., points) and a function assigning a positive real number to each pair of points. This function has to satisfy three axioms (symmetry, positive definiteness, and the triangle inequality). Therefore, a space can be fully described if the objects and the inter-object distances are given. Hence it is not unreasonable that psychological research on space perception and on spatial memory has focused a great deal on judgment of distances.

The general situation can be characterized as follows: On the one side we have the *physical space*. Or, to be more precise, we have those aspects of physical space that a theory under consideration selects as being relevant for spatial behavior. Second, we have a set of processes that extract information from physical space. Third, we have storage processes that build a *memory representation* from visual perception. And finally, in a psychological experiment, there is a set of *decoding processes* used by the subject to fulfill the experimenter's requirements. Hopefully, these processes also reveal something about the form of the mental representation cognitive psychologists are interested in.

Distance judgments have received so much attention because researchers hope that it might be possible to “measure” subjective space or to “measure” the mental representation using distance judgments as a measuring device. If we knew the structure of the mental representation, then we could see, for instance, how spatial memory is used in navigation. We also may be able to present spatial information more efficiently, design better instruments, and develop help systems like geographic information systems.

There are, however, serious problems. These problems arise because, at the outset, there are too many unknowns. It will not be possible, without additional assumptions, to identify both the structure of the representation and the processes working thereupon. This is possibly the reason why psychologists have been looking for analog representations. A great deal is known about the processes which transform physical space into perceptual representations. If we can assume that the processes working on the mental representation resemble the perceptual processes to some extent, then interpretation of results becomes much easier.

Research on distances in mental representations, henceforth cognitive distances, has taken two approaches. One is judgments of distances. Several methods have been used to obtain distance judgments. The experiments reported in this chapter are examples of this approach and the discussion presented here will focus on distance judgments.

The second approach uses what has been called the *spatial priming paradigm*. By measuring response times in recognition experiments researchers tried to identify cognitive distances (McNamara, Ratcliff, & McKoon, 1984; Wagener & Wender, 1985). More recently, however, this approach has undergone some severe criticism (Clayton & Habibi,1991; Wagener, Wender, & Rothkegel, 1997).

1.1 Types of Distances

From a psychological point of view we have to distinguish between several kinds of distances because it appears that quite different psychological processes are involved when these distances are assessed. With respect to *distance perception* we restrict ourselves to the visual modality here. It is obvious, of course, that spatial information can be obtained through other senses as well (like hearing or touching). The visual modality has been used in most investigations. It must be mentioned, however, that kinesthetic sensations, as experienced while walking, also play a role in perception of distances. Furthermore, there is apparently an interaction between kinesthetics and vision (Wagener, 1997), and activities carried out during learning may also have an influence (Mecklenbräuker, Wippich, Wagener, & Saathoff, this volume).

Distance perception: People do not perceive distances per se, rather distances are seen between objects. This gives rise to the first distinction between *egocentric* and *exocentric* distances. Egocentric distances are distances originating from the observer. That is, the observer perceives the distance between himself or herself and one point in the environment.

Exocentric distances refer to distances between two objects other than the observer. However, it must be specified what constitutes an object. Distance perception and perception of length are closely related. If we speak, for example, of the length of a rectangle such as a sheet of paper, we mean the distance between the two corners of one of its sides. This is where perception of exocentric distances and perception of *size* become almost indistinguishable.

There is evidence that egocentric and exocentric distances are perceived differently. For example, Loomis, Da Silva, Philbeck, & Fukusima (1996) found that egocentric distances in the range from 1.5 m to 12 m were judged quite accurately. This was measured by having participants walk, with their eyes closed, to an earlier viewed location. Yet in the same experiment, observers produced substantial errors in the comparison of exocentric distances.

Research on egocentric distances goes back to the 19th century. For egocentric distances, several variables have been identified that contribute to the perception of depth, that is, to the perception of egocentric distances. Most important are the vergence of the eyes, the visual angle, binocular disparity, the texture gradient, and changes in retinal position produced by movements, the so-called optical flow (cf. Baird, 1970; Foley, 1980; Gogel, 1993; Gilinsky, 1951; Cutting, 1996). For the present context, two main results are of interest: (1) visual space is not a linear transformation of physical space (Luneburg, 1947); (2) short physical distances are overestimated, whereas longer distances are underestimated. If one fits a power function between physical distances and distance estimates, the exponent of the function is frequently less than one (Kerst, Howard, & Gugerty, 1987; Wender, Wagener-Wender, & Rothkegel, 1997).

If we accept that spatial memory contains analog representations, an interesting question is: Which of these depth cues play also a role when judging distances from memory? As of yet, not much research has been done along these lines.

Exocentric distances are apparently not just differences of egocentric distances. This is not even the case when the endpoints of the exocentric distance to be judged lie on a straight line originating from the observer (Loomis et al., 1996).

With respect to exocentric distances further cases have to be distinguished. Exocentric distances corresponding to a line in a horizontal plane or to a line in a vertical, frontal parallel plane are judged differently from distances corresponding to lines in oblique planes. The latter, so-called 3D-lines, are obviously more difficult to judge and judgments are reportedly more in error.

With regard to perception, another important distinction has to be made. First, there are distances that can be seen at once by the observer. That is, the observer can perceive the whole distance without changing his or her position, even without moving the eyes. These distances have been called *perceptual distances* (Baird, 1970). They have to be to distinguished from distances which require the observer to change position, turn around, or travel around some visual barriers.

Perceptual distances have to be further subdivided. There is evidence that distances close to the observer, approximately within reach, are judged differently than longer distances. For longer distances, there may be another relevant distinction between points not too far away and distances that are really far such as buildings close to the horizon and astronomical objects (Higashiyama & Shimono, 1994). It appears that untrained observers are almost unable to judge very long perceptual distances with some degree of accuracy. There may exist an upper bound corresponding to the largest distance that can be reliably judged by an observer (Gilinsky, 1951).

In contrast to perceptual distances there are distances that cannot be perceived without moving around. Examples would be distances within a neighborhood, or on a campus, in the center of a small town, or even in a large supermarket. To evaluate such distances, obviously memory comes into play. Such distances have been called *environmental distances* by Montello (1988).

Again, for environmental distances, it matters how long they are. Small distances that are within walking range will be judged differently from distances that are experienced during a longer drive or flight. Apparently, not only the length of the distance matters but also the way it is experienced, i.e., the mode of transportation over the distance.

1.2 Modes of Learning

According to our hypothesis, distance estimation from memory is made using the mental representation of spatial information. Insofar as the spatial representation depends on the mode of learning, distance estimates will be affected. There are several ways in which spatial information can be learned. Perhaps the most natural way is by navigating through the environment (by walking, driving, etc.). It is conceivable that different modes of navigation result in different mental representations.

Knowledge of environmental distances, which is acquired by direct experience in environments, may be derived from multiple, partially redundant information sources. These sources are (1) number of environmental features, (2) travel time, and (3) travel effort or expended energy (cf. Montello, 1997).

Number of features has been the most frequently discussed source of environmental distance information, where features would be any kind of object in the environment that is perceptible - visually or in any other modality - during locomotion. Substantial empirical support exists for number of environmental features as an important source of distance information (cf. Sadalla, Staplin, & Burroughs, 1979).

Travel time also seems to be an important piece of information for environmental distance, for example, separation between places is often expressed in temporal terms. Surprisingly, nearly all of the empirical evidence on the relationship of travel time to subjective distance is negative (e.g., Sadalla & Staplin, 1980). It should be noted that nearly all of the studies concerned with the influence of travel time have been carried out with small experimental configurations and short temporal duration. Also, it should be noted that in a model of travel time and subjective distance, subjective speed should be considered.

Travel effort, that is, the amount of effort or energy a person expends while traveling through an environment, is a third potential source of information. Journeys that require more effort might be judged longer in distance. Although this idea is appealing, there is little clear evidence for the role of effort as a source of distance information. Possibly, to demonstrate the influence of travel effort, longer trips under a larger spatiotemporal scale may be necessary.

The role of environmental features in distance knowledge is most strongly emphasized by the existing empirical evidence. Further empirical support is needed to investigate the role of travel time and travel effort. In this regard the investigation of environments with larger spatiotemporal scales seems necessary.

A second mode of learning spatial information is from texts. A text may be explicitly written as a route description, yet also narratives describing some events convey spatial information because events take place in space (and time). There has been a substantial amount of research on how people acquire spatial information from texts (Bower & Morrow, 1990; Taylor & Tversky 1992; van Dijk & Kintsch, 1983; Wagener & Wender, 1985). The general conclusion has been that the same mental representations are built regardless of whether the information is perceived by viewing or by reading.

A third way to learn spatial information is by reading maps. This can be a very efficient way when entering a new area. There are, of course, individual differences. Reading a map immediately leads to survey knowledge. A lot of psychological research has been done by using maps as stimulus materials. The question is whether map reading and traveling lead to the same representation. Many researcher implicitly have assumed that they do. Nonetheless, there are also authors with a different opinion (c.f., Chown, Kaplan, & Kortenkamp, 1995).

Finally, psychological experiments have used different techniques to present spatial stimuli like photographs, slide shows, video tapes, and more recently, virtual reality. There is some research comparing the different modes of presentation although many questions are still unresolved.

1.3 Methods of Judgment

The results of distance estimation from perception or from memory do furthermore depend on the experimental method that is used to obtain the estimates. We can distinguish between verbal and nonverbal methods. In verbal methods, the subject has to respond by providing an estimate either directly on a scale like meters or in comparison to a second stimulus as in ratio or magnitude estimation. In contrast there are nonverbal methods where observers have to choose between several comparison stimuli or have to produce an analog estimate (using a caliper for example) or have to walk a distance. There is evidence that verbal and nonverbal techniques do not give the same results and that nonverbal techniques are more accurate (Leibowitz, Guzy, Peterson, & Blake, 1993).

1.4 Survey Knowledge from Route Learning

Spatial knowledge can be obtained by navigating through an environment or a configuration of objects (Antes, McBride, & Collins, 1988), it can be acquired from maps (Denis, 1996) or by reading or hearing verbal descriptions of spatial settings (Franklin & Tversky, 1990; Morrow, Bower, & Greenspan, 1989; Wagener & Wender, 1985). These different sources of information about spatial layouts may lead to differences in the resulting spatial knowledge.

According to a widely adopted model (Siegel & White, 1975) spatial learning in an environment usually takes three consecutive steps. At first, landmarks are learned and then their spatial and temporal connection. The connection of landmarks leads to route knowledge which is contrasted to configurative or survey knowledge (Evans, 1980; Hirtle & Hudson, 1991; Levine, Jankovic, & Palij, 1982; Moar & Carleton, 1982; Siegel & White, 1975; Stern & Leiser, 1988). Additional effort is necessary for the development of survey knowledge from route knowledge.

A new environment (e.g., after having moved to a new city) is usually learned by navigating through this environment. This implies that the environment cannot be seen as a whole, but different objects or landmarks will be learned in a certain order.

Learning a new environment from a map, on the other hand, permits the direct retrieval of spatial relations between objects or landmarks without reference to the routes connecting them (Thorndyke & Hayes-Roth, 1982). As the acquisition of information and the information itself are different for route learning and map learning, it may be hypothesized that these differences will show in the spatial representation. Using a priming technique, some researchers found effects for different sequences of learning objects in a spatial configuration (Herrman, Buhl, & Schweizer, 1995; Wagener-Wender, Wender, & Rothkegel, 1997).

Increased experience through traveling affects the content of the memory representation. As one travels and becomes more familiar with a variety of routes through an environment, points of intersection for multiple routes may be identified. Along with knowledge about route distances and knowledge of compass bearings along the routes, a reorganization of the spatial representation into a survey representation may be supported. Thus, direct retrieval of spatial relations between points (landmarks) without reference to the routes connecting them seems possible (e.g., Thorndyke & Hayes-Roth, 1982). Empirical evidence supporting this notion has been presented by Appleyard (1970) and Golledge and Zannaras (1973) in natural environments. For instance, survey knowledge improved with longer residence in a community and also in experimental settings (Allen, Siegel, & Rosinski, 1978; Foley & Cohen, 1984). Thorndyke and Hayes-Roth (1982) compared judgments of distances, orientations and locations of objects in an office building for secretaries and research assistants who worked in the office building and students to whom the office building was not familiar. Whereas the secretaries and research assistants had acquired their knowledge of the building solely from navigation, the students had acquired knowledge of locations solely from studying a map. Employees who had worked at the office building for only a short time could judge Euclidean distances between different rooms in the building only by estimating the lengths of the component legs on the routes connecting the rooms and the angles between different legs on the route. Students who had acquired their knowledge about the building through a map had no problems in judging Euclidean distances. The Euclidean distance judgements of employees who had worked in the building for a longer time resembled the results of the students who had learned the map.

So far, the results support the notion that survey knowledge may develop out of route knowledge. But this view is also criticized in recent publications. Montello (in press) argues against a strict sequence of modes of representations. In his view, survey knowledge can develop in parallel to route knowledge (see also Chown, Kaplan, & Kortenkamp, 1995). Bennet (1996) goes one step further in questioning the evidence for survey representations. According to his view, there is no study that demonstrates conclusively that mental maps exist at all, in either humans or animals.

1.5 Implicit Versus Explicit Representations

The question of which aspects of space are preserved in mental representations is an important topic in the research on spatial representations. The possible answers range from topological spaces, where only neighborhood relations are encoded, to richer metric spaces, where spatial relations are represented at an interval scale level (or even higher).

Although in this chapter some results concerning these questions are reported, the main focus is slightly different. The primary question addressed here is not at what scale level spatial relations are represented in mental representations, but rather how they are stored and retrieved. Therefore, we introduce a distinction between explicit and implicit representations of spatial relations.

If a spatial relation is explicitly encoded, there is a chunk in memory from which the spatial relation of interest can be read out immediately. There is no need to integrate different information, and the information is already separate from other, irrelevant information. An example of an explicitly encoded spatial relation would be the proposition “the distance between Bonn and Trier is 150 km”.

In contrast, if a spatial relation is implicitly encoded, there is no chunk in memory that stores this and only this relation. Rather, the information has to be computed (in a loose sense of the word) by integrating relevant bits of information while ignoring irrelevant information. One example of an implicitly stored spatial relation is distance information in a mental image of a spatial configuration. In this case, distances could be computed by mental scanning from one point to the other, and taking the time needed as a measure for the distance in question (e.g., Kosslyn, Ball, & Reiser, 1978). It is important to note, however, that the implicit-explicit dichotomy does not map to the distinction between analog and propositional representations. It is easy to construct examples of propositional representations, where some of the spatial relations are stored implicitly. For instance, if route knowledge is represented by a set of propositions encoding distances between neighboring objects, distances between objects that are not direct successors on the route are implicitly encoded. They have to be computed by integrating interobject distances between neighboring objects along the path. If Euclidean distances have to be computed, angles along the paths must be taken into account (Thorndyke & Hayes-Roth, 1982).

In the experiments reported below, the time needed to judge spatial relations is used to test hypotheses concerning representations and retrieval processes of spatial relations. Depending on the representation-process pair, different variables should affect reaction time for these judgments.

2 Experiment 1

Experiment 1 addresses two issues, a methodological one and a theoretical one. The methodological question we tried to answer with this experiment was whether reaction times for distance estimations are useful for testing hypotheses about representations and processes involved in this task. The theoretical question was, given that reaction time is a suitable measure, what types of representations and processes are actually involved in distance judgments.

In research on spatial memory, little use has been made of reaction times for spatial judgments (e.g. McNamara et al., 1984). Most studies in this field dealing with reaction times are spatial priming studies where participants had to decide as fast as they could whether an item was present in a previously learned configuration or not (McNamara, 1986; McNamara, Hardy, & Hirtle, 1989; McNamara, Ratcliff, & McKoon, 1984; Wagener & Wender, 1985; Wagener-Wender, 1993; Wender & Wagener, 1986; Wender & Wagener, 1990). While these studies were conducted to test hypotheses about spatial representations, the judgments do not necessarily reflect spatial judgments since it was sufficient to remember only whether the presented item was in the learned set or not (Clayton & Habibi, 1991; Hermann, Buhl, & Schweizer, 1995; Sherman & Lim, 1991; Wagener, Wender, & Rothkegel, 1997).

In Experiment 1, participants were asked to judge distances between objects along the shortest possible path. Path length and number of objects on the path were used as independent variables. Depending on the representation and processes involved in this task, different outcomes would be expected. If distances are explicitly encoded, reaction time should be independent of both path length and number of objects. If distances have to be computed by combining explicitly stored distance information for neighboring objects (henceforth *summation model*), reaction time should increase with increasing numbers of objects. If distances are estimated using a simple mental scanning process, reaction time should be positively related to path length. Thorndyke´s (1981) *analog timing model* would predict increasing reaction times with both increasing number of objects and increasing path length.

The design of Experiment 1 also allows us to examine the scale level of the metric object positions along a path are represented in. If positions are represented on an ordinal scale, distance estimates should only be a function of the number of objects along a path. If, in contrast, positions are represented on an interval scale, distance estimates should be affected by the length of the path.

2.1 Method

Participants. A total of 35 Persons (20 female, 15 male) participated in the experiment. Most of them were psychology students at the University of Trier. They were given course credit for participation.

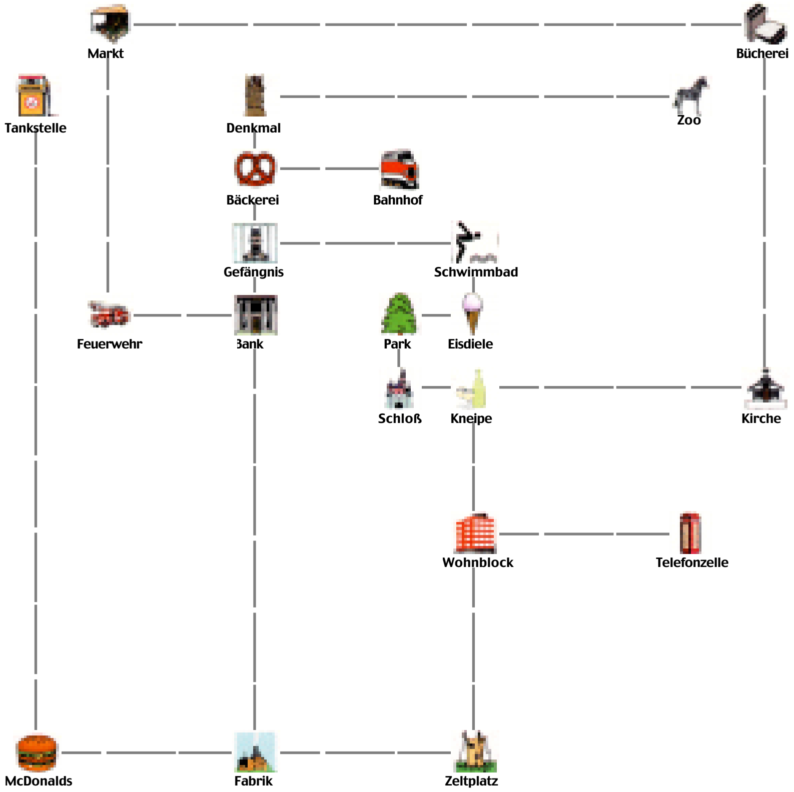

Fig. 1. Spatial layout used in Experiment 1

Material. The spatial layout that participants were required to learn was a map of 21 objects. The objects were small pictures with names listed below them. All objects were items that can occur in a town. The objects were connected by dashed lines symbolizing streets. There was at least one route connecting every pair of objects.

The experiment was carried out on a Macintosh PowerPC 7100 with a 14-inch Apple color monitor connected to it.

In the navigation phase, a small part of the map was displayed in a 6.5 by 6.5 cm large window. Maximally two objects could be visible at once in this window. A small black dot was present in the center of the window, symbolizing a taxi. By pressing the arrow keys on a Macintosh extended keyboard, participants could “move” the taxi up, down, left, or right along the dashed lines on the map. Movement was simulated by scrolling the visible part of the map, while the location of the window and the location of the dot relative to the window was kept constant.

Design. The main dependent variable in this experiment was reaction time for distance judgments. In addition, distance judgments themselves were analyzed. The major independent variables were path length and number of objects. Path length refers to the shortest distance between two objects along the route. Number of objects refers to the number of objects between two objects along the shortest possible route. Both variables were varied independently in three steps, resulting in a 3 x 3 factorial design. Path length was either 3, 6, or 9 units. Number of objects was either 0, 1, or 2. Both factors were within-subject factors. The map was constructed in a way to ensure that two critical location pairs existed for every combination of path length and number of objects.

Each participant received the same map of locations and paths, but objects were assigned randomly to the locations for each participant. In the distance estimation task, all participants had to estimate distances for the same set of location pairs, but the order of items was randomized for each participant.

Procedure. Experiment 1 consisted of four phases: navigation phase, learning check, distance estimation, and map drawing.

Participants were told to imagine that they had moved into a new town and that they wanted to work as a taxi driver in this town. Therefore they had to learn the shortest routes from any object to any other object.

Navigation Phase. Participants were allowed to move freely along the streets with the goal of learning the shortest routes between the locations in the town. They were also told they had to estimate route lengths at a later time. There were no time restrictions for the navigation phase, but participants were told that we expected learning to last about 30 minutes.

Learning Check. Immediately after the navigation phase, participants´ knowledge of the map was tested. On each trial a pair of object names was presented. Participants´ task was to write down the names of all objects along the shortest path connecting the presented objects on a sheet of paper. They were told to write down the names in the order of appearance along the path. After writing down the names they had to hit the return key to see the correct solution. They had to check their answer against the solution and press the “R” key if the answer was correct. In this case the next items were presented. If the answer was wrong, they had to press the “F” key. Whenever they hit the “F” key, participants were automatically put back into the navigation phase, where they had to visit all objects along the correct path before returning to the learning check. They were told they could press the return key as soon as they had visited all objects along that path or that they could also stay longer in the navigation phase if they wanted to improve their knowledge about the map. The learning check consisted of 9 probes. In the first set of 3 probes, the path between the presented objects contained 1 object. The solution for the second set of 3 probes encompassed 2 objects, and for the third set, three objects were included.

Distance Estimation. In the distance estimation task, participants were presented two objects, one at a time. First, the anchor object appeared in a dialog window. Participants were instructed to imagine the position of the anchor in the map and to press the return button as soon as they were fully concentrated. After the return button was pressed, the dialog window disappeared, and two seconds later the target object appeared in a new dialog window. Now participants had to estimate the distance between the anchor and the target as quickly as possible. They were told to use the length of one dash found in the dashed lines that symbolized the streets as the unit of measurement, that is, they were told to estimate how many dashes were on the shortest possible route between the anchor and the target object. To avoid counting strategies during the navigation phase, participants were told the unit of measurement only at the beginning of the distance estimation phase. They were instructed to respond verbally and to press the return button simultaneously. Reaction time was measured from the onset of the target stimulus presentation until the return button was pressed. After the return button was pressed, the dialog containing the target object disappeared and a third dialog was presented, where participants had to enter their estimates on the keyboard. Each participant had to answer 21 probes. The first 3 probes served for practice purposes and were not included in the analysis.

Map Drawing. At the end of the experiment participants were asked to draw a map of the routes on a sheet of paper.

2.2 Results

Informal inspection of the route maps showed that most maps were in close correspondence to the stimulus maps. Only the maps of four participants showed a strong deviation from the stimulus map, therefore, their data were removed from further analysis. After inspection of the response time distributions, an outlier criterion of 12,000 ms was set.

Figure 2 shows mean reaction time as a function of path length and number of objects. For the smallest route length, number of objects does not have any effect on reaction times. For route lengths 6 and 9 reaction time increases with increasing number of objects. An ANOVA with the factors “path length” and “number of objects” yielded a significant effect for the number of objects factor, $F(2,23) = 24,97$, $p < .001$. There was no significant effect for the path length factor, $F(2,23) = 0.50$, $p = .61$, but the interaction reached significance, $F(4,21) = 6.58$, $p = .001$.

The same analysis was conducted for distance estimates as the dependent variable. Figure 3 shows mean distance estimates as a function of path length and number of objects.

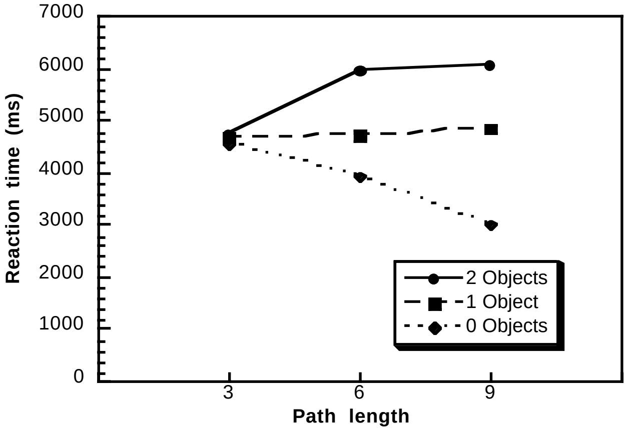

Fig. 2. Mean reaction times as a function of path length and number of objects on the path in Experiment 1.

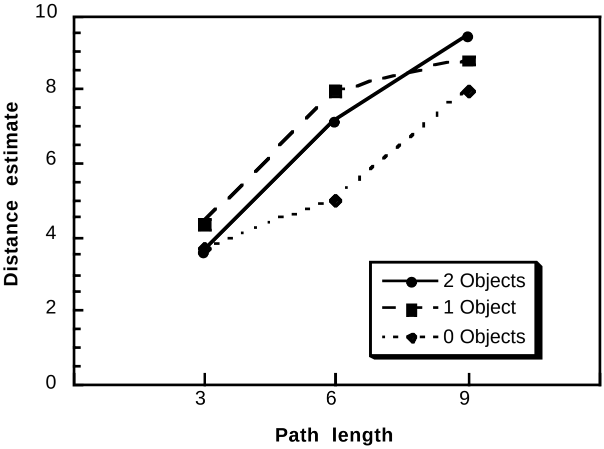

Fig. 3. Mean path length estimates as a function of path length and number of objects on the path in Experiment 1

Path length estimates were analyzed in the same way as reaction times. Figure 3 shows that distance estimates are sensitive to the actual path length, F(2,29) = 163,43, p <.001, and the number of objects, F(2,29) = 23.19, p < .001. The interaction was also significant, F(4,27) = 12.27, p = .001.

Figure 3 also shows that short distances were overestimated (by 0.86 on average) while long distances were underestimated (by 0.31 on average).

2.3 Discussion

The results of Experiment 1 show that reaction times for distance judgments are sensitive to variations in the spatial relations to be estimated (e.g. Baum & Jonides, 1979; Denis & Zimmer, 1992; McNamara et al., 1984). Although the reaction times and their variances are much higher than in simple binary choice tasks as in spatial priming studies, they contain enough systematic variation to show reliable effects.

The effect of number of objects is in line with Thorndyke´s (1981) analog timing model as well as with the summation model. But in addition to the effect of number of objects, the analog timing model predicts an increasing reaction time with increasing path length which is not supported by the data. Thus, concerning the main effects, the summation model is the only one supported by the data. Yet the summation model does not predict an interaction between number of objects and path length. In fact, none of the models mentioned above predicts this interaction. We could not think of any model predicting an interaction between path length and number of objects that predicts no main effect of path length. Since one cannot rule out the possibility that the interaction is due to the specific map used in this experiment, we decided to determine whether the effect can be replicated with a different map. This was done in Experiment 2.

Although the effect of the number of objects on reaction time is in line with the hypothesis that distances along a route are determined by summing distances between neighboring objects along that route, a possible alternative explanation cannot be ruled out by these results. It might still be the case that all spatial relations for all possible object pairs are explicitly encoded, but longer time is needed to retrieve this information if more objects are on the path to be estimated. This hypothesis would predict the same pattern of results as the summation model. Therefore, the models cannot be tested against each other with the data from Experiment 1. This issue is also addressed in Experiment 2.

The analysis of path length estimates supports the notion that object positions along the route were represented at a scale level higher than an ordinal scale. Path length estimates were sensitive to variations of actual path lengths while controlling for effects of the number of objects on the path. The analysis also shows that path length estimates tend to increase with increasing number of objects on the path (although two data points are not in line with this; see Figure 3). This result is in accordance with the view that the number of environmental features or "clutter" affects distance estimates (Kosslyn, Pick, & Fariello, 1974; Sadalla, Staplin, & Burroughs, 1979; Thorndyke, 1981). The effect that short distances were overestimated while long distances were underestimated is also in line with evidence from other studies (e.g., Björkman, Lundberg, & Tärnblom, 1960; McNamara & LeSueur, 1989; Wender, Wagener-Wender, & Rothkegel, 1997).

Both effects can be explained with a modified form of the *uncertainty hypothesis* (Radvansky, Carlson-Radvansky, & Irwin, 1995; see Berendt & Jansen-Osmann, 1997, for an alternative model). According to the uncertainty hypothesis, exponents below one in the power function relating estimated distances to physical distances are due to the fact that information about some distances may not be available and has to be provided by guessing. These guesses show a tendency to avoid extreme responses and favor more moderate responses. The result is a regression toward the mean.

To account for the number of objects effect, the uncertainty hypothesis has to be slightly modified. If distances are estimated by summing up distances between neighboring objects along the route, forgetting applies only to these elementary distances. If some of the elementary distances are forgotten and have to be guessed, the sum of elementary distances along a route should also regrade toward the mean. In addition, this modification also allows an explanation of the number of objects effect. If a certain proportion of the elementary distances are forgotten and have to be guessed, they are independent of the actual distances. Therefore, estimated path lengths should increase with increasing numbers of objects along the paths.

3 Experiment 2

Experiment 2 was designed with two goals in mind. The first goal was to replicate the findings of Experiment 1 with a different spatial layout by using the same factors as in Experiment 1. The second goal was to test one further prediction of the hypothesis that distances are estimated by combining elementary distances.

If the calculation of a distance in one trial involves elementary distances that were already retrieved in the previous trial, distance estimation should be faster compared to a condition where in the previous trial an unrelated set of distances was retrieved. This *repetition effect* may be due to easier retrieval of the elementary distances already used before, but it might also be the case that the effort of combining distances is reduced because some of the calculations have already been performed in the previous trial and the result is still remembered.

If a repetition effect could be demonstrated, this could also rule out a possible alternative explanation of the results of Experiment 1. If an increase in reaction time caused by an increasing number of objects on the path to be estimated is due to slower accessibility of explicitly stored distance information, there should be no repetition effects for overlapping paths in subsequent trials.

3.1 Method

Participants. A total of 47 persons (23 female, 24 male) served as participants. They were paid for their participation.

Material. The map used in Experiment 2 was similar to the map used in Experiment 1.

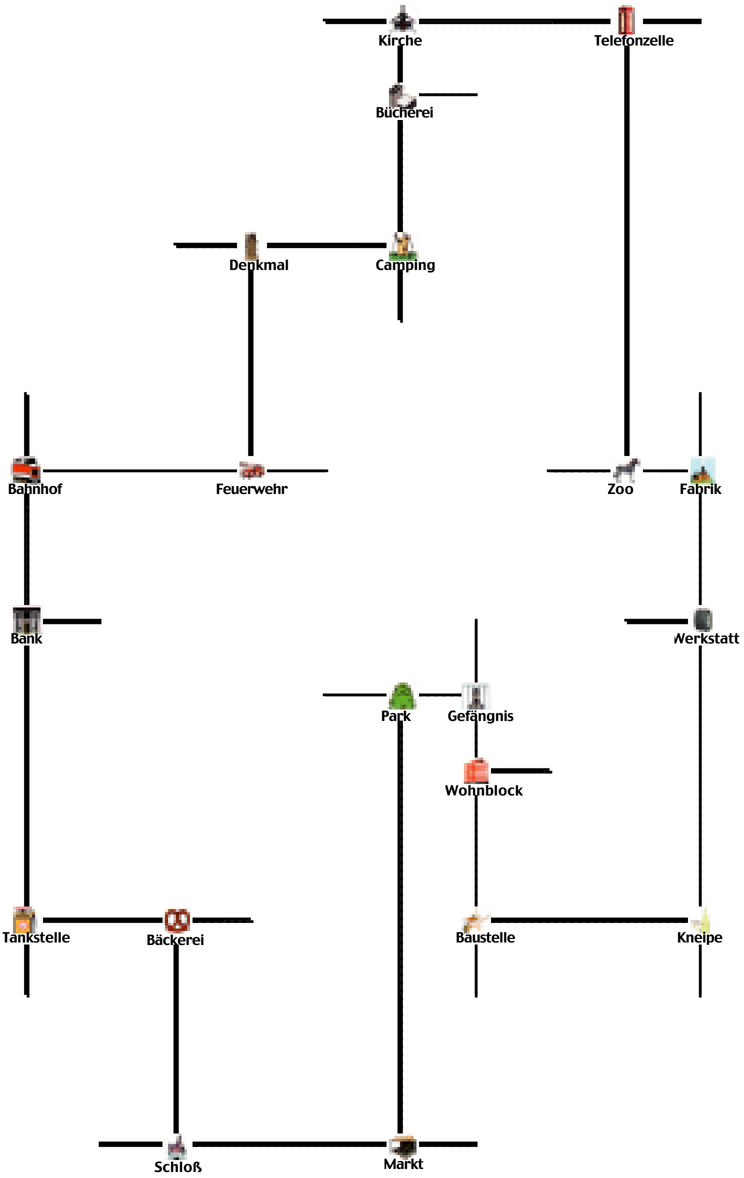

Fig. 4. Spatial configuration used in Experiment 2

There was one closed route connecting all objects. The objects were a subset of the objects used in Experiment 1. They were displayed in the same manner. Each object was placed on an intersection of the street system. One of the streets at an intersection was a dead end, the other street was part of the closed route. All dead ends were of the same length. Streets were symbolized using a thick black line with a dashed white line in the middle. As in Experiment 1, only a small part of the configuration was visible at one time. The sides of the visible square had the same length as a dead end.

Experiment 2 was conducted on a Macintosh PowerPC 7200 computer with a 17 inch Apple 1710 AV color monitor. The technique used for simulating movement was the same as in Experiment 1.

Design. As in Experiment 1, the main dependent variable was reaction time for distance judgments. Judgments themselves were also analyzed. The most important independent variable used in this experiment was path overlap. In the *subroute condition,* the path to be estimated in the critical trial was a part of the path estimated in the previous (preparation) trial. For instance, in an alphabetically ordered list of locations along the path, the length of the path between locations B and D would have to be estimated in the critical trial (see Figure 5).

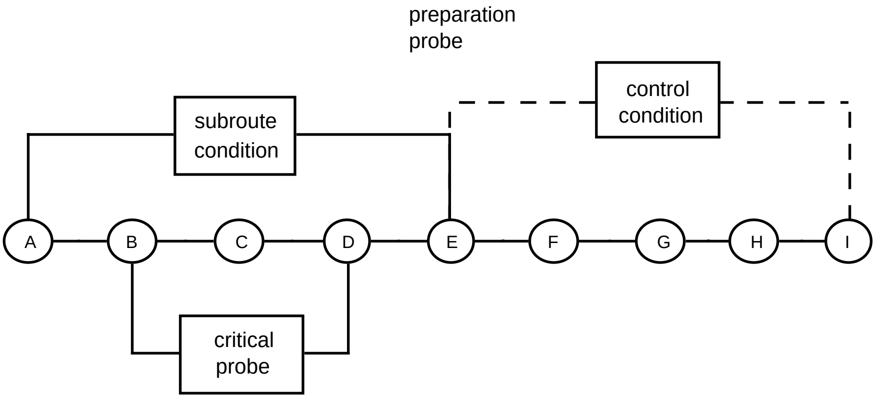

Fig. 5. Example of the paths used in the subroute condition and control condition

In the subroute condition, the preparation trial would have asked for the distance between locations A and E. In the *control condition*, the critical trial was identical to the subroute condition, only the preparation trial differed. To rule out the hypothesis that all distances are represented explicitly and only access times increase with increasing number of objects on the path, the subroute condition should differ from the control condition only in one aspect, namely, the availability of partial route information from the preparation trial. Therefore, we tried to keep possible priming effects constant. Since reaction times were measured with onset of the target object, priming effects are only critical for the target object. Therefore, we tried to keep the nearest distance between the objects presented in the preparation trial and the target object in the critical trial constant. For the example mentioned above, this means that in the preparation trial of the control condition, the path length between locations E and I had to be estimated.

For the critical items, the major independent variables used in Experiment 1 were also used in Experiment 2. Path length was varied in two steps (the length of 3 vs. 6 dead ends, i. e., 14 vs. 28 cm). Number of objects was varied in two steps as well (0 vs. 1 object on the path). All variables were varied independently resulting in a 2 x 2 x 2 factorial design, using within-subjects variation on all factors. There were two critical item pairs for each combination of path length and number of objects. Each critical item pair was presented twice, once in the subroute condition and once in the control condition. The second time a critical item pair was used in a probe, anchor and target were reversed. To reduce repetition effects, the order of probes was randomized for each participant separately for the first and second occurrence, and all item pairs were estimated once before the second occurrence of an item pair. There were a total of 35 probes: 16 critical probes, 16 probes for the preparation trials, and 3 additional training items.

Procedure. *Navigation Phase*. The navigation phase was identical to Experiment 1.

Learning Check. After participants completed the navigation phase, their knowledge of the distances in the spatial layout was tested. Three objects from the city were displayed in a dialog box on the computer screen, one at the top and two at the bottom. They had to judge which of the two objects at the bottom was closer (on the path) to the object at the top. After participants selected an object, they were given feedback. If the answer was correct, the next question appeared. If the answer was incorrect, they were automatically returned to the navigation phase. They had to renavigate to all three objects displayed in the question, but they were also told that they could stay longer in the city to explore it further if so desired. After exploring the map again, they could proceed with the learning check by hitting the return key. The learning check consisted of 10 questions.

Distance Estimation. The distance estimation procedure was identical to Experiment 1 with one exception. Participants were told to use the length of the dead end streets as a unit of measurement, specifically, they were told to estimate how many dead ends would fit into the path connecting a given object pair.

Map Drawing. As in Experiment 1, participants were asked to draw a map of the objects and streets.

3.2 Results

For reaction times on critical items an ANOVA with factors “path overlap”, “path length”, and “route distance” was computed. Reaction times in the subroute condition (M=4631 ms) were shorter than reaction times in the control condition (M=5044 ms), F(1,46)=6.04, p<.02.

Reaction times were also shorter for paths with no objects (M=4445 ms) than for paths running through one object (M=5229 ms), F(1,46)=13.63, p=.001. There was no main effect for the route length factor, F(1,46)=.46. None of the interactions were significant.

The correspondence between estimated path lengths and actual path lengths was quite low. The correlation coefficient computed over all estimates had a mean of .58 and a standard deviation of .30. To test whether the pattern of results changes when only participants with good knowledge of the maps are taken into account, the ANOVA was repeated with the subset of participants with correlation coefficients higher than .50, thus leaving 32 subjects for the analysis. The pattern of results for this subset showed no substantial deviation from the results for the whole group of subjects.

As in Experiment 1, estimates of path lengths were analyzed as well. While there was no significant difference between the subroute condition and the control condition, F(1,46)=.45, distance estimates increased with increasing path length, F(1,46)=36.86, p<.001, and with increasing number of objects on the path, F(1,46)=7.54, p=.009. None of the interactions reached significance (all F<.84). As in Experiment 1, small distances were overestimated (by 0.40 on average) while large distances were underestimated (by 1.16 on average).

3.3 Discussion

Experiment 2 was designed to replicate the findings of Experiment 1 and to test one further prediction. As in Experiment 1, there was a reliable main effect of number of objects on the path to be estimated. The finding that path length has no effect on reaction times is also in line with the results of Experiment 1. Only in one aspect do the results of Experiment 2 differ from Experiment 1. The interaction between path length and number of objects could not be replicated. The interaction found in Experiment 1, therefore, might be due to the specific map used.

With regard to the effect of path overlap, the results corroborate the hypothesis that distances are estimated by summing up distances between neighboring objects. Since priming effects were held constant between the subroute condition and the control condition, this result is at variance with the notion that all interobject distances are stored explicitly and that only access times differ.

With regard to the distance estimates, Experiment 2 replicated the basic results of Experiment 1. As already noted in the discussion of Experiment 1, these results can also be quite simply explained in connection with the summation model.

Taken together with the results of Experiment 1, we conclude that in path learning, distances between neighboring objects are represented explicitly, while distances between objects further apart have to be computed by summing up elementary distances.

4 Experiment 3

Experiment 3 was designed to test whether survey knowledge can emerge from a route learning task by using reaction times for spatial judgments. Participants were asked to judge Euclidean distances after learning a configuration in which Euclidean distance and path length were varied independently. Thorndyke and Hayes-Roth (1982) found evidence that route learners had no survey knowledge in an initial stage of learning. Error patterns of distance judgments, bearing judgments, and positional judgments revealed that participants had to combine the legs of routes to come to an estimate. After extended practice however, their error patterns came close to the ones of map learners.

Experiment 3 uses reaction times to distinguish between route representations and survey representations. If Euclidean distances are estimated by mentally combining the legs of the connecting path, reaction time should be an increasing function of the number of objects on the path. If, on the other hand, a survey representation has been developed where Euclidean distances can be estimated by mental scanning, reaction time should increase with increasing Euclidean distance.

In addition to the verbal distance judgments used in Experiment 1, bearing estimates produced by mouse movements were introduced. This technique was used because we hypothesized that it is a nontrivial task to translate a mentally represented distance into a verbally reported number. We felt that judging bearings on a 360 degree scale using the computer mouse might tap the participants´ knowledge more directly. If reaction times for bearing estimates showed the same results as reaction times for distance estimates, this would corroborate the results from the distance estimates (Montello & Pick, 1993; Sholl, 1987).

Participants learned a map and were subsequently asked to judge spatial relations, that is, distances and bearings. For some critical test items, route distance and Euclidean distance were varied independently.

4.1 Method

Participants. A total of 46 Persons (26 female, 20 male) participated in the experiment. Most participants were psychology students at the University of Trier. They were given course credit for their participation.

Material. A map was constructed as the learning configuration that consisted of 14 objects. The objects were a subset of the items used in Experiment 1. They were displayed in the same way. Each object was connected with two neighboring objects by a dashed line. The lines should symbolize paths connecting the objects. The path formed a closed route. An object was placed on every turn of the route. Experiment 3 was conducted on a Macintosh PowerPC 7100 computer with a 14-inch Apple color monitor.

Design. The main dependent variable used in Experiment 3 was reaction time for spatial judgments (distance estimates and bearing estimates). The estimates themselves were analyzed as well. Type of judgment, path length, and Euclidean distance were the major independent variables used in this experiment. Euclidean distance was varied in two steps. The short Euclidean distance was 6.4 cm, the long one 12.8 cm. As in Experiment 1, path length refers to the shortest distance between two objects along the path. Because it is not entirely clear which aspects of the route affect reaction times if Euclidean distance is estimated by combining distance information along the route, the number of objects along the route and the number of turns were varied together with path length. The short route was 27 cm long, went past two objects, and had three turns. For the long route, these three variables were doubled in value. Type of judgment, Euclidean distance, and path length were varied independently, resulting in a 2 x 2 x 2 factorial design. All factors were varied within subjects.

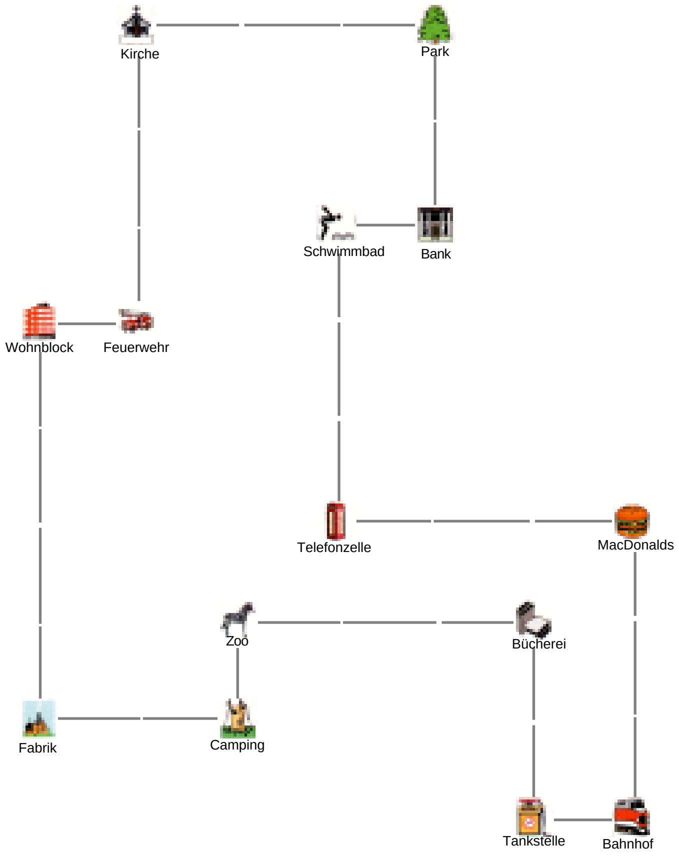

Fig. 6. Spatial configuration used in Experiment 3

Because we wanted to keep the map as simple as possible, only one critical location pair existed in the map for each combination of path length and Euclidean distance. This implies that only four distance estimates and four bearing estimates could be used for the factorial analysis. Because this could mean that the data are not stable enough to register possible effects, additional location pairs were used for distance estimates and bearing estimates. In these additional probes, Euclidean distance and path length were not varied independently. Therefore, they could not be submitted to an ANOVA; instead it was planned to analyze them using partial correlation coefficients. In total, there were 27 probes, three training probes, four probes for the factorial analysis, and 20 additional probes.

To make sure that the bearings to be estimated are independent from the distances in the critical item pairs, the map was rotated in 90 degree steps between subjects meaning that the whole route system for participant 2 was the same as the one for participant 1, except it was rotated by 90 degrees. As in Experiment 1, objects were placed randomly on the locations for each participant. The order of probes was also randomized for each participant and both types of judgments.

Procedure. The experiment consisted of 5 phases: navigation phase, learning check, distance estimation, bearing estimation, and map drawing.

Navigation Phase. At the beginning of the experiment, participants were told that they had to familiarize themselves with a city so that they would be able to estimate crow flight distances and bearings from memory at a later stage of the experiment. They were instructed to use the arrow keys on a Macintosh extended keyboard to navigate through the city. They were also told they could navigate in any direction and change direction as often as they wished. They could explore the city as long as they wished, but were told we expected the learning phase to take about 30 minutes.

Learning Check. The learning check was identical to Experiment 2, with the exception that participants had to base their judgments on Euclidean distance rather than on path length.

Distance Estimation. The distance estimation task was also identical to Experiment 1, again with the exception that participants had to judge Euclidean distances instead of path lengths.

Bearing Estimation. In the bearing estimation task, participants had to judge the direction of a target object compared to an anchor object. On each trial, the anchor object was presented until participants hit the return key. Participants were told to press the return key only after they could imagine the position of the anchor object in the map and were fully concentrated. After the return key was pressed, the anchor object disappeared and a second dialog box appeared with the target object at the top and a bearing gauge at the bottom. The bearing gauge consisted of a circle and a line originating at the center of the circle. The end of the line followed mouse movements. Participants were instructed to move the end of the line out of the circle in the direction to where the target object was situated compared to the anchor object and to press the mouse button as soon as the direction of the line corresponded to the remembered bearing. A similar technique has been used by Shelton and McNamara (1997) to assess bearing estimates after varying amounts of imagined rotation of the observers from the original viewpoints.

Map Drawing. As in Experiment 1, participants were asked to draw a map of the objects and the connecting route on a sheet of paper.

4.2 Results

To eliminate subjects with poor configurational knowledge from the analysis, distance estimates were correlated with actual distances in the configuration for each subject. Subjects with correlation coefficients lower than .50 were excluded, leaving 28 subjects for further analysis. Informal inspection of the map drawings revealed that the excluded subjects were also the ones with the lowest correspondence of the drawn maps with the stimulus maps.

For the critical items an ANOVA with factors “type of judgment”, “path length”, and “Euclidean distance” was computed. Only the Euclidean distance factor reached (marginal) significance, F(1,27)=4.08, p=.053. Reaction times for distance estimates and bearing estimates were higher for location pairs with large Euclidean distances than for location pairs with small Euclidean distances.

In addition to the ANOVA, correlation analyses were conducted for the entire set of items (excluding training items). Partial correlations of reaction times for distance judgments and bearing judgments with path length as the predictor were computed in which the effect of Euclidean distance was partialled out. Likewise, Euclidean distance was used as a predictor while partialling out effects of path length. Reaction times for distance judgments increased with increasing Euclidean distance, r=.41, p<.01. Path length did not reveal any influence, r=-.05, p=.74. For bearing estimates, the partial correlation yielded a marginally significant decrease of reaction times with increasing Euclidean distance, r=-.29, p=.08. Again, route distance did not show any linear effect, r=.16, p=.54. To examine whether the decrease of reaction times with increasing Euclidean distance in the bearing judgments goes along with decreasing errors, absolute deviations of the bearing estimates from the actual bearings were correlated with Euclidean distances. This analysis revealed a decrease of estimation errors with increasing Euclidean distance, r=-.40, p<.01.

4.3 Discussion

The distribution of correlations between participants´ distance estimates and actual distances shows that participants had difficulties judging Euclidean distances after route learning. This is not surprising, since combining distances and angles along a route to compute Euclidean distances is a nontrivial task. Since participants with correlation coefficients lower than .50 were excluded from further analysis, the results only apply to participants who were able to achieve this goal more or less satisfactorily. However, the main question pursued in Experiment 3 was not whether persons are able to judge Euclidean distances accurately after a route learning task, but rather whether persons use a route representation to form Euclidean distance estimates, or are able to form a survey representation before estimating Euclidean distances. In both cases, distances and angles along a path have to be combined mentally. The difference only concerns whether the results of these computations are integrated into the spatial representation or not. If the Euclidean distance estimates have to be computed from distances and angles along a route for every judgment, the time needed for the judgment should increase with increasing number of information to be integrated. In contrast, if participants are able to form a survey representation in form of a mental image, they are able to judge spatial relations between pairs of objects by mental scanning. In this case, the time needed to come to an estimate should be a function of Euclidean distance. Indeed, the results of the distance estimation task support the notion that participants were able to form a survey representation. Both the analysis of variance and the regression analysis show increasing reaction times with increasing Euclidean distance and no effects of route distance.

With regard to the bearing estimation task, the picture is not so clear. While in the analysis of variance there is no evidence that the pattern of results in the bearing estimation task is different from the distance estimation task, the correlation analysis shows a decrease of reaction time with increasing Euclidean distance. The decrease of errors with increasing Euclidean distance shows that this is not an artifact in form of a speed-accuracy tradeoff. Thus, for bearing estimates, the results of the analysis of variance clearly contradict the results of the correlation analysis. This leads to the question of which analysis can be trusted more. On the one hand, the data used in the ANOVA are better controlled for possible artifacts. For instance, by the between-subjects rotation of the entire map the factors are not confounded with the bearings to be estimated. On the other hand, much more data are used in the correlation analysis. The results of the correlation analysis support neither the predictions for survey representations nor for route representations.

One possible explanation might be that in spatial representations, the positions of objects are represented in areas of uncertainty. This is claimed by Giraudo and Pailhous (1994). This implies that bearings and distances between objects also have intervals of uncertainty. For distances, the intervals of uncertainty are independent of the distances themselves (as long as the uncertainty regions do not overlap). In contrast for bearings, the intervals of uncertainty decrease with increasing distances. If participants tried to keep a certain level of accuracy independently of the distance, this could mean that reaction times for bearing estimates increase with decreasing distance. Although this explanation is highly speculative, it provides a possible account for the dissociation of reaction times for distance estimates and bearing estimates.

The results of bearing estimates parallel the results of the distance estimates with regard to the effect of path length. None of the analyses revealed any effect of path length. Thus, while there is no support for route representations, there is at least some support for survey representations. However, this should not be taken as evidence that survey knowledge arises spontaneously whenever people learn routes. It is quite conceivable that people navigating more complex routes that are not closed without the goal of being able to judge Euclidian distances and bearings never develop a survey representation.

5 Conclusions

The experiments reported above use reaction times for spatial judgments to test hypotheses about the representation of spatial relations. All experiments show that reaction times for these judgments are sensitive to variations in the spatial properties of the relations to be judged.

Experiment 1 and 2 deal with distance estimates along a route. The results support the notion that in route learning, only distances between neighboring objects are represented explicitly, while distances between objects that are not direct successors on the route have to be mentally computed.

Experiment 3 uses reaction times for bearing estimates and distance estimates to test whether survey knowledge can emerge in a route learning task. While reaction times for distance estimates supported this notion, reaction times for bearing estimates neither conformed to the predictions made for survey representations nor to the predictions made for route representations. Thus, at least for the dissociation in reaction times for distance estimates and bearing estimates, one cannot help but state that further research is needed to resolve this issue.

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