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What makes a route appear longer? An experimental perspective on features, route segmentation, and distance knowledge

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Five experiments performed in a desktop virtual-reality setting investigated the influence of environmental features—that is, noticeable landmarks along the route—on distance estimation. Landmarks were of two types: Either they simply "filled" the route or they "filled" and also segmented it, thereby inducing a hierarchical structuring of the route. Previous research had left the question open of whether a filling or a segmenting feature leads to an overestimation of a distance along the route. Our experiments showed different results dependent on the kind of space: If an environment was learned from a route perspective, filling and segmenting environmental features led to overestimations of distances, while the segmenting of a route induced by a grouping of similar features did not. If the environment was learned from a map that afforded a survey perspective, route structuring induced through a segmenting feature or by phenomenal grouping led to an overestimation of distances, whereas features that merely filled the route did not.

In everyday life, knowledge of the distance between two places is important because it helps people to better plan their way. This knowledge, which we call distance knowledge, allows people to save time and energy. However, estimated distances do not always coincide with objective distances. One example is the frequent observation that the same path to and from a specific place is estimated differently. Such subjective distances violate axioms of a metric (Baird, Wagner, & Noma, 1982; Cadwallader, 1979; McNamara & Diwadkar, 1997), and they are strongly influenced by the structure of the space (McNamara, 1991; Montello, 1995). In

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addition, the perception and cognition of a space appear to depend on its size, location, and the way people interact with it. A number of classifications of different spaces have been proposed in the literature. Tversky (2003) distinguishes between the space of body, the space around the body, the space of navigation, and the space of graphics. The last two were named environmental and pictorial space by Montello (1997).

Environmental space is larger than the body and can only be apprehended with locomotion; pictorial space is projectively smaller than it and refers to small flat spaces, like a map. The perception of the space benefits the acquisition of different kinds of spatial knowledge: The perception of an environmental space results mostly in route knowledge; the learning from a map results in map or survey knowledge (Siegel & White, 1975).

These two forms of knowledge are associated with different mental representations. Whereas route knowledge is usually modelled as consisting of a set or sequence of representations of landmarks or places or views of these, linked by procedures specifying how to get from one to the other (Thorndyke, 1981), survey knowledge is modelled as based on a two-dimensional representation. In the present study, we focus on distances that are perceived in environmental and in pictorial spaces. These are called environmental and pictorial distances, respectively.

Psychophysical research indicates that people's knowledge about distances does reflect objective distances. The general shape of the relationship can be described by a psychophysical power function: A subjective distance d_s is related to the corresponding objective distance d_o as $d_s = \alpha \times d_o^{\beta}$, with the parameters $\alpha > 0$ and β around 1 differing in magnitude between studies. In a meta-analysis of 70 studies of distance estimation, Wiest and Bell (1985) found that the main determinant of the exponent was whether the subjective distance was perceived, retrieved, or inferred, with the exponent most often below 1 and decreasing from perceived to retrieved to inferred distances.

Subjective distances do not equal objective distances, and a number of very different factors have been identified as influencing distance estimates in environmental spaces. Prominent among these factors are the number and the kind of environmental features, the structure of the route, travel time, travel effort, familiarity, and the context—for example, the location or reference point from which the distance estimations were conducted. In previous research, these factors have been investigated independently of one another. It is unclear, for example, whether some of these effects are special cases of others. The studies reported in the current paper focus mainly on the two most prominent effects: those of environmental features and those of structure. (For an overview of the other effects mentioned, see Montello, 1995, 1997.) These effects are not investigated further; for example, travel time, travel effort, and familiarity are held constant. Two different measurement methods were used in this study: mapping and magnitude estimation. They were chosen because they both generate distance estimates that are generally highly correlated with each other and with physical distances (see Montello,1991, for a complete overview of measurement methods in distance cognition).

Feature accumulation and route structuring

The *feature accumulation effect* (FA) describes an increase in distance estimates with the number of features of the route or environment retrieved: The more items that exist between the startpoint and the endpoint of an estimate, the longer the subjective distance will become. The term was coined by Montello (1995) in a review of earlier studies (Sadalla & Magel, 1980; Sadalla & Staplin, 1980a, 1980b; Sadalla, Staplin, & Burroughs, 1979). These experimental studies used laboratory pathways whose features were road intersections, road turns, or names of the intersecting roads. For instance, Sadalla and Magel (1980) found that a path containing seven right-angle turns was estimated as being longer than a path of the same length containing two right-angle turns. The results of the study by Sadalla and Magel can be replicated in a virtual environment for adults (Jansen-Osmann & Berendt, 2002) and for children (Jansen-Osmann & Wiedenbauer, 2004b).

The *route structuring effect* (RS) describes the influence that hierarchical structuring of the route has on route distance estimates. Routes are hierarchically structured: Routes contain *stretches*, which in turn contain one or more landmarks. Stretches can be different blocks along a street, or otherwise distinguished regions. Distances between landmarks in different stretches are overestimated relative to distances between landmarks in the same stretch. Also, distances between landmarks in different stretches have been found to depend only on which stretch the landmarks belonged to, not on where they were located within this stretch (Allen, 1981, 1988; Allen & Kirasic, 1985). Spatial hierarchies have also been found to lead to the overestimation of straight-line distances (e.g., McNamara, Hardy, & Hirtle, 1989). A hierarchical structure of a route can be induced not only by segmenting environmental features, but also by a grouping of environmental features. For example, a crossroad segments the blocks on either side of the crossroads, while a set of buildings that look similar to one another and dissimilar to buildings before them and after them along the route forms a perceptual group, which is different from the parts of the route on either side of this group. Both cases appear to have been included in the work of Allen and his colleagues. Therefore, we call the effect of hierarchies on distance estimates the "route structuring" rather than the "route segmentation" effect (as Montello, 1995, calls it in his survey).

The role of structure induced by grouping in perceptual organization has been well known since the studies of Wertheimer (1923) and the Gestalt psychologists. Gestalt factors contribute to the perception of visual and other stimuli as grouped. It remains to be tested, however, whether or not the effect of Gestalt factors also influences distance knowledge. So far, the influence of Gestalt factors on a successively perceived sequence of events has mainly been investigated with respect to sound sequences (cf. Metzger, 1966). In other words, we wanted to investigate whether there is an effect of a hierarchical structure of a successively perceived sequence of environmental features along a route—that is, whether there is a route structuring effect—and, if so, whether it occurs when structure is induced by segmentation, when it is induced by grouping, or in both cases. It should be noted that the effect of structure on distance estimates may be independent of the presence of structure: Features or other factors may induce a structure, but this structure may not influence subjective distances.

The purpose of the present paper is to investigate the two important factors of environmental features and of structure and how they interact in influencing distance estimates. Our goal is to identify the relationship between these two effects. In previous work, they have not been related to one another theoretically or tested against each other (see Montello, 1995). The two effects overlap in their assumption that an environmental feature increases the distance estimate; their straightforward explanations differ in their assumptions about the nature of this feature: whether it has to "fill" the route (FA), or to segment the route

(RS). Filling as well as segmenting features are perceived by people traversing a route, but filling features do not segment that route.

So are the FA and RS effects really two different effects, due to differing mental processes and representations, or is one a special case of the other? Three possibilities are conceivable, and they lead to distinct predictions for result patterns:

1. RS is a special case of FA: The presence of features between the start and goal of a distance estimate increases that estimate (FA). Route structure is induced by the presence of a feature that segments one route stretch from the next, and route structure increases distance estimates by virtue of the presence of that segmenting feature. There is no independent RS effect—that is, route structure can only affect distance estimation when structuring is induced through a feature. When it is induced by a factor other than a feature (usually, a factor such as similarity that leads to parts of the environment being grouped into a route stretch), route structure will not influence distance estimates. Note that the effect on distance estimates may therefore be independent of the question of whether segmenting features, or other factors leading to the formation of route stretches, induce a structure at all. If RS is a special case of FA, route structure may be present without influencing distance estimates. In our experiments, mental structure was present, as reported by participants.
2. FA is a special case of RS: The structuring of a route leads to an overestimation of the distance between locations in different stretches (RS). This may be regarded as a categorization effect (Allen & Kirasic, 1985). A feature (any feature) leads to a segmentation of the route into a stretch in front of it and one behind it—that is, it increases distance estimates by virtue of segmenting the route. There is no independent FA effect—that is, features can only increase distance estimates when they segment. Thus, either all features segment (this converts every feature into a separate stretch, making the notion of route stretches vacuous), or there are segmenting features (which lead to overestimations) and nonsegmenting features. This implies that if, with regard to a certain route, it is established that there is a mental structuring with stretches that contain more than one feature, distances across features within these stretches should not be overestimated.
3. FA and RS are independent effects. Thus, distances across features that merely fill space will be overestimated. Distances across stretches will also be overestimated, regardless of how this structure is induced. There is no prediction concerning the relative sizes of the FA and RS effects.

The experiments described in this paper were designed to test predictions that are critical for deciding which of the three cases hold. To this end, the subjective distances of three types of path have to be compared: an empty path, a path over a stretch boundary induced by a segmenting feature, and a path over a stretch boundary induced by a grouping factor. All three paths cover the same objective distance. Table 1 gives an overview of the predictions that follow from the description of the three cases above.

Table 1 describes all order relations between the subjective distances of the three paths that are logically possible if both an FA and an RS effect exist. It is also possible that one or both of the effects do not exist (in this case the prediction would be that the respective paths are estimated no differently from the empty paths), or that the reverse of one or both of the effects holds (in this case the respective path would be estimated as shorter than the empty

TABLE 1
Predictions concerning subjective distances depending on the relations of the FA and RS effects

Subjective distances of the path types that appear in the route configuration	*S*	*F*	*G*
Case 1: RS is a special case of FA			
1.S: Route with structure induced by segmentation	(S=F) > E		
1.G: Route with structure induced by grouping			F > (G=E)
Case 2: FA is a special case of RS			
2.S: Route with structure induced by segmentation	S > (F=E)		
2.G: Route with structure induced by grouping			G > (F=E)
Case 3: FA and RS are independent effects			
3.S: Route with structure induced by segmentation	S > E, F > E		
3.G: Route with structure induced by grouping			G > E, F > E

S = path segmented by segmenting feature. F = filled path. G = path segmented by grouping factor. "E" refers to the empty path; ">" means "significantly larger than; "=" means "no significant difference", with "*(A = B) > C*" (etc.) standing for "both *A* and *B* are significantly larger than *C*, but they do not differ significantly from each other".

path). However, these constellations cannot be expected based on the evidence available in the literature, so these additional cases are not discussed further.

Several theoretical approaches have been offered for the feature accumulation and route structuring effects. It should be noted that the experiments presented in this paper address empirical questions that are relevant for all of these models. We therefore give only a brief overview of the proposed models and return to this question in the General Discussion. Accounts of the FA effect rest on characteristics of human memory (information storage model, Milgram, 1973; Sadalla et al., 1979), on psychophysics (scaling hypothesis, Baird et al., 1982; Briggs, 1973; Sadalla & Magel, 1980), or on the process of constructing a subjective distance (analog timing model, Thorndyke, 1981). The RS effect has been traced back to the use of hierarchical representations in retrieval (Allen, 1981; McNamara, Hardy, & Hirtle, 1989). It is likely that hierarchical (or categorical) representations interact with non-hierarchical spatial representations (category adjustment model, Huttenlocher, Hedges, & Duncan, 1991; Newcombe, Huttenlocher, Sandberg, Lie, & Johnson, 1999; partial hierarchies, McNamara, 1986). The work presented in this paper centres on the question of how the two effects are related and is thus most closely connected to the theoretical account of Berendt (1999) who presents FEATURE, a computational model of route distance knowledge that can account for both the FA and the RS effects, and which integrates aspects of previous models and resolves inconsistencies found between them.

EXPERIMENTS

The experiments described below can be divided into two parts: (a) The first three experiments concern the acquisition of distance knowledge and investigate the interaction of feature accumulation and route structuring in an environmental space; (b) the last two investigate feature accumulation and route structuring in a pictorial space.

EXPERIMENTS 1–3

EXPERIMENT 1[1]

Influence of filling and segmenting features on distance cognition in an environmental space (mapping technique)

The relationship between the feature accumulation and route structuring hypotheses has remained unsolved, yet there is a connection between the two effects. On the one hand, route structuring may be considered a hierarchical effect—stretches are containers of landmarks. On the other hand, route structuring may be considered a feature effect—structure can be induced by features. Our experiment was designed to investigate feature accumulation and route structuring in one experimental setting: (a) whether distance estimation is influenced by a "normal" feature and/or by one with a segmenting role, and (b) whether or not there is a difference between the estimates influenced by these two kinds of features.

We investigated the following hypotheses:

1. The distance estimate between two landmarks across a landmark (filled path) is larger than the distance estimate between two landmarks that are immediate successors on the route (empty path)–feature accumulation effect.
2. The distance estimate between two landmarks across a segmenting landmark (segmented path) is larger than the distance estimate between two landmarks that are immediate successors on the route (empty path)–route structuring effect.

It remains to be tested whether or not the distance estimate between two landmarks across a landmark (filled path) differs from the distance estimate across a segmenting feature (segmented path)–feature accumulation vs. route structuring.

Method

Participants

A total of 15 students of Gerhard Mercator University Duisburg volunteered for Experiment 1: 8 male (average age 23.7 years) and 7 female (average age 24.0 years). Participants were tested in single sessions lasting about 20 minutes each.

Materials

The basis of the experiment was a virtual street created with the software Superscape VRT 4.00. The straight street contained 18 identical houses, which were symmetrically placed at both sides. From the beginning of the route, one could see the first houses, but neither the remaining houses nor the crossroads. Figure 1 shows the participants' perspective into the virtual street.

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[1]This experiment was described earlier in Berendt and Jansen-Osmann (1997). Its description is repeated in detail here because it serves as the foundation for the remaining experiments. Experiment 1 and 2 are described in a German paper (Jansen-Osmann, 2001).

Figure 1. The participants' perspective into the virtual, segmented street.

The virtual street was segmented by crossroads. A survey view of the virtual street is shown in Figure 2.

There were three different kinds of paths along the street between two houses to be tested: empty, filled (with another house in the middle), and segmented (by crossroads). The first three paths were all of the same objective length ("short"—12 units of the software), as were the other three paths

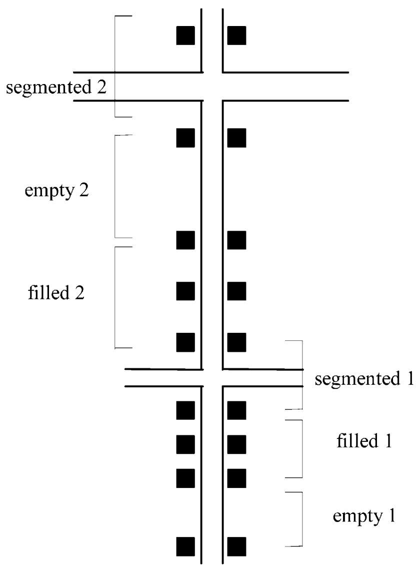

Figure 2. Survey view of the virtual, segmented street.

("long"—20 units). In a postexperimental exploration all participants reported that only the crossroads structured the route.

Procedure

Participants sat in front of a 17" monitor, which was isolated from other room elements. Eye height was not controlled; participants could interact with the computer in the same way that they interact with a normal desktop computer. A joystick was used to move through the virtual environment. They explored the virtual street three times with the help of this joystick by pushing it as far forward as possible, so that speed was controlled. When they had explored the street once, the viewpoint was reset to the beginning of the street by pressing a key. This operation ensures that the street can only be explored in the "forward" direction. Each trial lasted about four minutes. Participants did not know beforehand that they would have to estimate a distance. They were told to regard the virtual street attentively. After exploration, they were asked to register the positions of the houses by marking them with arrows along a vertical line on an A4 paper sheet. The vertical line partitioned the sheet into two halves; its beginning was marked by a horizontal bar. Participants were asked to take care to draw the distances between the houses correctly. On the protocol sheet, the beginning of the street was marked; houses could be positioned anywhere starting from that point. We call this retrieval method *mapping without correction*.

Experimental design

The factors "kind of path" (empty, filled, segmented) and "length of path" (short, long) were manipulated within subjects. The dependent variable was the distance estimate of the single paths. Distance estimates were measured to the nearest millimetre and transformed into percentages of the drawn length of the whole route. A repeated measurement analysis of variance was conducted.

Results

Figure 3 shows that the distance estimates varied with the kind of path. The factors "kind of path" and "length of path" had a significant influence on the distance estimates, $F(2, 28) = 11.61$, $p < .001$, $\eta^2 = .453$, and $F(1, 14) = 6.65$, $p < .05$, $\eta^2 = .323$, respectively. There was no interaction between these two factors, $F(2, 28) = 0.27$, $p = .704$, $\eta^2 = .019$.

The filled and segmented paths were estimated as significantly longer than the empty paths, $F(1, 14) = 22.27$, $p < .001$, $\eta^2 = .614$, and $F(1, 14) = 18.91$, $p < .001$, $\eta^2 = .575$, respectively. Filled paths seem to be estimated as longer than segmented paths, but this difference did not reach statistical significance, $F(1,14) = 4.26$, $p = .058$, $\eta^2 = .233$. The long paths were estimated as significantly longer than the short paths, $F(1, 14) = 6.65$, $p < .05$, $\eta^2 = .323$, as reported above.

Discussion

The experiment was conducted to test the feature accumulation and route structuring hypotheses. The results confirm both hypotheses: Filled and segmented paths were estimated as longer than empty paths. The overestimation of segmented paths in comparison to the empty paths was less pronounced than that of filled paths, so the presence of the segmenting feature had an effect, but the segmentation did not cause an additional increase in the estimate. Expressed differently, the segmenting feature appears to have had the same effect as

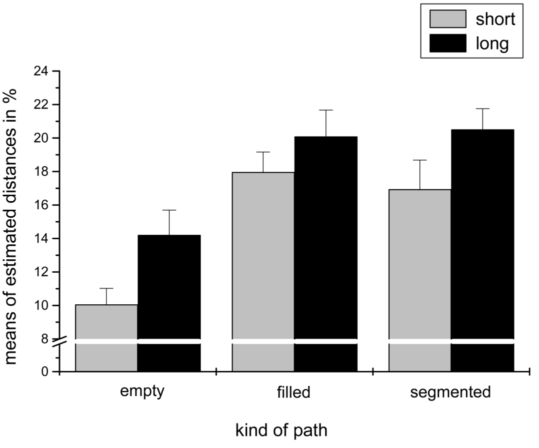

Figure 3. Mean values and standard errors of distance estimates (as a percentage of the drawn length of the whole route) in Experiment 1.

a regular feature, but no effect beyond that. This indicates that the importance of structuring for distance estimation lies in the existence of an environmental feature rather than in its role.

The results are consistent with rows 3.S and 1.S in Table 1. Therefore, we can infer that both an FA and an RS effect exist in environmental spaces and that the route structuring effect may be a special case of the feature accumulation effect. However, it is also possible that two different processes accounted for the overestimation (a) of the filled path and (b) of the segmented path. This raises the following question: Does structuring induced by grouping, in the absence of a segmenting feature, also influence distance estimation? If the overestimation of the segmented path in Experiment 1 was due to the segmenting feature, a structure induced merely by grouping should not have any effects. If the overestimation was due to a different process that is triggered by a structured route, structure induced by grouping should also lead to overestimation. To distinguish between these two possible explanations (Case 1 and Case 3 in Table 1, respectively), we conducted Experiment 2.

EXPERIMENT 2

Influence of perceptual grouping on distance cognition in an environmental space (mapping technique)

The goal of this experiment was to investigate the influence of structuring by grouping instead of segmenting features. Grouping along the route was induced through similarity based on colour. We wanted to find out whether this kind of structuring (grouping by similarity of colour) would function in the same way as the structuring created by crossroads (segmentation by a segmenting feature). In an independent exploration, we asked the participants whether or not they perceived structure within the route and, if so, what factor caused it. All of them reported a structuring only through the similarity of the houses into the three groups shown in Figure 4. This indicated that the colour of the houses was sufficient to induce hierarchical structuring.

We investigated the following hypotheses:

1. The distance estimate between two landmarks across a landmark (filled path) is larger than the distance estimate between two landmarks that are immediate successors on the route (empty path).
2. The distance estimate between two landmarks that, based on similarities, are grouped together with two different sets of other landmarks (path segmented by similarity) is larger than the distance estimate between two landmarks that are immediate successors on the route (empty path).

No hypothesis was formulated with respect to filled paths compared to paths segmented by similarity, because in contrast to Experiment 1, the two cases cannot be traced back to one common reason.

Method

Participants

A total of 15 students of Gerhard Mercator University Duisburg volunteered for Experiment 2: 5 male (average age 24.4 years) and 10 female (average age 20.4 years). Participants were tested in single sessions lasting about 20 minutes each.

Materials

The basis of the experiment was a virtual street created with the software Superscape VRT 4.00, similar to the one described earlier. The straight street contained 18 houses, which were symmetrically placed at both sides and looked almost identical except for their colour. Houses 1 to 4 of each side were coloured white, Houses 5 to 8 of each side were coloured red, and the last house was coloured blue. Unlike in Experiment 1, there were no segmenting crossroads. A survey view of the virtual street is shown in Figure 4.

Figure 4 shows that there are three kinds of objective "paths" along the street between two items to be tested: empty, filled, and segmented by similarity. The first three paths (empty 1, filled 1, and segmented by similarity 1) were all of the same objective length, as were the other three (empty 2, filled 2, and segmented by similarity 2). Figure 4 shows that Paths 3 and 6 were segmented through a phenomenal grouping of the buildings.

Procedure

The procedure was the same as that in Experiment 1.

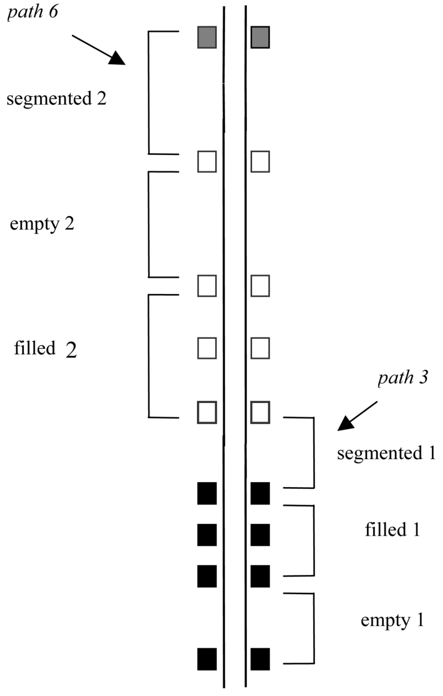

Figure 4. Objective distances of the virtual street from a survey perspective.

Experimental design

The factors "kind of path" (empty, filled, segmented by similarity) and "length of path" (short, long) were manipulated within subjects. The dependent variable was again the distance estimate of every single path. A repeated measurement analysis of variance was conducted.

Results

Figure 5 shows the mean values and standard errors of distance estimates as a percentage of the drawn length of the whole route, depending on the kind of path. The distance estimates varied with the kind of path, $F(2, 28) = 7.37$, $p < .01$, $\eta^2 = .453$.

For both short and long paths, the filled paths were estimated as longer than the empty paths, $F(1, 14) = 8.88$, $p = .01$, $\eta^2 = .388$. They were not estimated as longer than the paths segmented by similarity, $F(1, 14) = 2.98$, $p = .11$, $\eta^2 = .175$. Estimates of the paths that were segmented by similarity did not differ from estimates of the empty paths, $F(1, 14) = 0.65$, $p = .43$, $\eta^2 = .044$. Again, the objectively long paths were estimated as longer than the objectively short paths, although this did not reach statistical significance, $F(1, 14) = 3.92$, $p = .068$, $\eta^2 = .219$. There was no significant interaction between these two factors, $F(2, 28) = 1.47$, $p = .25$, $\eta^2 = .095$. Furthermore, there were no individual differences concerning distance estimation and descriptive grouping of houses.

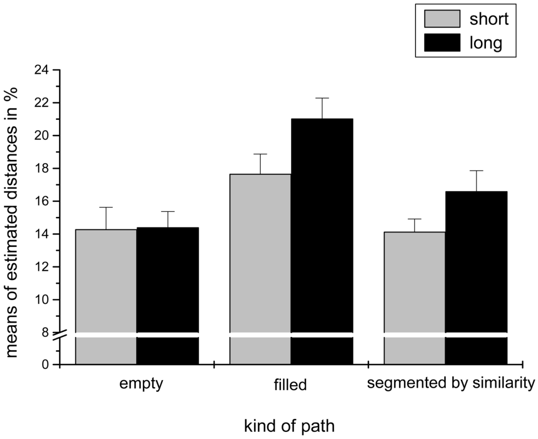

Figure 5. Mean values and standard errors of distance estimates (as a percentage of the drawn length of the whole route) in Experiment 2.

Discussion

The results show that filled paths were overestimated in relation to paths that were segmented by a grouping factor: The existence of segmenting features, but not the existence of the kind of perceptual grouping that was induced here, is important for the acquisition of distance knowledge (Jansen-Osmann, 2001). These results are consistent only with row 1.G in Table 1—although the overestimation of F relative to G was present but failed to reach significance. Note that this is the least important part of row 1.G: The most important predictions are that F > E (feature accumulation effect), but G = E (no route structuring effect). From the combination of Experiments 1 and 2, we conclude (a) that both segmenting features and grouping factors can induce structure in a route, but that only the former has an effect on subjective distances, implying (b) that in environmental spaces, the RS effect appears to be a special case of the FA effect.

This means that a segmenting feature appears to be "simply another" feature in the sense of feature accumulation concerning distance estimation in environmental spaces. This result was confirmed in two other experiments, which differed from Experiment 1 only in their measurement methods (Jansen-Osmann, 1999). In one experiment, a mapping technique with correction was used. A total of 15 participants explored the same virtual street as that in Experiment 1, but were asked to place nine wooden blocks along a marked street on a white sheet of paper on a table. They were allowed to correct their answer until they reached an optimal construction concerning the distances between the houses. In a second experiment, the middle house in the filled path condition was coloured green, and the participants were asked only to draw the seven white houses. The results of both experiments showed a clear feature accumulation and route segmentation effect: The filled and segmented paths were both estimated as being longer than the empty paths, with no difference between the estimation of the filled and segmented paths.

Although all these measurement methods differ, they have one thing in common—namely, that they require distances to be transformed into another space (Montello, 1991). The tasks required participants to translate the route perspective on the scene into a survey perspective. Different kinds of spatial representation may be involved for these two types of perspective. To avoid this, another measurement method in which the distance knowledge is retrieved with a psychophysical ratio-scaling method is needed to complement the value of the used distance estimation method.

A second desirable variation concerns the layout of the route. In the first two experiments, the paths to be estimated were presented in the same order to all participants. This may have created a context that emphasized or obliterated certain effects. The two issues were addressed in the third experiment.

EXPERIMENT 3

Influence of filling and segmenting features on distance cognition in an environmental space (magnitude estimation technique and variation of the order of paths)

In this experiment, we investigated the following hypothesis:

> If participants estimate distances between houses with magnitude estimation, then route structuring and feature accumulation may occur. These effects are independent of the order of the path within the whole route.

Method

Participants

To capture a sizeable part of the huge number of route configurations that are possible when ordering the paths differently, the number of participants was increased relative to Experiments 1 and 2. A total of 40 students from Heinrich Heine University Düsseldorf volunteered for Experiment 3:16 male (average age 26.44 years) and 24 female (average age 23.13 years). Participants were tested in single sessions lasting about 20 minutes each.

Materials

The basis of the experiment resembled the virtual street created with the software Superscape VRT 4.00 as used in Experiment 1. The middle houses of the filled paths (Houses 3 and 6) were coloured differently (light grey). Furthermore a 10th house, which was coloured red, was added behind the last white house at the end of the route. The objective distance between the last white house and the red house was 12 units, so that this distance equalled the length of the short empty path. The order of the six paths of interest was varied randomly. From the 6! possibilities (720), 40 were drawn randomly.

Procedure

The learning phase was identical to that of Experiment 1. Every participant received a different virtual street. Each of the 40 different arrangements of the six paths was presented to only one participant. After exploration, participants had to estimate the distance between the seven white houses in metres. They were told that the distance between the last white house and the red house was 40 m and that they had to estimate the distances between the seven white houses with that distance in mind (magnitude estimation). Participants were asked to estimate only the six paths of interest. Every participant had one sheet of paper for each distance estimate. The length of the comparison path (distance between the last white house and the red house) was repeated at the top of each sheet. Below this, participants were asked to specify, in metres, the distance between two houses. The questions followed the order of presentation of the houses. For example, participants whose street layout started with a filled path were first asked to estimate the distance between Houses 1 and 3. To do so, they estimated the distance between the first and the second white house they had seen (in between these two, there was a grey house).

Experimental design

The factors "kind of path" (empty, filled, and segmented) and "length of path" (short, long) were manipulated within subjects. The dependent variable was again the distance estimate of the single paths, measured with magnitude estimation. A repeated measurement analysis of variance was conducted.

Results

Figure 6 shows the mean values and standard errors of distance estimates in metres, depending on the kind of path. There were statistically significant influences of the factors "kind of path", $F(2, 78) = 34.06$, $p < .001$, $\eta^2 = .466$, and "length of path", $F(1, 39) = 9.76$, $p < .01$, $\eta^2 = .2$.

For both short and long paths, the filled paths were estimated as longer than the empty and segmented paths: filled–empty, $F(1, 39) = 61.73$, $p < .001$, $\eta^2 = .613$; filled–segmented, $F(1, 39) = 8.98$, $p < .01$, $\eta^2 = .187$. However, the segmented path was estimated as being longer than the empty path only for short paths: interaction, segmented–empty, $F(1, 39) = 5.99$, $p < .05$, $\eta^2 = .133$. The overall interaction between "kind of path" and "length of path" failed

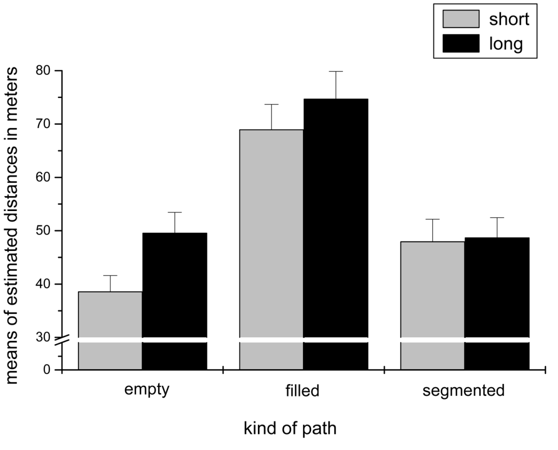

Figure 6. Mean values and standard errors of distance estimates (in metres) in Experiment 3 (magnitude estimation).

to reach significance, $F(2, 78) = 2.69$, $p = .075$, $\eta^2 = .065$. Objectively long paths were estimated as longer than short paths.

Why was there no route segmentation effect for the long paths when magnitude estimation was employed? We hypothesized that this could have been an effect of the configuration. In the virtual streets used in Experiment 1 where a route segmentation effect was observed, the segmented long path was always located at the end of the route. At this location, it can be regarded as segmenting the block before it from the space outside the route. We therefore classified the 40 configurations used in Experiment 3 according to type of path before and after the long segmented path. A clear relationship emerged in this exploratory analysis: The long segmented path was estimated as longer than the long empty path under one of two conditions: (a) when the long segmented path was located at the beginning or at the end of the route, and (b) when the short segmented path was located next to it.

Restricting our analysis to the 26 cases with this kind of configuration, we found clear feature accumulation and route structuring effects in the magnitude estimates: There were statistically significant influences of "kind of path", $F(2, 50) = 21.52$, $p < .001$, $\eta^2 = .463$, and "length of path", $F(1, 25) = 6.76$, $p < .05$, $\eta^2 = .213$ (see Figure 7). There was no significant difference between these two factors, $F(2, 50) = 1.04$, $p = .356$, $\eta^2 = .04$.

The filled paths and the segmented paths were estimated as longer than the empty paths: filled–empty, $F(1, 25) = 58.63$, $p < .001$, $\eta^2 = .701$; segmented–empty, $F(1, 25) = 6.01$, $p < .05$, $\eta^2 = .194$. There was no significant difference between the filled and the segmented paths, $F(1, 25) = 0.89$, $p = .355$, $\eta^2 = .034$. Objectively long paths were estimated as longer than objectively short paths.

Discussion

The results of this experiment extend the results received in the previous experiments: Filled paths were estimated as longer than empty paths, regardless of where they are positioned

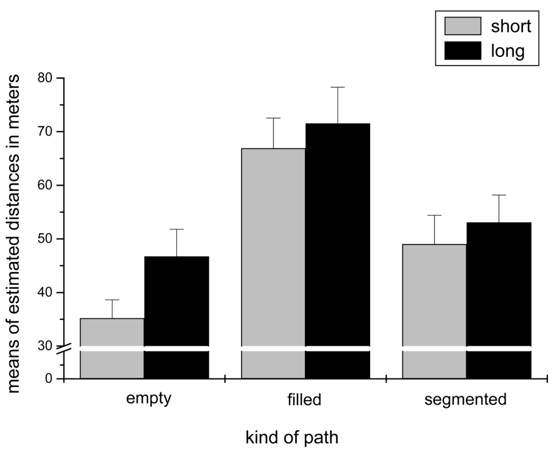

Figure 7. Mean values and standard errors of distance estimates (in metres) in Experiment 3 (magnitude estimation in 26 selected cases).

within a route and of what retrieval method is used. It is possible, however, that the magnitude estimation method we used strengthened the feature accumulation effect, because the instruction to estimate the distance between one house and the one after the next may have drawn participants' attention to the fact that the path was filled.

While a pronounced feature accumulation effect was found, only a partial route structuring effect was observed. The short segmented path was estimated as longer than the empty path of the same length; the long segmented path was only overestimated when it was at the beginning or end of the route or next to the short segmented path. The results concerning the routes with the discussed configuration type are in accordance with the results and interpretation of Experiments 1 and 2—that is, Case 1 in Table 1. Results concerning all routes indicate that there is an FA effect (thus ruling out Case 2 in Table 1), but they hint at the possibility that under certain circumstances, there may be no RS effect (a case not covered in Table 1). Since the complete absence of an RS effect is not in accordance with the majority of evidence in the literature, we interpret this finding as indicating that the segmenting stimuli may not have been effective in segmenting the path because the intersecting road was too narrow for the relatively large distance between the houses. For this reason, the segmentation may only have an influence on distance estimation when it is amplified or coupled with other attributes of segmentation such as another segmented path or an exceptional position within the whole configuration of the route. In other words, the characteristics of the environment surrounding a segmenting feature may establish a context that governs this feature's influence on distance estimation. This assumption could be tested by further experiments in which the order of the paths is varied systematically, which has not been done until now. An interesting outcome would be to see how spatial layout and the ordering of elements in the scene impact distance knowledge. A first step would be to replicate the first experiment with a variation of path order.

One avenue for further work would be the choice of a different segmenting feature. For example, the results of Denis, Pazzaglia, Cornoldi, and Bertolo (1999) suggest that reorientation points (turns) in a route are most critical for verbal route descriptions (apart from the start- and endpoints); it is conceivable that turns also have a stronger effect on subjective distances. However, the choice of a segmenting feature with a stronger effect might actually strengthen our main conclusion. It is likely that it would tend to increase the RS effects found in Experiments 1 and 3. This could lead to either (a) subjective distances $F = S > E$ in Experiments 1 (recall that in the present version, S was, nonsignificantly, smaller than F) and in Experiment 3 for all route configurations (in the present version, S was smaller than F), or (b) $S > F > E$ in Experiments 1 and/or 3. The change in the segmenting feature would not affect the results of Experiment 2. An outcome as described by (a) would be in full accordance with Case 1 in Table 1 and thus support our conclusion that RS is a special case of FA even more strongly. An outcome as described by (b) would only indicate that route structure may have an additive effect when coupled with the presence of a feature, but that structure on its own is not enough to increase subjective distances (see Experiment 2).

At first glance, the results seem to be inconsistent with those of a study done by McNamara et al. (1989) who documented an overestimation of distances for objects in different subjective regions of space compared to objects in the same region. However, we could not really compare the results because of the two different knowledge acquisition methods used in these studies. The preceding results only concern knowledge acquisition in a "route perspective", the perspective from within the space in which one is situated and moves around (Nigro & Neisser, 1983; Schweizer, Herrmann, Janzen, & Katz, 1998). In the study by McNamara et al. (1989), participants had to learn from a survey perspective by studying two-dimensional spatial layouts of an environment.

This leads us to the question of whether or not an independent route structuring effect, which could not be found in the three experiments described above, can be observed when the route is represented in a survey view. One possible way to answer this question is to investigate pictorial distances—for example, survey knowledge acquired from reading a map. There are further studies that have investigated structuring in pictorial distances (Hirtle & Kallmann, 1988; McNamara, 1986). In these studies, structuring was induced by barriers like lines on a map, which segmented the pictorial space. There was clear evidence that structuring increases estimates of pictorial distances. Estimates of pictorial distances have also been found to increase with the number of intervening features (Thorndyke, 1981). To investigate this further, we conducted two experiments on feature accumulation and route segmentation in routes learned from a survey perspective.

EXPERIMENTS 4–5

EXPERIMENT 4

Influence of filling and segmenting features on distance cognition in a pictorial space (mapping technique)

In this experiment, we investigated the following hypotheses:

1. If the virtual street is learned from a survey representation, there will be a feature accumulation effect.
2. If the virtual street is learned from a survey representation, there will be a route structuring effect.

Method

Participants

A total of 15 students of Gerhard Mercator University Duisburg volunteered for Experiment 4: 8 male (average age 23.7 years) and 7 female (average age 24.0 years). Participants were tested in single sessions lasting about 15 minutes each.

Materials

The basis of the experiment was a survey view of the virtual street as used in Experiment 1, created with the software Superscape VRT 4.00 as described above. This overview contained 18 houses in the form of black boxes, which were symmetrically placed at both sides (see Figure 2 for a schematic view). In a postexperimental exploration all participants reported that only the crossroads structured the route.

The route configuration from Experiment 1 was used for all participants for two reasons: (a) to ensure optimal comparability with Experiment 1, such that the only difference between Experiments

1 and 4 was whether an environmental or a pictorial space was learned, and (b) to use a route configuration that had been shown to generate a route structuring effect for paths of all lengths.

Procedure

Participants sat in front of a monitor, on which the survey view of the virtual street was presented. They were instructed to study the street attentively for 3 minutes. They did not know beforehand that they would have to estimate a distance. After exploration, subjects were given the task of registering the positions of the houses by marking them along a vertical line on an A4 protocol sheet (see Experiment 1).

Experimental design

The factors "kind of path" (empty, filled, and segmented) and "length of path" (short, long) were manipulated within subjects. The dependent variable was again the distance estimate of the single paths. A repeated measurement analysis of variance was conducted.

Results

There were statistically significant influences of the factors "kind of path", $F(2, 28) = 8.72$, $p = .001$, $\eta^2 = .384$, and "length of path", $F(1, 14) = 18.32$, $p = .001$, $\eta^2 = .567$. There was no significant interaction between these two factors, $F(2, 28) = 2.15$, $p = .153$, $\eta^2 = .133$.

Figure 8 shows the mean values and standard errors of distance estimates as a percentage of the drawn length of the whole route, depending on the kind of path. The distance estimates varied with the kind and length of path. For both short and long paths, the segmented paths were estimated as longer than the empty paths and longer than the filled paths: segmented–empty, $F(1, 14) = 9.03$, $p < .01$, $\eta^2 = .392$; segmented–filled, $F(1, 14) = 13.68$, $p < .01$, $\eta^2 = .494$. There was no difference between the filled and empty paths,

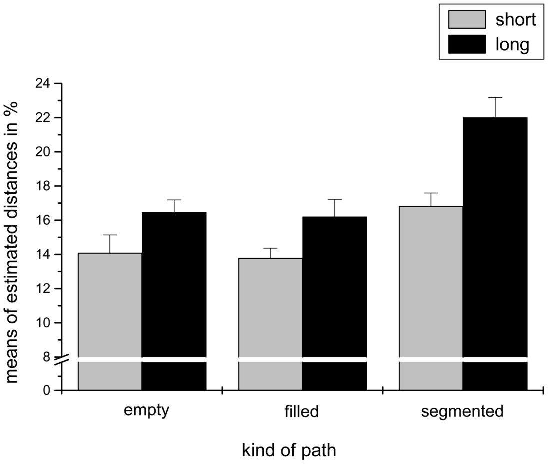

Figure 8. Mean values and standard errors of distance estimates (as a percentage of the drawn length of the whole route) in Experiment 4.

$F(1,14) = 0.07$, $p = .789$, $\eta^2 = .005$. The objectively long paths were estimated as longer than the objectively short paths.

Discussion

The results show that segmented paths were overestimated in relation to empty and filled paths. In other words, there is evidence that the existence of a segmenting feature, and not a normal "merely filling" feature increased pictorial distance. This result is in accordance with many other studies (e.g., Cohen, Baldwin, & Sherman, 1978; Hirtle & Kallmann, 1988; Kosslyn, Pick, & Fariello, 1974; McNamara, 1986). The results of Thorndyke (1981) also suggest that, to have an effect on distance estimation, features must intervene in mental scanning—that is, that they must segment parts of the route from one another.

The results are consistent only with row 2.S in Table 1. We therefore draw the tentative conclusion that in pictorial spaces FA may be a special case of RS. In analogy with the experiments carried out in environmental spaces, this conclusion needs further support from a route with structure induced by grouping. This kind of route was investigated in Experiment 5.

EXPERIMENT 5

Influence of perceptual grouping on distance cognition in a pictorial space (mapping technique)

The goal of this experiment was to investigate the influence of structuring by grouping rather than segmenting features. In contrast to Experiment 2, the street was represented in a survey view. Experiments 1 and 2 indicated that the importance of structuring for distance estimation concerning route perspective lies in the segmenting role of an environmental feature rather than only in its existence. Therefore, if features and their role are decisive, structure induced by perceptual grouping should not influence distance estimation; if structuring is the decisive factor, structure induced by perceptual grouping should have an influence.

Based on the results from Experiments 1 and 2 (evidence for Case 1 in Table 1: RS as a special case of FA in environmental spaces) and Experiment 4 (partial evidence for Case 2 in Table 1: FA as a special case of RS in pictorial spaces), we expected to obtain further evidence for Case 2 in Experiment 5: an effect of the route structure induced by grouping, but no overestimation of the path across the "merely filling" features.

Method

Participants

In the literature on distance estimation, grouping features in pictorial spaces have been investigated far less often than the types of features described in Experiments 1 to 4; so in contrast to those experiments, we were not able to rely on the expectation of a strong effect. We therefore increased the number of participants relative to the previous experiment. A total of 35 students of Heinrich Heine University Düsseldorf volunteered for Experiment 5:17 male (average age 26.71 years) and 18 female (average age 26.89 years). Participants were tested in single sessions lasting about 15 minutes each.

Materials

The basis of the experiment was a survey view of the virtual street as used in Experiment 2, created with the software Superscape VRT 4.00 as described above. This overview contained 18 houses in the form of boxes, which were symmetrically placed at both sides and looked almost identical except for their colour. Boxes 1 to 4 of each side were coloured black, Boxes 5 to 8 of each side were coloured red, and the last house was coloured blue (see Figure 4).

Procedure

Participants sat in front of a monitor, on which the survey view of the virtual street was presented. They were instructed to study the street attentively for 3 minutes. They did not know beforehand that they would have to estimate a distance. After exploring the street, subjects were given the task of registering the positions of the houses by marking them along a vertical line on an A4 protocol sheet (see Experiment 1).

Experimental design

The factors "kind of path" (empty, filled, and segmented) and "length of path" (short, long) were manipulated within subjects. The dependent variable was again the distance estimate of the single paths. A repeated measurement analysis of variance was conducted.

Results

Figure 9 shows the mean values and standard errors of distance estimates as a percentage of the drawn length of the whole route, depending on the kind of path.

There was a statistically significant influence of the factor "length of path", $F(1, 34) = 159.53$, $p < .001$, $\eta^2 = .824$. The objectively long paths were estimated as longer than the objectively short paths. Furthermore, there was a statistically significant influence of the factor "kind of path", $F(1, 34) = 5.41$, $p < .01$, $\eta^2 = .137$. For both short and long paths, the segmented paths were estimated as longer than the empty paths and longer than the filled paths: segmented–empty, $F(1, 34) = 9.55$, $p < .01$, $\eta^2 = .219$; segmented–filled, $F(1, 34) = 7.48$,

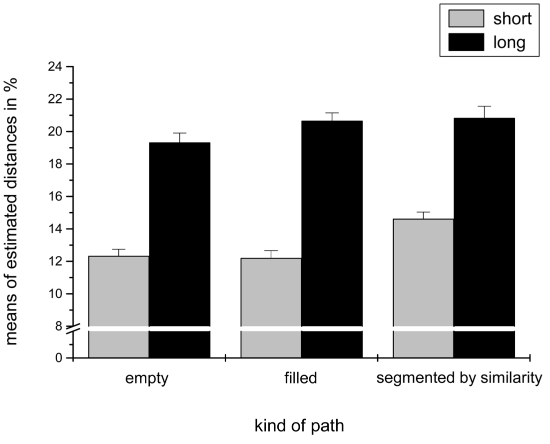

Figure 9. Mean values and standard errors of distance estimates (as a percentage of the drawn length of the whole route) in Experiment 5.

$p < .01$, $\eta^2 = .18$. There was no difference between the filled and empty paths, $F(1, 34) = 1.52$, $p = .226$, $\eta^2 = .043$. There was no significant interaction between the two factors, $F(2, 68) = 2.87$, $p = .068$, $\eta^2 = .078$.

Discussion

The results met our expectations. We obtained further evidence for Case 2: an effect of the route structure induced by grouping, but no overestimation of the path across the "merely filling" features (row 2.G in Table 1). Based on the findings from Experiments 4 and 5, we can assume that the existence and the role of the segmenting feature play an important role concerning distance estimation in pictorial space. Distances will be overestimated if there is a segmenting feature like a physical barrier or a perceptual grouping through colour.

This is partly in accordance with a study of Hommel, Gehrke, and Knauf (2000): They presented survey representations of objects, which were grouped by colour or shape. They investigated verification times for spatial relations along with unspeeded distance estimations between objects, in both a perception and a memory condition. Evidence was found of a hierarchical structuring induced by the perceptual grouping factors: Judging distances between objects in a speeded verification task took less time if the two objects were grouped by similarity. However, this grouping had no effect on unspeeded distance estimates.

GENERAL DISCUSSION

The five experiments showed that feature accumulation and route structuring have different influences depending on the space in which the distances were perceived. Whereas feature accumulation is important during virtual route learning, route structuring induced through a segmenting feature is important during map learning. One explanation might be that during virtual route learning, opposing pairs of houses are grouped together and form categories, and that intersections serve as additional boundaries, whereas during map learning, only the intersections serve as category boundaries and induce a distance overestimation.

The investigation of distance estimation in environmental spaces (Experiments 1–3) yielded consistent evidence of a feature accumulation effect. We found much weaker evidence of a route structuring effect. Experiments 1 and 2 showed that route structure only had an influence on distance estimates when structure was induced by a segmenting feature, which led us to conclude that route structuring can be regarded as a special case of feature accumulation in environmental spaces. Experiment 3 showed that even this type of route structuring effect may only occur under certain circumstances—namely, the environment around a segmentation must "support" the effect of that segmentation. In a pictorial space, no clear relation between the two effects could be demonstrated. However, there was evidence that a categorization effect does occur when distances are pictorial, or when the spatial configuration is presented as a "whole" (Cohen, Baldwin, & Sherman, 1978; Hirtle & Kallman, 1988; Kosslyn et al., 1974; McNamara, 1986). Our last two experiments indicate that route structuring induced through a segmenting feature or through a perceptual grouping is a kind of a categorization effect when learning occurs from a survey representation.

The different influence of feature accumulation and route structuring in pictorial and environmental space is in accordance with Tversky's (2003, p. 78) assertion that "each space reviewed subserves different functions involving different spatial elements and reference frames". Each space has a different mental structure, and there are different factors influencing this structure (see also Couclelis & Gale, 1986; Gärling & Golledge, 1989; Montello, 1993). The processing of environmental and pictorial spaces involves different working memory systems (Deyzac, Logie, & Denis, 2001); these processes are likely to lead to different effects of route features and structures on subjective distances.

Future research regarding distance estimation in an environmental space or the space of navigation should be concerned with the influence of the measurement method, context effects, and the limitations of distance estimations in virtual environments:

1. A possibility of investigating the influence of the measurement method in future experiments is to use paired comparisons. In such an experiment the houses must differ, yet not play a segmenting role along the virtual street. Using desktop virtual reality software as in the experiments presented here, one could produce this variation in an economic manner. With such an experiment we would be able to contrast our results with the results of Allen and Kirasic (1985) more directly.
2. Another area of future research is the investigation of various kinds of context effect. The literature offers a wide range of evidence that certain features can establish contexts that influence distance estimations in specific ways. For example, Holyoak and Mah (1982) showed that reference points establish contexts that distort subjective distances. Their account of this effect, the implicit scaling model, has been expanded to also account for the effects of reference points on the retrievability of other spatial features (contextual scaling model; McNamara & Diwadkar, 1997). Our findings suggest that in environmental as well as in pictorial spaces, the effect of hierarchies on distance estimates may, to a stronger extent than expected so far, depend on characteristics of the configuration of a space and of the features that constitute this configuration. Therefore, one should investigate the effects of aspects of the route configuration on the estimates of individual paths and the role of reference points.
3. Since the results reported here contradict previous findings, the question arises as to whether some results described in the literature may be artifacts of the knowledge acquisition methods used before—for example, slide presentations (Allen & Kirasic, 1985). The discontinous presentation of scenes might lead to segmentation per se. To avoid this kind of segmentation we used virtual environments, which are becoming increasingly appreciated in spatial cognition research. Some of the main advantages of virtual environments are that they allow for the creation of environments of different complexity, for on-line measurement during navigation, and for controlling the amount of exposure to the environment as well as the type and position of landmarks (Péruch, Belingrad, & Thinus-Blanc, 2000). The appropriateness of virtual environments as a tool to investigate spatial cognition has been evaluated by studies in which results obtained in physical spaces were replicated in a virtual environment. For example, Ruddle, Payne, and Jones (1997) could replicate the results of direction and distance knowledge obtained in real-world settings (Thorndyke & Hayes-Roth, 1982) in a virtual environment; May and Klatzky (2000) showed that the effect of irrelevant movements on path integration was similar in real and desktop virtual environments. Virtual environments allow participants to acquire distance knowledge (Jansen-Osmann & Berendt, 2002; Jansen-Osmann & Wiedenbauer, 2004a; Willemsen & Gooch, 2002), knowledge about directions (Albert, Rensink, & Beusmanns, 1999), and route and survey knowledge (Gillner & Mallot, 1998; Jansen-Osmann, 2002). However,

there may also be drawbacks, especially when desktop virtual reality systems are used, and no proprioceptive sensory information is generated (Witmer, Bailey, Knerr, & Parsons, 1996). Findings concerning this question have not been uniform. While Westerman, Cribbin, and Wilson (2001) found navigation to be less efficient in an immersive virtual environment than in a desktop virtual environment, Waller, Knapp, and Hunt (2001) found no difference in learning the spatial representation of mazes between wire-frame virtual and real-world conditions. Witmer and Kline (1998) found that egocentric distances were underestimated more strongly in immersive virtual environments than in real environments. In contrast, Waller's (1999) findings indicate that people can judge exocentric distances in virtual environments nearly as well as they can in a physical environment. Our own studies replicated findings concerning the influence of turns on distance estimation obtained in a real environment (Sadalla & Magel, 1980) and in a virtual environment (Jansen-Osmann & Berendt, 2002).

Future work should also pay attention to the *psychophysics* of distance estimation in virtual spaces. In a virtual reality setting, the effects of environmental features appear to be similar to the effects in a physical space. However, the relation between objective and subjective distances appears to be different: Path length had a significant or near-significant effect in all but one of our experiments, but the size of this effect was very small. Due to the pronounced effect of features and/or structure, each pair of estimates (e.g., empty short path–empty long path in Experiment 1, or filled short path–filled long path in Experiment 3) must be considered separately. Regarding the estimates as the results of a power function on objective distances leads to exponents between 0.2 and 0.6—much smaller than those observed in physical spaces. This finding may be related to the observation that in comparison with physical environments, in virtual environments distances tend to be underestimated, and more errors tend to be made (e.g., Willemsen & Gooch, 2002; Witmer & Sadowski, 1998). Witmer and Sadowski suggest that poor binocular disparity cues or distortions of pictorial depth cues may be responsible for a different distance perception. Future research should therefore investigate possible interactions between qualitative influences of environmental features and the underlying psychophysics in environmental virtual spaces (desktop or immersive) as well as in differently sized and differently structured virtual environments.

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