THE INFLUENCE OF TURNS ON DISTANCE COGNITION

New Experimental Approaches to Clarify the Route-Angularity Effect

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ABSTRACT: Three experiments investigated the route-angularity effect, which is demonstrated when a greater number of turns along a route increases the estimated length. So far, a route-angularity effect has not been demonstrated in school-age children. Because of the lack of a developmental theory, this finding could only be explained by a minor control of environmental features or by the experimental design. The experiments were conducted in a controlled virtual environment. In the first experiment, 11-year-old children explored two routes of equal length, which differed in the number of turns. Each child explored only one of the two routes in the second experiment. Only the first experiment demonstrated an influence in the number of turns on distance estimation. This result was confirmed in the last experiment with adults. If participants had no possibility to compare the routes in respect to their number of turns, both routes were estimated as equally long.

Keywords: *distance estimation; route-angularity effect; environmental space; virtual environments; late childhood*

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In everyday life, knowledge of the distance between two places is important because it helps people plan their ways between these places in an environmental space—a space that cannot be perceived from a single vantage point—in an economic manner. This so-called distance knowledge allows people to save time and energy. Our own experience tells us that subjective, estimated distances do not always coincide with objective distances. Furthermore, subjective distances are not always metric, for example, they are not necessarily symmetric (McNamara & Diwadkar, 1997).

One's memory for distance can be distorted by numerous factors: travel time, travel effort, structure of the route, and the number and kind of environmental features along the route (Montello, 1997). The most frequently discussed source of environmental distance information in literature has been the number of features perceived during travel and/or recalled at the time of estimation. One prominent hypothesis in this context is the so-called feature-accumulation hypothesis coined by Montello (1997). This hypothesis states that the number and memorability of the landmarks on a given route directly affects the estimated length of the route. The route is estimated to be longer if more landmarks are memorable (Sadalla & Magel, 1980; Sadalla & Staplin, 1980a, 1980b; Sadalla, Staplin, & Burroughs, 1979). In this sense, landmarks are any kind of objects in the environment or structural elements that can be perceived during the exploration of the environment, such as intersections, turns, and signs.

Using laboratory pathways, Sadalla and his colleagues manipulated the number of right-angle turns, the number of intersections, and the memorability of words presented as part of pathways. Their results indicated that increasing the number of pathway features encountered and recalled by participants leads to increased distance estimates. Sadalla and Magel (1980) could show that a route that enforced a change in direction more often—in this case, seven right-angle turns—was estimated to be longer than a route of the same physical length containing only two right-angle turns.

Sadalla and Magel (1980) offered three possible explanations for the route-angularity effect: the storage hypothesis, the scaling hypothesis, and the effort hypothesis. The *storage hypothesis* is based on the information storage model proposed by Milgram (1973). A strongly segmented route

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contains more information, necessitates more information processing activity, and leads to a larger amount of stored information. This amount of information determines the distance's subjective size. The *scaling hypothesis* assumes that the psychophysical function for distance estimation is a power function with a positive exponent less than 1.0 (Wiest & Bell, 1985). This implies that the ratio of estimated distance to physical distance will be smaller for longer distances. Because longer segments are relatively underestimated as compared to shorter segments, a route with more turns will be overestimated in comparison to a route with less turns. The third hypothesis is the *effort hypothesis*; here, participants estimate the length of a walked route based on the effort expended in walking. Walking complex routes is assumed to be more laborious than walking less complex routes; this implicates that a route with more turns (the more complex one) is estimated as being longer.

Herman, Norton, and Klein (1986) could not replicate this route-angularity effect in experiments with 8-, 10-, and 12-year-old children. In each of the three experiments, the children had to explore two different routes, differing in the number of turns (two vs. zero turns; one vs. four turns; and two vs. eight turns). Neither an effect of age group nor number of turns was found. In all three experiments, the route with more turns was not overestimated in comparison to the route of equal length but with less turns. This is in contrast to the experiments of Sadalla and Magel (1980). Because of a missing developmental theory, Heft (1988) concluded that "the status of the so-called 'angularity-effect' in relation to children is uncertain. We must wait for a more adequate test to the hypothesis" (p. 98).

Why could Herman and his colleagues not demonstrate the route-angularity effect? An explanation based on familiarity can be immediately rejected because the adults in the Sadalla and Magel (1980) study were generally unfamiliar with the test environment. This familiarity hypothesis does not seem to be plausible for the following reasons. First, Sadalla and Magel (1980) did not find any difference whether their participants had to explore the paths one or three times. Second, the first experiment in the study of Herman et al. (1986) was conducted in an unfamiliar environment.

Taking this into account three other possible explanations remain:

1. The cognition of distances is a developmental process; therefore, children may consider different factors when estimating the distance of a given route. The distance estimation of children at school age might be influenced by other factors than the estimation process of adults.

This explanation seems to be implausible. In fact, there are many studies that investigate the influence of age on distance estimation. They showed that the spatial representation and distance estimation of older children is more precise than that of younger children (S. Cohen & Cohen, 1982; R. Cohen, Weatherford, & Byrd, 1980; Herman & Siegel, 1978). Furthermore, distance estimation depends, especially for younger children, on the type of activity or task demanded (e.g. R. Cohen, Weatherford, Lomenick, & Koeller, 1979; Herman, Kolker, & Shaw, 1982). In addition, distance estimations are influenced by barriers; for example, preschoolers overestimated distances between objects separated by opaque or transparent barriers (Kosslyn, Pick, & Fariello, 1974; Newcombe & Liben, 1982). Kahl, Herman, and Klein (1984) concluded that all children of three age levels (8, 10, and 12 years old) overestimated a path with a large number of segments, as compared to a path of the same length with fewer segments. This seems to be in accordance with studies done with adults (e.g. Allen & Kirasic, 1985). When these results are compared, the studies provide empirical evidence to suggest a fundamentally different influence that environmental features have on children at the age of 11 or 12 years than they have on adults.

2. The difference between the results of the studies of Herman et al. (1986) and Sadalla and Magel (1980) is because of different experimental designs.

Although in the first study, the children were randomized to one of the two groups (exploring the route with less turns vs. exploring the route with more turns), in the latter, participants had to estimate both routes. Thus, a special design—either a between-subjects design or a within-subject design—may induce the use of a special retrieval strategy.

3. The different results are due to the different ways of control of other environmental features.

In the study of Sadalla and Magel (1980), participants explored routes marked with tape on the floor in a psychological building by walking through them. Besides the turns, no other environmental features or space events (Thiel, 1970), which are defined as changes in the environmental area, existed. In contrast to that, the space events, and consequently the features, were not always controlled in the study of Herman et al. (1986). In the second and third experiment, paths through portions of the children's school (for example, a vestibule, two hallways, a cafeteria, and a lobby) were chosen.

In summary, two or three explanations may account for the different results in the two studies mentioned above: the use of a within- versus between-subjects design, the different control of environmental features, and a possible developmental explanation.

Nowadays, virtual environments are being used more and more frequently to conduct research in the field of spatial cognition. Desktop systems and immersive systems, and an intermediate solution between both of them, are useful options for the simulation of spatial environments. In desktop systems, conventional desktop computer displays are used, whereas an immersive virtual environment is one in which the user is perceptually surrounded by the virtual environment through the use of special output devices such as head-mounted displays. Intermediate solutions are those that make use of a projection screen or three-dimensional monitors (Jansen-Osmann, 2002). Advantages of using virtual environments are the following: Spatial relations can be varied quickly and in an economic manner; participants can operate in a self-determined way; and real as well as fictional environments can be simulated (Goldin & Thorndyke, 1982). Furthermore, one can "create environments of varying complexity, make on-line measurements during navigation, control many spatial learning parameters, such as the amount of exposure to the environment and the number, position, and the nature of landmarks" (Péruch, Belingrad, & Thinus-Blanc, 2000, p. 255). We know that people can acquire knowledge about directions (Albert, Rensink, & Beusmanns, 1999) and distances (Jansen-Osmann & Berendt, 2002; Willemsen & Gooch, 2002), are able to develop route and survey knowledge (Gillner & Mallot, 1998; Jansen-Osmann, 2002), and can navigate effectively in a virtual reality environment (Darken & Silbert, 1996; Ruddle, Payne, & Jones, 1999). Furthermore, the potential for virtual environments as useful spatial training media was appreciated in literature (Foreman, Stanton, Wilson, & Duffy, 2003; Waller, 2000).

There are some concerns regarding distance estimation. Witmer and Sadowski (1998) showed relative underestimation of distances in virtual environments, as compared to real environments. But Witmer and Kline (1998) showed that traversing this distance in a larger virtual environment improves the ability to estimate that distance. Jansen-Osmann and Berendt (2002) showed that results obtained in a real environment concerning the influence of turns on distance estimation by Sadalla and Magel (1980) could be replicated in a virtual environment. In the study of Jansen-Osmann and Berendt (2002), participants had to explore one route with two turns and one with seven turns in a desktop virtual environment. Experiment 1 employed ratio estimation and drawing methods and replicated Sadalla and Magel's (1980) findings of a route-angularity effect. Experiment 2 employed a reproduction method and extended the results by showing that, relative to physical distance, the route with fewer turns was underestimated, whereas the route with more turns was overestimated. The results of this study suggest that the route-angularity effect can be verified in a virtual environment.

Resuming the three explanations (developmental theory, type of design, and control of environmental features), we think that the latter two are the most plausible. We started to rule out the influence of feature number and space events. This is in accordance to Herman et al. (1986), who concluded that “future research examining this effect must be conducted under conditions in which the events encountered along a path are strictly controlled” (p. 533). We expected that the route-angularity effect could be verified in a controlled environment by investigating distance knowledge in children at school age. Herman et al. did not find an age difference concerning distance estimation. For this reason, we firstly limited our study to children at the age of 10 to 11. Therefore, Experiment 1 was carried out with the aim of replicating Herman and colleagues’ study in a controlled virtual environment.

EXPERIMENTS

EXPERIMENT 1

Hypothesis. Children at middle school age show a route-angularity effect in a controlled environment.

METHOD

Participants. Twenty children at the age of 10 to 11 years (*M* age = 10.9) volunteered in Experiment 1: 10 boys and 10 girls. The children were recruited through the local newspaper. All parents gave written informed consent to take part in the study. The participants were randomly assigned to two groups (see below).

Materials. Three routes were simulated with the software 3DGame Studio on a 233 Mhz PC (see www.conitec.com). A typical corridor of the routes is shown in Figure 1.

The routes consisted of a set of corridors: Route A, 40 units in length and containing two turns; Route B, 40 units in length and containing seven turns; and Route C, a straight of 20 units in length. The survey views of Routes A through C resembled those of the original study by Sadalla and Magel (1980) and of the replication in a virtual environment (Jansen-Osmann & Berendt, 2002). They are shown in Figure 2.

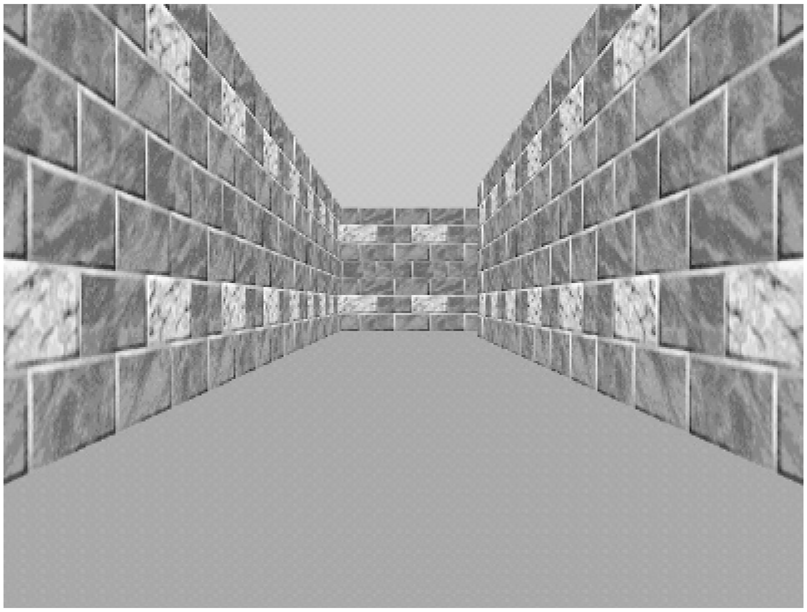

Figure 1: An Insight in One of the Virtual Routes

Children were seated in front of a 17-inch monitor and were familiarized with the routes by active navigation with a joystick. In the following test phase, participants received a protocol sheet, which contained a horizontal line. On this line, Route C was marked with start-point X and goal-point Y, whereby the length was about one third of the total length of the line.

Procedure. The children were tested individually in a single session that lasted approximately 15 minutes and took place in a laboratory at the Heinrich Heine University of Duesseldorf, Germany. First, the children had to become familiarized with the use of a joystick or, if they were already used to it, with the special joystick's rotation and translation settings. When they could easily manage the navigation procedure, the experiment started. The children were instructed to explore the three routes, whereby Route C was always the last one and the order of exploring Route A and Route B was varied between children. The children did not know beforehand that they had to estimate distances. The time needed to explore the routes was registered.

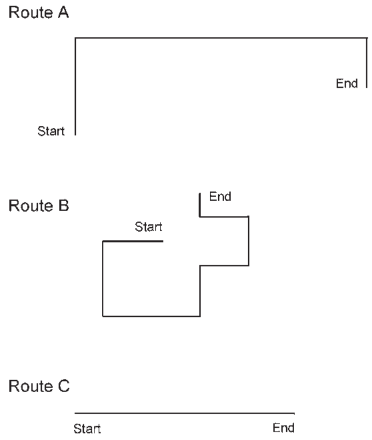

Figure 2: Overview of Routes A, B, and C

In almost the same manner as in the studies mentioned above (Jansen-Osmann & Berendt, 2002; Sadalla & Magel, 1980), distance estimation was retrieved by two methods: ratio estimation and route drawing. In the ratio-estimation task, children were asked to mark the lengths of Routes A and B in relation to Route C on the protocol sheet, starting from the starting-point X. In the route-drawing task, children had to draw Routes A and B on a blank sheet of paper. The marked and drawn lengths were measured in millimeters.

Experimental design. There were two experimental factors: the kind-of-route factor and the order-of-route-exploration factor. The kind-of-route factor was manipulated within subjects (Route A with two turns and Route B with seven turns); the order-of-route-exploration factor was a between-subjects factor (exploration of Route A before Route B and exploration of Route B before Route A). There were five dependent variables:

1. estimation of the route length via ratio estimation (measured in millimeters);
2. length of the route drawing (measured in millimeters);
3. number of turns in the drawing;
4. kinds of turns in the drawing (a sequence of left turns and/or right turns); and
5. time needed to explore the routes.

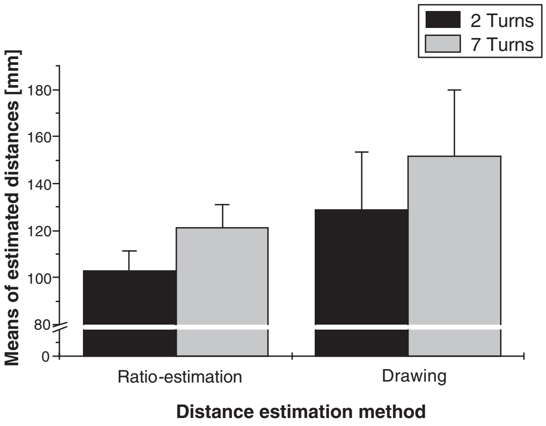

Figure 3: Means and Standard Errors of Estimated Route Lengths (Ratio-Estimation and Drawing Techniques—Experiment 1)
NOTE: Error bars indicate standard errors.

RESULTS

Distance estimation (ratio-estimation technique). Figure 3 (left side) shows the mean values and standard errors of the route lengths estimated via ratio estimation.

Route A, with two turns, was estimated as being shorter than Route B, with seven turns (Route A: $M = 103.1$ mm, s$M = 8.1$; Route B: $M = 121.1$ mm, s$M = 9.99$). The difference was significant, $F(1, 18) = 15.85$, $p < .001$. In comparison to the standard value (Route C), which was half as long as the other two routes (74 mm), both experimental pathways were underestimated. Furthermore, there was a main effect for order of route exploration, $F(1, 18) = 4.65$, $p < .05$, and an interaction between the two factors (kind of route and order of route exploration), $F(1, 18) = 6.14$, $p < .05$. A route-angularity effect occurred only when the children had explored the route with two turns first. In this case, Route A, with two turns, was estimated shorter than route B, with seven turns (Route A: $M = 116.5$ mm, s$M = 15.37$; Route B: $M = 145.7$ mm, s$M = 19.16$). There was no route-angularity effect when children explored the route with seven turns first (Route A: $M = 89.7$ mm, s$M = 5.13$; Route B: $M = 96.5$ mm, s$M = 5.65$).

Distance estimation (drawing technique). Figure 3 (right side) also shows the mean values and standard errors of the drawn route lengths. Route A was estimated as being shorter than Route B (Route A: M = 128.7 mm, sM = 24.8; Route B: M = 151.9 mm, sM = 28.05); the difference was significant, $F(1, 18) = 4.55$, $p < .05$.

Drawing of the routes. Analysis of the number of turns in the drawings showed that, on average, the number of turns was remembered quite accurately. Route A, containing two turns, was drawn with a mean of 2.65 turns (sM = .47), and Route B, containing seven turns, was drawn with a mean of 6.1 turns (sM = .57). Thirty percent of the children estimated the number of turns of Route A correctly, but none of them was able to correctly estimate Route B. In the analysis of the direction of route drawing, only those drawings that contained the right number of turns were considered; therefore, only drawings of Route A were considered. Four children (20%) had reproduced the order of turns correctly.

Exploration time. The time needed to explore Routes A and B differed significantly, $F(1, 18) = 111.01$, $p < .001$. More time was needed to explore Route A (M = 40.5 s, sM = .26), in comparison to Route B (M = 36.33 s, sM = .37). This difference, which seems to be counterintuitive, can be explained easily by taking into account the following two reasons. First, the rotation speed set for the joystick caused the exploration of a route with more turns to take a shorter amount of time. Secondly, children tended to cut the corners. This implicates that children needed less time to explore Route B (the one with more corners). Therefore, time as an explaining factor for overestimation of length can be ruled out. Otherwise, children should have taken more time to explore Route B.

DISCUSSION

At first, the results seem to confirm the route-angularity effect in children. A route with more turns was estimated as being longer than a route of the same objective length with fewer turns. This result does not depend on the exploration time because Route A, which was estimated shorter, was not explored in less time than was Route B. Furthermore, the effort hypothesis could be excluded. All children had been familiar with the use of a joystick or had enough time to become familiar with it. There was certainly no difference in the effort to explore both routes. For this reason, the effort hypothesis need not be considered further to explain the results. Even in Sadalla and Magel's (1980) original study, it seemed to be a questionable explanation because it is not very plausible that taking a short walk with more turns requires more effort. A statement about the scaling hypothesis (a statement about the compression of the longer turns in comparison to the shorter ones) cannot be made within this experiment. This is because neither ratio estimation nor the drawing technique demanded explicitly the estimation of every single segment. To test the scaling hypotheses, an experiment where explicit estimations of every single segment's length will be tested seems reasonable (see General Discussion).

Contrary to the study of Sadalla and Magel (1980), exploration time for the route with more turns was shorter than exploration time for the route with less turns. One reason for this could be the width of the routes, which made it possible to cut the corners. Consequently, walked distance and exploration time could be saved. It might be unexpected that the route with more turns needed less time to be explored but was estimated as being longer. It seems quite critical, though, to equal objective and subjective exploration time. Events that occur during a time interval may lengthen or shorten subjective time estimation (Block, 1992; Zakay, 1989; Zakay, Tsal, Moses, & Shahar, 1994). These authors assume that there are two processors: a temporal and a nontemporal one. If attention is concentrated on the temporal processor, time seems to pass by more slowly. If attention is concentrated on nontemporal events, attention is detracted from the temporal processor, and time seems to pass more quickly. Within this experiment, we could not decide if the events (the turns) have lengthened or shortened subjective time and how this subjective time estimation correlates with distance estimation.

In contrast to the studies of Jansen-Osmann and Berendt (2002) and Sadalla and Magel (1980), there was a significant influence of the order of exploration, at least if the ratio-estimation method is used: The route with less turns was only underestimated when it had to be explored first. Therefore, the context of the learning situation seems to influence distance estimation in children. This leads us to another question: Does the route-angularity effect appear if children only have to learn and estimate one route? This corresponds to our second possible explanation (see above): We assume that the effect does not appear in a between-subjects design.

Next to the use of the ratio-estimation technique, we also used another distance-estimation technique: a reproduction method, which did not require scale translations and the representation in another medium. In contrast to the reproduction technique, the ratio-estimation technique and drawing technique have a drawback: Distances estimated can be compared only with each another. The use of the reproduction technique allows statements concerning overestimation or underestimation with respect to the physical lengths of the routes.

EXPERIMENT 2

Hypothesis. The route-angularity effect does not appear in a between-subjects design in children at middle school age.

METHOD

Participants. Forty children at the age of 11 and 12 (*M* age = 11.75) volunteered for Experiment 2: 19 boys and 21 girls. All children were pupils at the Lise-Meitner-Gymnasium in Leverkusen, Germany, at the 6th-grade level. All parents gave written informed consent to take part in the study. The children were randomly assigned to one of two groups (see below).

Materials. The materials were Route A, B, and C from Experiment 1 and a virtual room with some objects in it. For the reproduction technique, we used a straight Route D, which was 3 times as long as Route C. Again, children were seated in front of a 17-inch monitor and learned the routes by active navigation with a joystick. The protocol sheet was the same as in Experiment 1.

Procedure. The children were tested in a single session that lasted about 15 minutes in a dark classroom at the Lise-Meitner-Gymnasium. After becoming familiarized with the use of a joystick, the experiment started. Half of the children were instructed to explore Route A, the other half Route B. After this, they were asked to explore the virtual room for 80 seconds, which corresponded to the exploration time needed for the second route in Experiment 1. This spatial task was chosen to equal the time between the learning phase and the estimation phase across experiments. After exploring the virtual room, they had to explore Route C. Children did not know beforehand that they had to estimate distances. The time needed to explore the routes was registered.

In this experiment, distance estimation was first retrieved by ratio estimation. Again, children were asked to mark the length of the explored route in relation to Route C on the protocol sheet, starting from starting-point X; the marked length was measured in millimeters. After that, the children had to draw the explored route on a blank sheet of paper. We did not record the length of the drawn route because we could not compare the distance estimation because of a missing standard value. In the next test phase, children were asked to walk Route D until they thought they had walked the length of Route A or B, respectively, and then to stop.

Experimental design. There was one experimental factor: kind of route. This factor was manipulated between subjects (Route A with 2 turns; Route B with 7 turns). There were four dependent variables:

1. estimation of the route length via ratio estimation (measured in millimeters);
2. estimation of the route length via reproduction technique (measured in units of the software);
3. number of turns in the drawing; and
4. time needed to explore the routes.

RESULTS

Distance estimation. Figure 4 shows the mean values and standard errors of the route lengths estimated via ratio estimation.

There was no difference between the estimation of Route A, with two turns, and Route B, with seven turns (Route A: M = 108.5 mm, sM = 5.1; Route B: M = 111.2 mm, sM = 9.51). There was no route-angularity effect when the children had to explore only one route.

Furthermore, the lengths estimated via the reproduction technique were transformed into percentages of the respective route's "physical" length (the length in the software's internal units). Figure 5 shows the mean values and standard errors of the estimated route lengths compared to their physical lengths.

Both routes were underestimated to the same degree when compared to their physical length. There was no difference between the estimation of Route A, with two turns, and Route B, with seven turns (Route A: M = 84.15%, sM = 5.84; Route B: M = 74.15%, sM = 6.27). There was no route-angularity effect when children had to explore only one route.

Drawing of the routes. The number of turns was remembered quite accurately. Route A, containing two turns, was drawn with a mean of 2.4 turns (sM = .2), and Route B, containing seven turns, was drawn with a mean of 7.1 turns (sM = .6). Eleven children (60%) estimated the number of turns of Route A correctly. Eight of them had reproduced the order of turns correctly. One child was able to correctly estimate the number of turns of Route B.

Exploration time. Again, the time needed to explore Routes A and B differed significantly, $F(1, 18) = 127.73$, $p < .001$. More time was needed to explore Route A (M = 40.65 s, sM = .25), as compared to Route B (M = 36.65 s, sM = .25). There was no correlation between time needed and distance estimation.

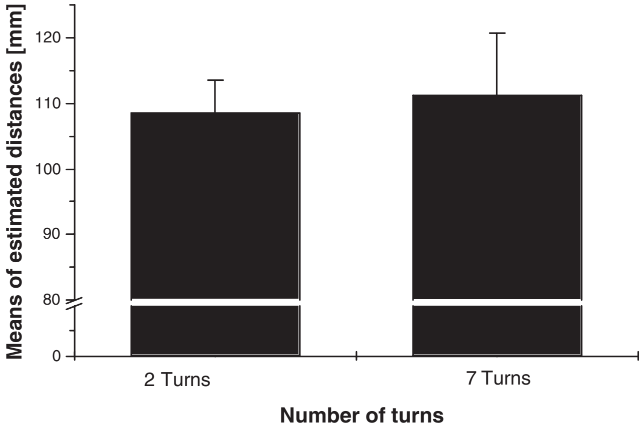

Figure 4: Means and Standard Errors of Estimated Route Lengths (Ratio-Estimation Technique—Experiment 2)

NOTE: Error bars indicate standard errors.

DISCUSSION

When using a between-subjects design, the results from Experiment 1 could not be replicated. Children at the 6th-grade level did not show a route-angularity effect when they explored and estimated only one route. This is valid for both the ratio-estimation and the reproduction technique. The results of the reproduction technique show that both routes were underestimated in comparison to their physical length. This is in accordance with the well-known relationship between subjective and objective distances, which can be described by a psychophysical power function: For distances retrieved from memory, the exponent is below 1.0 (Wiest & Bell, 1985). Furthermore, studies have shown that an underestimation of distances learned in virtual environments is common (e.g., Willemsen & Gooch, 2002; Witmer & Sadowski, 1998).

It seems to be reasonable that the difference between the results of the studies of Herman et al. (1986) and Sadalla and Magel (1980) is because of different experimental designs. Although in the first study, children were randomized to one of the two groups (exploring the route with less turns vs. exploring the route with more turns), in the latter study, participants had to estimate both routes. Our assumption is as follows: When children had the chance to compare the two routes on the basis of the number of features, this was used as a heuristic. If this possibility was excluded, they had to use

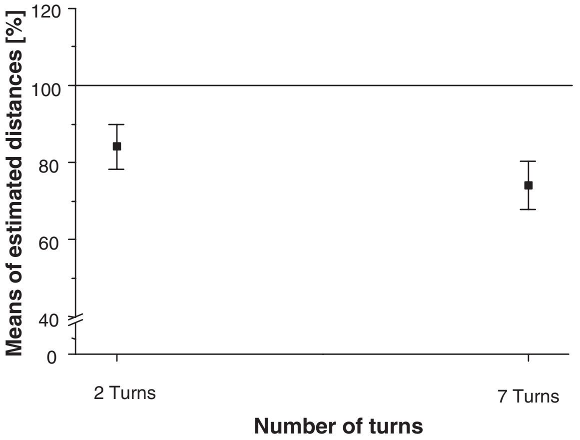

Figure 5: Means and Standard Errors of Estimated Route Lengths Relative to Physical Route Lengths (Reproduction Technique—Experiment 2)
NOTE: Error bars indicate standard errors.

another strategy; for example, a mental scanning of the time used to explore the route could have been used.

Based on the results of these two experiments, we can reject Hypothesis 3 mentioned in the introduction. Both experiments were conducted in an environment where all features and space events were controlled; therefore, the route-angularity effect seems to depend on the kind of design; more precisely, the strategy that was induced through this design. To confirm this assumption, a developmental influence must be excluded. For this reason, we investigated the route-angularity effect in adults with help of a between-subjects design. We assumed that the route-angularity effect does not appear in a between-subjects design in adults.

EXPERIMENT 3

Hypothesis. The route-angularity effect does not appear in a between-subjects design in adults.

METHOD

Participants. Forty adults, 20 males and 20 females (*M* age = 27.2 years), volunteered for Experiment 3. They were recruited through local advertisements at the Heinrich Heine University and in local newspapers. Participants were randomly assigned to one of two experimental groups (see below).

Materials. The material was identical to that of Experiment 2.

Procedure. The adults were tested in a single session that lasted approximately 15 minutes. Each session was conducted in a laboratory at the Heinrich Heine University.

The learning was identical to that of Experiment 2.

Experimental design. There was one experimental between-subjects factor: kind of route (Route A, with two turns; Route B, with seven turns). There were three dependent variables:

1. estimation of the route length via ratio estimation (measured in millimeters);
2. number of turns in the drawing; and
3. time needed to explore the routes.

RESULTS

Distance estimation. Figure 6 shows the mean values and standard errors of the route lengths estimated via ratio estimation.

There was no significant influence of the kind-of-route factor. Statistically, no route was estimated longer than the other one (Route A: $M = 144.5$ mm, $sM = 9.65$; Route B: $M = 131$ mm, $sM = 8.31$).

Drawing of the routes. The number of turns was remembered quite accurately. Route A, containing two turns, was drawn with a mean of 1.9 turns ($sM = 0.37$), and Route B, containing seven turns, was drawn with a mean of 5.3 turns ($sM = 1.6$). Seventeen subjects (85%) estimated the number of turns of Route A correctly; furthermore, they all reproduced the order of turns correctly. Four subjects (20%) were able to correctly estimate the number of turns of Route B; none of them reproduced the order of turns correctly.

Exploration time. Again, the times needed to explore Routes A and B differed significantly, $F(1, 38) = 310.33$; $p < .001$. More time was needed to explore Route A ($M = 40.8$ s, $sM = .22$) in comparison to Route B ($M = 36.08$ s, $sM = .15$). There was no correlation between time needed and distance estimation.

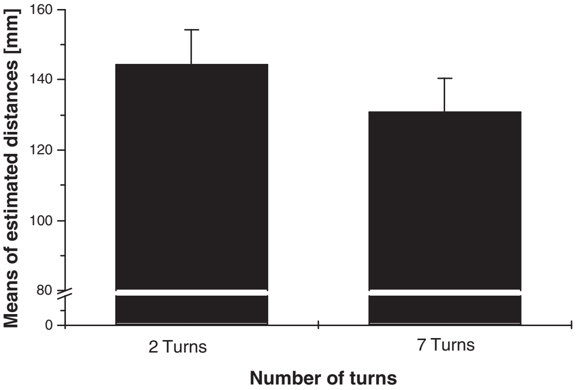

Figure 6: Means and Standard Errors of Estimated Route Lengths (Ratio-Estimation Technique—Experiment 3)

NOTE: Error bars indicate standard errors.

DISCUSSION

Comparable to the children's study, there was no route-angularity effect when adults had to estimate only one route. This indicates that there is no developmental difference between adults and children at middle school age concerning the influence of number of turns on distance estimation. Our results suggest that the route-angularity effect depends on the experimental design. Sadalla and Magel (1980) could demonstrate this effect because every participant had to explore and estimate both routes.

GENERAL DISCUSSION

THE ROUTE-ANGULARITY EFFECT DEPENDS ON THE EXPERIMENTAL DESIGN

The results of the experiments described above unequivocally show that the route-angularity effect depends on the kind of experimental design. In a within-subject design, children at middle school age (Experiment 1) and adults (Jansen-Osmann & Berendt, 2002; Sadalla & Magel, 1980) underestimated a route with less turns in comparison to a route of equal length with more turns. This proved to be a stable finding across at least three different measurement methods: ratio-estimation technique and drawing technique

(Experiment 1 and Jansen-Osmann & Berendt, 2002), as well as reproduction technique in Jansen-Osmann and Berendt (2002). In a between-subjects design, children at the age of 11 and 12 years (Experiment 2) and adults (Experiment 3) showed no route-angularity effect. Under this condition, a route with more turns was not estimated as being longer than a route of equal length with less turns. This result also proved to be stable across ratio-estimation technique and reproduction technique (Experiment 2); the use of the last technique allows the conclusion that both routes were underestimated. Furthermore, it could be confirmed that adults and children at middle school age do not show a fundamental difference concerning the influence of turns on distance cognition. This is in accordance with other studies that found no differences in distance estimations between adults and children in late childhood (e.g. Allen, 1981; Plumert & Hund, 2001).

MECHANISM OF DISTANCE ESTIMATION

When taking these results into account, many open questions remain. The main question is, What mechanism might be responsible for the different results dependent on the kind of experimental design? There are at least three different explanations:

1. First possible mechanism: The first explanation—a quite simple one—is as follows: Children in Experiment 1 had to explore and estimate two routes. Perhaps they assumed, because of the experimental design, that the two routes could not have been of the same length, and therefore, they estimated the route with more information as being longer.
2. Second possible mechanism: The second explanation takes into account that it seems to be more difficult to learn and estimate more than one route, especially for children. Whereas only 30% of the children drew the number of turns correctly for the route with less turns in Experiment 1, it was 60% in Experiment 2. If the task is difficult, children and adults might use the number of features along a route to estimate the length of that route. In this case, the number of features seemed to be the most prominent heuristic to use. If the task is easier (in terms of estimating only one route), the number of features loses its importance as a heuristic. In this case, their heuristic might be based on the time needed to explore the route. When the route length is retrieved, participants mentally scan the route, whereby the mental scanning is deduced from the exploration time. The scanning process results in a more exact reconstruction of the route than the comparison of the number of features. Against this explanation it could be argued that there were no correlations between exploration time and distance estimation in Experiments 2 and 3. Also, Thorndyke's (1981) proposed analog timing model, which assumes that par-

ticipants perceptually scan a route from start to destination and use scan duration to determine path distance, appears to be invalid. His assumption that distance estimates increased as a linear function of the number of intervening points (in this case, turns) does not seem to be correct for the route-angularity effect. The failure of applying this model seems to lie in the fact that the occurrence of longer scanning times corresponding to longer distance estimates has been mainly observed for pictorial distances.

3. Third possible mechanism: In Experiment 1, the children estimated the distances of the routes only after they had explored both routes. The learning of one route may have interfered with the learning of the other route.

THE USE OF DESKTOP VIRTUAL ENVIRONMENTS

These results were obtained under conditions in which the events encountered along the paths were strictly controlled, namely, in virtual environments. This means that the results could not be influenced by a lack of control of other features or space events. Virtual environments seem to be a suitable research tool to simplify the investigation of spatial knowledge. However, next to the positive aspects, there seem to be some potential drawbacks, especially in the use of desktop virtual reality systems, which do not involve proprioceptive sensory information. In this sense, Witmer, Bailey, Knerr, and Parsons (1996) argue against the use of desktop virtual environments because they do not allow for the integration of self-motion as being equivalent to actual environmental experience. Their students had to learn routes through an office building, either through real exploration, desktop virtual exploration, or verbal instruction. The results showed that virtual experience may not be quite as effective as real exploration. In contrast to that, Waller, Knapp, and Hunt (2001) showed that there was no difference in learning the spatial representation of mazes between wire-frame virtual and real-world conditions. They assumed that differences between individuals on characteristics such as gender, prior computer use, and cognitive ability accounted for more variance in spatial tasks than did the type of virtual environment. Richardson, Montello, and Hegarty (1999) take an intermediate position. They suggest that similar cognitive mechanisms are involved in a desktop virtual and real learning condition but also that participants are susceptible to disorientation after rotation. One might suppose that the use of an immersive virtual system, where updating at least the head position is possible, could ameliorate spatial learning. However, a study by Westerman, Cribbin, and Wilson (2001) showed that the efficiency of navigation was poorer in an immersive virtual situation in comparison to a desktop virtual situation. Furthermore, nausea occurred in 25% of participants in this virtual immersive situation. Ruddle, Payne, and Jones (1997) showed that the investigation of more cognitive processes holds for both desktop and immersive virtual reality systems. Recently, Chabanne, Péruch, and Thinus-Blanc (2003) showed that knowledge acquired from a desktop virtual environment can be transferred to the corresponding real-world environment. However, it has to be mentioned that some skills apparently transfer better than others. Kozak, Hancock, Arthur, and Chrysler (1993) failed to show transfer of a pick-and-place task from a virtual environment to a real environment.

We can presume that the use of desktop virtual environments depends on differences in individuals and the kind of task. Using desktop virtual environments to investigate the route-angularity effect is allowed because we proved, in an earlier study, that the results of Sadalla and Magel (1980) could be replicated in a desktop virtual environment.

FUTURE RESEARCH

In this article, we investigated an important issue because of an existing discrepancy in the literature, and we can clearly rule out the importance of the experimental setting used. More work has to be done to clarify the underlying mechanisms and the developmental course. There are several possibilities to accomplish this clarification:

1. Interference effect: To exclude a possible interference effect, another experiment should be conducted in which the participants have to learn and to estimate the first route and thereafter learn and estimate the second one.
2. Estimates of single segments: We should focus on one possible explanation concerning the route-angularity effect, namely, the scaling hypothesis, which leads us to the question of whether longer segments are underestimated in comparison to shorter ones and whether segments, toward the end of the route, are more and more compressed. We have to investigate if this shrinking appears in the same manner when estimating one or several routes. To clear this point, an experiment where explicit estimations of every single segment's length is tested seems reasonable. One possibility might be to place a landmark at every turn and to ask the participants to estimate the distance between single landmarks and the starting point or between consecutive landmarks. This procedure assumes that the route is well known. The use of the drawing technique in Jansen-Osmann and Berendt (2002) and in the experiments described here proved that this was not the case. Participants had difficulties when asked to correctly draw a replication of the route with seven turns.

3. Exploration time: Experiments 2 and 3 did not show any correlation between the time needed to explore the route and the estimated distance, even if this might be expected. A more detailed investigation should be conducted. One possibility to examine the influence of time on distance estimation is to systematically vary the time needed for exploration. It would be easy to adjust the joystick's translation and rotation velocity so that the exploration time could be varied for every route. Varying the number of features and the exploration time allows for a comparison between the importance of time and number of features as heuristic factors when participants have to estimate only one route. There is evidence from a study by Herman, Norton, and Roth (1983) that adults and children rely more on exploration time than on the number of perceived features when they have to estimate the distance of a route. Their participants explored one route, which was segmented in two parts of the same length. Walking speed was varied; participants needed either the same exploration time for both parts or quadruplicate for one part. Objects were presented in both parts of the route. Although there was no influence in the number of the objects, exploration time played an important role: The more time participants needed for exploration, the longer the routes' length was estimated.
4. Developmental course: The main goal was not to investigate the developmental course of the route-angularity effect, even if it seems to be very valuable. To provide a convincing picture of the relative stability of the presence or absence of the route-angularity effect over the course of middle and late childhood, additional age groups should be tested. Previous research on route learning has pointed to age-related change in the 7-to-11-year period (Allen, 1981).
5. Model-based research: Lastly, our research should, and will be, more model based. Assuming that the analog timing model (Thorndyke, 1981) does not hold reliable in any case for environmental distances, a cognitive model for distance estimations in environmental space, Feature, was constructed (Berendt, 1999). Future research should also investigate the route-angularity effect considering the constraints of Feature.

CONCLUSION

The results of our experiments provide evidence that the route-angularity effect depends on the experimental design. Children between the ages of 10 and 12 and adults showed no difference concerning the influence of number of turns on distance estimations. If participants had to estimate only one route, the number of features seemed to lose importance. In further studies, the underlying mechanism and the developmental course should be investigated.

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