Each of 34 subjects answered two spatial questions about each of 32 schematic maps from memory. The maps had been used before for performing two navigation tasks, resembling driving a car or flying a plane. The two questions were about the distance between and spatial orientation of two map cities. These cities either were on the same navigation path or belonged to different paths (defining action-similarity), and were either connected by lines or not (defining perceptual similarity). Results showed an expected effect of action-similarity on distance estimation (action-sharing made the cities seem closer to each other), but only when cities were not connected by lines. Cities that were connected by lines were judged to be closer to each other than non-connected cities (expected effect of perceptual similarity). No similarity effects were observed on the speed of verifying orientation statements. Theoretical and practical implications of these findings are indicated.

BACKGROUND

This paper reports an experiment into the effects of action-similarity and perceptual similarity on the speed and accuracy of memory-based spatial judgments about objects (“cities”) in a map-like display. We define action-based similarity as the phenomenon that performing the same action on different spatial objects may influence the degree to which those objects are experienced as belonging together, i.e., by letting subjects travel to some cities and skip other cities that are present on the same map.

Perception-based similarity is defined by us as the phenomenon that spatial objects are experienced as belonging together on the basis of perceptual Gestalt laws governing the spatial configuration of those objects, i.e., by drawing line segments (“roads”) in the map to connect cities.

Two types of memory-based spatial judgment were used to test the effects of similarity: distance estimation (for which precision is the most relevant parameter) and verification of spatial orientation statements (for which speed is the most relevant parameter).

At the beginning of each of a number of trials, subjects were asked to complete two navigation exercises in so-called induction tasks, using a schematic map containing cities. One of the exercises resembled driving a car around the map from city to city. The other exercise resembled flying a plane around the same map from city to city.

PROBLEM STATEMENT AND HYPOTHESES

Action-based similarity

Hommel and Knuf (2000) found evidence for action-based grouping on the speed of verifying statements about the relations between houses on a map-like display: statements were verified faster if these houses had previously been associated with similar (rather than different) actions. However, no effects were found on the accuracy of estimating distances between houses. Hommel and Knuf also showed that using meaningful object-action associations (such as opening doors of houses) makes it easier to observe action-based effects, as compared to using arbitrary associations (such as pointing at or clicking on houses).

In this study, we employed an induction task more representative of real traveling than the one used by Hommel and Knuf (2000): subjects were to physically navigate (travel) along a series of “cities” and to skip other cities that were present on the same map. It was hypothesized that action-based similarity would have a stronger effect under these circumstances, not only on the speed of verifying spatial orientation statements, but also on the accuracy of estimating distances (action-based similarity hypothesis).

Perception-based similarity

An effect of perception-based similarity was also expected on the basis of previous studies, e.g., McNamara et al. (1984) and Klippel et al. (2005), but only for the distance estimation task. Specifically, it was hypothesized that distances were estimated to be shorter for cities that were connected by line segments than for cities not so connected (perception-based similarity hypothesis).

Interaction

By combining the factors of action-based similarity and perception-based similarity in a factorial design, we were also in a position to test whether and how the two kinds of similarity would interact with respect to distance estimation. Two hypotheses come to mind.

Mutual reinforcement (over-additive interaction) hypothesis. When only one kind of similarity is present in the cities to be compared in the memory test task, it will have only moderate effects on the subjects’ distance estimations. However, in combination the two kinds of similarity will reinforce each other’s effects, because the two kinds tend to co-occur in real life. The result will be an over-additive interaction between the effects of perception-based and action-based similarity.

Mutual attenuation (under-additive interaction) hypothesis. Each kind of similarity, present without the other, will “afford” (remind the subject of) the other kind of similarity, because the two kinds tend to co-occur in real life. However, the combination of both kinds of similarity will provide partly redundant information and the two kinds will attenuate each other’s effects.
The result will be an overall effect which is smaller than the sum of the separate effects (under-additive interaction).

Subjects’ spatial memory was tested in a memory test task at the end of each trial. In this task, the map was removed from the display and subjects were to answer (from memory) the spatial questions. These either involved connected or unconnected cities, and either involved cities that were part of the same navigation path or were visited in different navigation paths. In order to prevent forgetting of the spatial layout before their memory was tested, subjects were given a memory consolidation task in between each induction and memory test task. In this task, they were forced to recall and re-memorize the names and locations of cities.

**METHOD**

**Subjects**

Thirty-four subjects participated in this study, all university students with normal eye vision.

**Stimuli and equipment**

On each of 32 experimental trials, a different map was used for various tasks, to be described below. Each map contained 12 labeled “cities” in the form of dots (see Figures 1 and 2). All maps were variations of two fixed base configurations: A and B. On the first 16 trials, configuration A was used, using the letters A through L as city labels. Configuration B was used on trials 17 - 32, using the labels M through X.

Maps were varied from trial to trial by randomly moving each city of the corresponding base configuration 2 to 8 pixels in an arbitrary direction (jitter). This was done in order to limit the complexity of map memorization with each new trial and make it more likely to observe effects of the similarity manipulations.

For each map, four of the 12 cities were predefined as being pairs of critical cities. One pair was designed to be used in the orientation statement verification task, the other was designed for the distance estimation task. These cities were not known to the subjects and could vary from trial to trial. (See Figures 1 and 2 for examples.)

The critical pairs were systematically varied with respect to the following dimensions (this was done separately for the distance estimation task and the orientation statement verification task):

- Whether or not the cities appeared in one of the two navigation paths during the induction tasks
- Whether or not the cities were connected by line segments.

In addition, the pairs were systematically varied with respect to the subjective distance between the cities and with respect to the precise orientation of the cities vis-à-vis each other.

The experiment was programmed in Macromedia Authorware version 7. The map display occupied most of the screen space of a 17 inch color monitor, leaving some space for explanatory remarks and feedback messages on the right-hand side of the screen.

**Procedure and tasks**

The experiment consisted of one practice trial, followed by 32 experimental trials. The same trials were presented to all subjects in the same order. This order is described below (for a summary, see Figure 3).

1. “Drive-car” task (Induction task 1). Subjects were presented with a display like the one shown in Figure 1. They were asked to “drive a car” by moving a car icon (using the arrow keys of the keyboard and the enter key) to four connected cities shown on the display, e.g. cities A, K, H and D in Figure 1. When a navigation error occurred (subject navigated to a wrong city or a city was visited too early) an error message appeared on the screen, inviting the subject to try again. If three errors had been committed, the experiment would continue to the next trial.

2. Memory consolidation task 1. The same map was presented as before, but this time without city labels. Subjects were given a list of six labels and asked to identify the location of the corresponding cities by clicking on them with the mouse. These cities included the four cities used in the drive-car task. The familiar cities either had to be clicked in the same order as used before, or in the reverse order, followed or preceded by the two unfamiliar cities. After successful identification, the corresponding city label would re-appear in the map. Not until all locations had been identified correctly would the experiment proceed to the next task.

3. “Fly-plane” task (Induction task 2). Subjects were presented with the same display as in Induction task 1, but now were asked to “fly a plane” to four cities (different from the ones used in Induction task 1) (see Figure 2). These cities were not connected by lines, e.g. cities F, B, I and C in Figure 2 (dotted line not shown to subjects).

4. Memory consolidation task 2. Same as Memory consolidation task 1, but this time the six cities included the four cities used in the fly-plane task.

5. Distance estimation task (Memory test task 1). The map display was no longer visible. Now, subjects were to estimate the distance between two cities from one critical pair from memory. They answered by moving a horizontal slider from its right-most position (maximum size) to the left, until the estimated distance was obtained, using the mouse.

Only accuracy was emphasized for this task. However, if after 45 seconds no response had been recorded yet, the experiment would automatically proceed to the next trial.

6. Orientation statement verification task (Memory test task 2). Again, the map display was no longer visible. Subjects were to verify a statement about the orientation of two cities belonging to the second critical pair from memory as fast and accurately as possible. For example: “Is C is to the right of D?”. In addition to to the right of, the following predicates could be used in the statements: to the left of, above, and below. Each predicate was used equally frequently. The predicates to the right/left of were only used for cities that were almost vertical and the remaining predicates were only used for cities that were almost horizontal. The subject responded by clicking with the mouse on one of two buttons (corresponding to yes or no). Again, if subjects needed more than 45 seconds of answering time, the experiment would automatically continue to the next trial.

On trials 1 – 16 (all derived from Configuration A) guided navigation was used: subjects were told the order in which the four cities were to be navigated in the induction tasks. However, on trials 17 – 32 (all derived from Configuration B) unguided navigation was used: subjects had to figure out themselves the
most efficient (least-cost) navigation path, though the first city was always given. This was done in order to create an extra opportunity for experiencing the spatial layouts in the second half of the experiment, though we realized this made the navigation exercise somewhat more difficult.

**Design and analysis**

**Independent variables.**
1. Action-based similarity: critical cities were, or were not, associated with the same navigation path.
2. Perception-based similarity: critical cities were, or were not, connected by line segments.
3. Type of navigation: guided or unguided. Confounded with type of base configuration (A or B) and order of presentation (first half, second half of experiment).

These independent variables were crossed completely in a $2 \times 2 \times 2$ within-subjects design. (The other factors mentioned in *Stimuli and equipment* were collapsed into the error term.)

**Dependent variables.**
1. For the distance estimation task: distance over-/underestimation, expressed by the algebraic difference between estimated and objective distance (in terms of number of pixels).
2. For the orientation statement verification task: response time (in seconds).

**RESULTS**

**Distance estimation task**

Table 1 shows the mean values for distance over-/underestimation for the various combinations of the independent variables (positive values indicate overestimation). In addition, the corresponding testing results are shown in this table.

It can be seen that there was a general tendency to overestimate inter-city distance: grand mean = 23 pixels (px).

The main effect of action-based similarity was not significant, $p > 0.10$, though there was a tendency to overestimate distance by a smaller amount when critical cities were associated with the same navigation path (which is in the expected direction): $M = 20.73\text{px}$, as compared to $M = 24.59\text{px}$ for cities not sharing such a path. Therefore, the action-based similarity hypothesis was not confirmed with respect to the distance over-/underestimation in an overall sense.

The main effect of perception-based similarity was significant, $F(1,33) = 11.44, p < 0.05$: distances were overestimated by a smaller amount for connected cities ($M = 18.12\text{px}$) than for not-connected cities ($M = 27.20\text{px}$), which was in the expected direction.

However, further analysis showed that this effect of connectedness only held when navigation was unguided (last 16 trials), $F(1,33) = 19.71, p < 0.05$ (significant interaction between type of navigation and perception-based similarity, not shown in table). In summary, the perception-based similarity hypothesis was confirmed, at least when navigation was un-guided (see next section for a discussion of this finding).

Finally, it can be seen in Table 1 that the interaction between perception-based similarity and action-based similarity was marginally significant, $F(1,33) = 3.22, p < 0.10$. Closer analysis reveals the locus of this interaction: for connected cities the effect of action-based similarity is not significant ($p > 0.10$). However, for not-connected cities distances were overestimated by a smaller amount if cities shared the same navigation path (which was in the expected direction), $M = 22.87\text{px}$, compared to cities not sharing such a path,
Table 1. Results for the distance estimation task (based on over-/underestimations expressed in number of pixels; positive values indicate overestimation). ME = main effect. I = interaction effect.

<table>
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<th>Action type (ME)</th>
<th>Connectedness (ME)</th>
<th>Conn × Action (I)</th>
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<th>Simple main eff. for Not conn</th>
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<td>Conn–Same</td>
<td>Same action</td>
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</tr>
<tr>
<td>Different action</td>
<td>Not.connected</td>
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</table>

$M = 31.53\text{px}$, $F(1,33) = 4.70$, $p < 0.05$. This lends support to the mutual attenuation hypothesis about the way the two kinds of similarity interact.

A similar (though not-hypothesized) interaction was observed when distance estimations were expressed in terms of the absolute, rather than the algebraic difference between estimated and objective distance, yielding a measure of estimation accuracy. Now, the data reveal that the distance between connected cities was estimated more accurately for not-action-shared cities than for action-shared cities. For non-connected cities there was no difference in estimation accuracy (significant interaction, $p < 0.05$, not shown in table).

Orientation statement verification task

On the average, only 54% of the answers were correct for this task, indicating the task was quite difficult. The average verification time was 5.07s.

The data revealed a non-significant main effect of action-based similarity, $p > 0.10$. Therefore, the action-based similarity hypothesis was not confirmed with respect to the orientation statement verification task.

In addition, neither the other main effect (i.e., of perception-based similarity) nor the interaction between the two types of similarity was significant ($p > 0.10$).

With respect to verification accuracy, the same (not-hypothesized) interaction was observed as was found for distance estimation accuracy, $F(1,33) = 4.11$, $p < 0.10$. For connected cities verification was more accurate when these cities did not share the same navigation path ($M = 53\%$ correct), as compared to action-shared cities ($M = 47\%$ correct). For non-connected cities the opposite pattern was observed: $M = 55\%$ correct for not-action-shared cities, and $M = 61\%$ correct for action-shared cities.

CONCLUSIONS AND DISCUSSION

Action-based similarity hypothesis

The results indicated that the expected effect of action-based similarity on distance over-/underestimation (smaller estimations for cities sharing the same navigation path) was observed for non-connected cities, but not in an overall sense. More research is needed to identify the precise conditions under which action-based similarity can be expected to affect people’s memory for distances.

Meanwhile, it seems that we were at least partly successful in inducing an action-based similarity effect on distance estimations. The greater resemblance of our navigation task to everyday navigation behavior (as compared to the tasks used in previous studies: Hommel & Knuf, 2000) may be responsible for this result.

However, the action-based similarity hypothesis was not supported by the data with respect to the speed of verifying orientation statements. Therefore, we were not able to confirm the findings of Hommel and Knuf (2000). One reason may be that our verification task was too difficult, judging by the average accuracies obtained for this task.

Perception-based similarity hypothesis

Our data support the perception-based similarity hypothesis with respect to distance over-/underestimation: distances between connected cities were judged to be shorter. This also confirms the findings reported earlier by McNamara et al. (1984) and Klippel et al. (2005).

However, it turned out the effect was only observed when navigation was unguided. Here, subjects were more actively involved in the navigation task, having to figure out themselves the optimal (least-cost) path along which the four cities should be navigated. It may be that the additional cognitive
effort involved in this task made subjects more aware of the precise spatial layout, but also made them more vulnerable for cognitive distortions. More research is needed to replicate this finding and understand the underlying cognitive mechanisms. Future research should also address the extent to which order of presentation of the types of navigation (first half, second half of experiment) and type of configuration (A, B) (both confounded with type of navigation) may have influenced the results.

Interaction
The distance over-/underestimation data reveal a marginally significant under-additive interaction between perception-based and action-based similarity. This lends support to the mutual attenuation hypothesis, though the precise form of the interaction was not predicted: distances between action-shared cities were estimated to be shorter, but this was only true for non-connected cities. For connected cities there was no effect of action-sharing on distance over-/underestimation.

More research is needed to verify the nature of the precise mechanism underlying this observation. The finding may be the result of a confound with order of presentation of the induction tasks: the “drive-car” induction task (presented first) was the only one on which connected cities could be navigated. On the other hand, non-connected could only be navigated on the “fly-plane” induction task (presented second).

Remaining findings
The accuracy data from both tasks reveal significant (but not-hypothesized) interactions between perception-based and action-based similarity: distances were estimated more accurately and orientation statements are verified more accurately if the cities involved in the tasks do not share the same action path (as compared to cities sharing such a path), but this was only true for connected cities. For not-connected cities the reverse pattern was observed.

At present, we do not have a plausible explanation for this effect. Future research should be aimed at replicating this finding in a more controlled way, because (as was the case for the interaction mentioned above) a confound with order of presentation of the induction tasks may be responsible for the finding.

Potential applications
Though this study was mainly theoretical in nature, potential applications of this type of research include the design of various systems requiring human interaction with spatial layouts: e.g., virtual navigation environments, interactive geographical information systems. Knowledge about the shortcomings of human spatial reasoning (e.g., this study’s finding that people have a tendency to overestimate the distance between spatial objects that are not connected somehow to each other) might be used to make these systems more adaptive to its users (e.g., warning for the danger of overestimation of distance). Alternatively, one could present users with a (temporarily) modified spatial layout in order to cancel out or somehow undo the effect of their cognitive limitations.

REFERENCES


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i Franklin Widjaja and Karen Schuil from Leiden University are acknowledged for conducting the research reported in this paper.