Effect of Visuo-Spatial Working Memory on Distance Estimation in Map Learning

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***Abstract*—This paper investigated the role of visuo-spatial working memory in distance estimation during map learning. Participants were asked to learn a map and perform a distance estimation task on the basis of the memorized map. The capacities of visual (i.e. visual cache) and spatial (i.e. inner scribe) components of visuo-spatial working memory were assessed for each participant and distance estimate errors were compared across high and low visuo-spatial capacity participants. The visual component predicted performance accuracy. In addition, low visual capacity participants provided longer distance estimates between two locations as a function of the number of intervening points between them. Although spatial component capacity also predicted estimated distances, it did not affect performance accuracy or estimated distance bias as a function of intervening points. It appears that distance is estimated on the basis of visual component capacity, and that low visual capacity individuals try to draw upon non-spatial information to support a limited visual capacity.**

Keywords—visuo-spatial memory; map learning; distance estimation

I. INTRODUCTION

It has been repeatedly shown that people depend on non-spatial information such as category and number of items to perform distance estimates. Kosslyn, Pick, and Fariello [1] found that people estimate distances of an object from them as longer when a barrier is between them than when there is no barrier. Thorndyke [2] revealed that cities between locations increases distance estimates when using a map. Hirtle and Jonides [3] demonstrated that longer distance estimates between locations were provided when clusters of landmarks organized on the basis of non-spatial attributes had to be crossed, as compared to within-cluster estimates. Rinck and Denis [4] showed that people depend on the number of rooms traversed when representing moved distances in mental imagery.

Although previous research has clarified the use of non-spatial information during distance estimates by focusing on distance bias, it is unknown individual differences in distance estimation processing, particularly individual differences in the extent to which individuals rely on non-spatial information to make spatial judgments. Some evidence supports a link between visuo-spatial ability and the strategy. By analyzing use of the rotation strategy during a cube comprehension task, Just and Carpenter [5] found that low-spatial ability participants rotate the cube in standard trajectories, whereas high-spatial ability participants rotate the cube in nonstandard trajectories that are the shortest for solving the problem. This study indicates that low spatial ability people tend to use lower spatial load strategies as compared to high spatial ability people, even when higher load strategies provide the best way to derive a solution. Garden, Cornoldi, and Logie [6] showed that those who used spatial strategies in route learning relied on visuo-spatial working memory, while those who used non-spatial strategies relied on verbal working memory. This suggests that spatial and non-spatial strategies call upon different abilities. Therefore, it may be useful for low spatial ability people to rely on non-spatial information in order to reduce spatial load and thereby compensate during spatial task performance.

Working memory theory supports such as idea. Baddeley and Hitch [7] proposed a working memory system that comprises the central executive for attention control and two domain-specific independent subsystems, the phonological loop and the visuo-spatial sketchpad for verbal and visuo-spatial materials, respectively. In this model, the two subcomponents have distinctive capacities as well as the option of drawing upon central executive resources. Furthermore, Logie [8] modified the working memory model from a singular visuo-spatial sketchpad conceptualization to a visuo-spatial working memory system that is subdivided into the visual cache and inner scribe. The visual cache stores visual information such as visual form and color. The inner scribe retains spatial information such as movement sequences and is considered to relate to the planning and execution of the movement. These two components have individual capacities and develop differently [9].

Therefore, it is hypothesized that low visuo-spatial working memory capacity individuals are likely to use non-spatial information during spatial task performance, in an attempt to reduce visuo-spatial working memory load. For example, low visuo-spatial capacity individuals may keep in mind the number of landmarks between two locations verbally instead of memorizing metric distance between them, which would then modulate the estimated distance as a function of the number of landmarks. In this case, the more landmarks the segment between two locations contains, the longer the estimated distance, resulting in a distance bias.

Although many studies implicate working memory in environmental learning [6, 10, 11], few studies deal with aspects of distance. Using analytic procedures, Allen, Dobson, Long, and Beck [12] found that two factors, spatial sequential

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memory and topological knowledge, predict environmental learning. This distinction between the two abilities is similar to that of two components in visuo-spatial memory. Route distance related to topological knowledge is mediated by sequential memory, although neither of the factors is related to Euclidean (i.e., straight-line) distance. Bosco, Longoni and Vecchi [13] assessed participants' visual and spatial working memory capacity, and investigated the relationship between the capacities and orientation task performance based on map learning. Visual capacity as measured by the Visual pattern test influenced total standardized scores for all orientation tasks. In addition, involvement of visuo-spatial working memory in the task is more relevant to men than women. However, neither visual nor spatial capacities predicted Euclidean (i.e., straight-line) or route distance estimate performance in this study. The distance judgment task used by Bosco et al. [13] was one in which participants were asked to identify the longest distance between a designated landmark and three alternatives, instead of providing the distances in the absence of choice options. Therefore, it is worth conforming whether the same result is obtained during a distance estimation task that requires more detailed distance representation.

On the basis of earlier work, the role played by visuo-spatial working memory in distance estimation remains to be clarified. In particular, the potential influence of visuo-spatial memory capacity on the use of non-spatial strategies for distance estimation remains unclear. The present study addressed this issue. The goal of this study was to confirm that low visuo-spatial working memory individuals rely more on non-spatial information when providing distance estimates, showing correspondingly greater distance estimation bias than high working memory individuals. A map was used for learning material. Participants estimated the distance between two locations on the memorized map. The number of intervening points (0, 1, 2) between locations was manipulated. Visuo-spatial working memory capacity was measured via two span tests, the Corsi block test and the Visual pattern test for spatial and visual capacities, respectively [9]. Visual capacity was expected to predict map distance estimation performance mainly because maps constitute visual material. However, spatial capacity may also support distance estimates through sequentially searching the lengths between two locations. Participants with low visual and/or spatial capacity are expected to rely more on number of intervening points to support distance estimates.

II. METHOD

A. Participants

Forty undergraduates of Hiroshima International University participated in the experiments.

B. Materials

The Visual pattern and Corsi block tests were used to evaluate visual and spatial capacities, respectively. Example materials for each test are shown in Figure 1, 2.

Three maps were constructed for the distance estimation task. These maps displayed a network of 17 or 18 points, using lines and dots. Example materials are shown in Figure 3. Letters of the alphabet were labeled upon each dot in an alphabetical sequence from lower left to upper right. Dots were laid out on the map in such a way to satisfy the factorial design of intervening points. One line between two dots was labeled 100m, to show the scale of the map. Test sheets for distance estimation were constructed, containing 10 pairs of dots for each map. The number of intervening points between each pair was 0, 1, or 2. A pair with no intervening points was the one showing map scale. This test pair was used to check whether participants correctly memorized the map scale. Average distance of pairs for each of the intervening conditions was 200m.

C. Procedure

Visual span test

Visual capacity was assessed using the Visual pattern test. During the test, a fixation point was presented at the center of the screen for two seconds. The participant was then presented with a 2 × 2 matrix pattern in which half of the cells were colored in white and the other half were colored in black. Two seconds later, the participant was shown another matrix pattern that was identical to the first, except that all of the previously colored cells were shown as blank. He or she was required to click the same cells that were previously colored in black. If a participant successfully completed two of three trials, a black cell and a white cell were added to the former matrix pattern. This procedure was repeated until the participant failed to click on more than two of three trials. Scores were calculated by adding the number of black-colored cells presented in the three most complex patterns for which all of the previously black colored cells were clicked successfully. This total was divided by 3 to derive a participant's visual span.

Spatial span test

Spatial capacity was assessed by the Corsi Block Test. During the test, a fixation point was presented at the center of the screen for two seconds. Nine identical blocks attached to a board were then presented on a computer screen. Two blocks were flashed sequentially at a rate of one block per second. The participant was required to click the same blocks in the correct order of presentation. If a participant successfully completed two of three trials, the number of blocks in the presented sequence increased to three. This procedure was repeated until the participant failed to click on more than two of three trials. Scores for each participant were calculated by adding the length of the three longest sequences for all of blocks previously flashed that were clicked in the correct order. This total was divided by 3 to obtain the participant's spatial span.

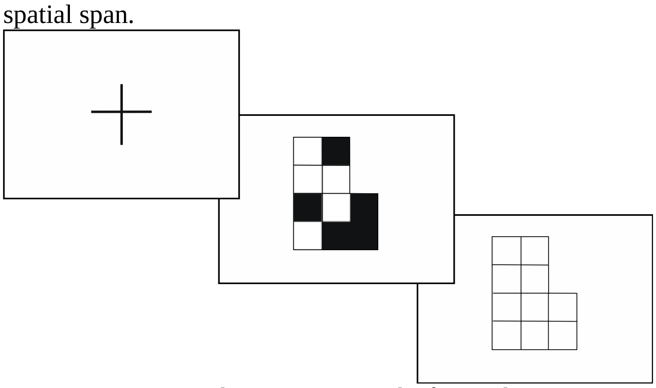

Figure 1. Example presentation stimulus for visual pattern test.

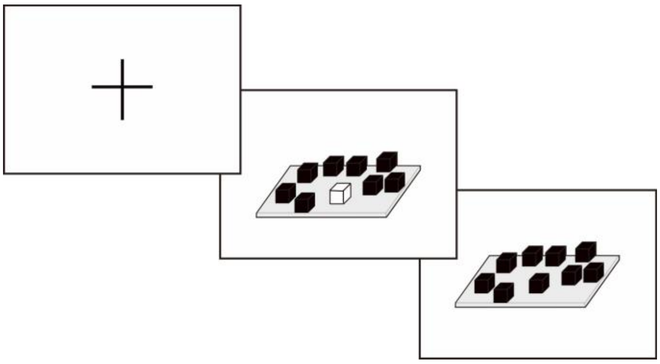

Figure 2. Example presentation stimulus for Corsi block test.

Distance estimation task

Participants viewed a map projected on the screen for 3 minutes. They were asked to memorize the locations of all dots on the map and their relationships. After the learning phase, a blank display was projected onto the screen. Participants were instructed to estimate the distance between dot pairs on the test sheet. They were then asked to draw the map they memorized on a white paper. Learning and test phases was conducted on one map for practice, and two maps for the test trials.

III. RESULTS

Absolute error was computed individually for each of three conditions and a pair that showed map scale. It was calculated as the difference between correct distance and estimated distance. If participants failed to provide the exact scale label (100m) of the map, all data relating to the map was excluded from further analysis. Similarly, if participants made mistakes on the drawn map with respect to total number, horizontal height or alphabetical label of dots, corresponding distance estimation data were discarded. Data from seven participants were completely excluded from analysis due to inadequately memorized maps.

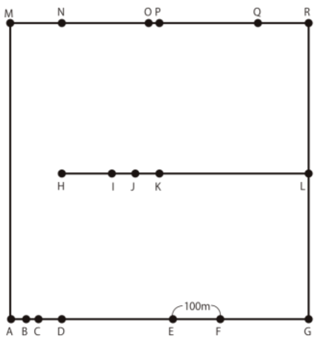

Figure 3. Example map used in the experiment.

Participants were allocated to the high visual group if their scores on the visual pattern test were above the mean (M = 8.79), and to the low visual group if their scores were below the mean. In the same way, participants were allocated to the high spatial group if their scores on the Corsi Block Test were above the mean (M = 5.71), and to the low spatial group if their scores were below the mean.

An initial analysis of variance (ANOVA) examined the effects of intervening points (0, 1, 2) × visual capacity (low, high) on estimated distance and absolute error (Figures 4，5). The main effect of intervening points was significant for estimated distances, $F(2, 62) = 12.60$, $p < .0001$. Distance estimates for 2 intervening points were longer than the estimates for 0 and 1 intervening points ($p < .0005$). Distances for 0 and 1 did not differ. The interaction was also significant, $F(2, 62) = 4.27$, $p < .05$. An interaction contrast showed that the simple main effect of intervening points was significant for low visual but not high visual participants. The main effect of visual capacity was not significant for estimated distances. On the other hand, the main effect of visual capacity was significant for absolute errors, $F(1, 31) = 4.47$, $p < .05$. High visual participants estimated distance more accurately than low visual participants. No other main effect or interaction was significant.

The next analysis examined the effect of intervening points (0, 1, 2) × spatial capacity (low, high) on estimated distances and absolute errors (Figure 6, 7). The main effect of intervening points was significant for estimated distances, $F(2, 62) = 10.58$, $p < .0005$. Distance estimates for two intervening points were longer than estimates for 0 or 1 intervening point ($p <. 001$). Distances did not differ between 0 and 1. The main effect of spatial ability was also significant, $F(1, 31) = 5.72$, $p < .05$. High spatial participants provided longer distance estimates longer than low spatial participants.

The interaction was not significant for estimated distances. There were no significant main effects or interaction for absolute errors.

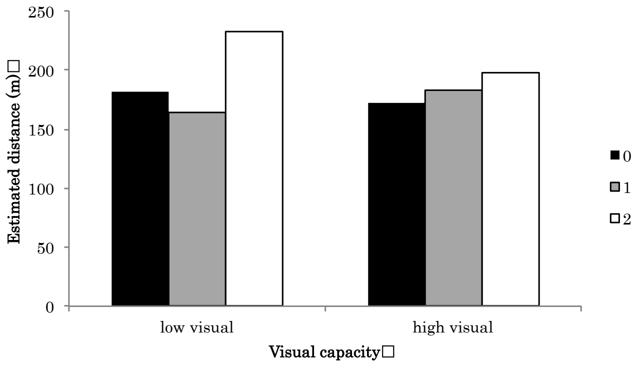

Figure 4. Mean estimated distance as a function of intervening points for low and high visual capacity groups.

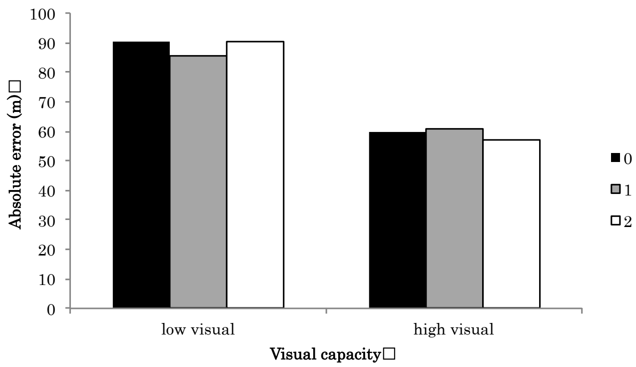

Figure 5. Mean absolute error as a function of intervening points for low and high visual capacity groups.

IV. DISCUSSION

The present study investigated the relationship between visuo-spatial working memory and distance judgments. The visual component of visuo-spatial memory predicted accuracy of distance estimates. In addition, visual capacity also affected the extent that participants depended on non-spatial information to make such judgments. Low-visual participants estimated the distance between two locations as longer, in relation to the number of intervening points between them. On the other hand, the spatial component had a different influence on distance estimates. High-spatial participants provided longer distance estimates, but spatial span did not affect accuracy. No evidence was obtained that low-spatial participants rely on non-spatial information, because distance bias was not enhanced as spatial capacity increased.

The study indicates that the processing of distance calls upon the visual component of visuo-spatial memory. This is consistent with the proposal that this subsystem stores visual figures or patterns [8]. Studies of mental imagery have pointed out that people can imagine memorized maps and scan the distant places on the map as if they were seeing them [14]. This study further indicates that it may be difficult for low-visual people to use such a visual strategy. It is more useful for these people to use non-spatial strategies associated with reduced visual load, such as using number of intervening points as a reference.

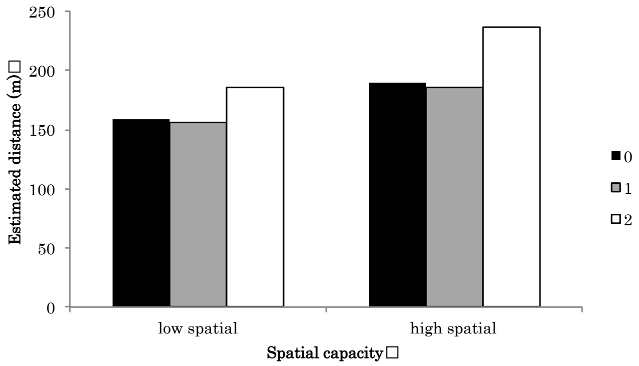

Figure 6. Mean estimated distance as a function of intervening points for low and high spatial capacity groups.

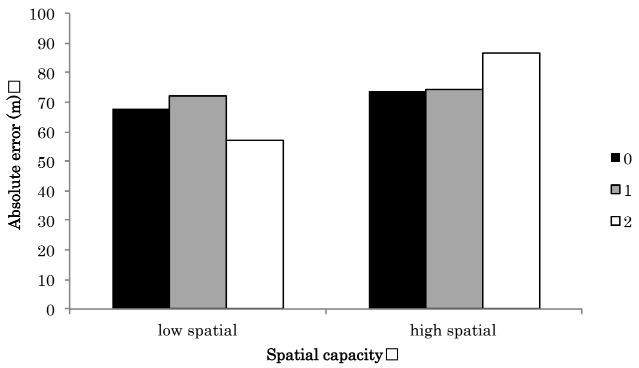

Figure 7. Mean absolute error as a function of intervening points for low and high spatial capacity groups.

The present findings are consistent with a concept model of distance processing proposed by Montello [15]. In his model, when information regarding distance estimates is already stored in long-term memory, people simply retrieve it. This seems to be the case for high visual people in this study. Conversely, when this is not the case and visual access to vistas is not permitted, prospective estimation is used if possible. Prospective estimation means step or pattern counting and is a heuristic strategy. This seems to be the case for low-visual people, although these individuals seemed to have some access to visual information. Combining Montello's model and the present results, distance estimate bias is the product of low-visual people using a heuristic strategy to lower cognitive load. Thus, it cannot be said that the bias always results in inaccuracy. In fact, the present results showed that estimates increase as a function of the number of intervening points between locations, but with no corresponding increase in absolute errors.

Although the spatial component did not affect distance estimate accuracy, it was observed that higher spatial capacity does lead to longer distance estimates. One possible explanation is that high spatial people divided the line on a map into segments in order to sequentially process it. This kind of segmentation could lead to an increase in items between locations.

In any case, however, it can be concluded that visuo-spatial memory affects distance estimates. This conclusion is different from that of Bosco, Longoni and Vecchi [13]. This could be due to differences in cognitive load between the tasks. In this study, participants were asked to provide metric distance estimates. This estimation procedure requires more detailed distance information than does the task of identifying the longest distance between a designated landmark and three alternatives. Thus, participants in present study relied on visuo-working memory to perform the task, enough that the results were influenced accordingly.

The present study highlights individual differences in spatial judgment bias caused by non-spatial information. Previous research has shown that non-spatial information does affect spatial judgments. For example, the positional relationship between two cities is affected by the region that each city belongs to [16]. Hills are judged steeper and distances are judged farther when physical fatigue is increased [17, 18]. The present study suggests the visuo-spatial working memory affects the extent to which people rely on non-spatial information for estimating spatial properties. The perspective of limited cognitive resources may be the key point to explain individual differences associated with other judgment biases.

Further research is needed to extend the present results to spatial learning without a map. Maps are visual material in that all locations are visually presented simultaneously. However, learning the environment through moving is sequential. In such a learning situation, the spatial component of visuo-spatial working memory might rather play a critical role, and spatial capacity might predict distance estimate bias as well as accuracy under such conditions.

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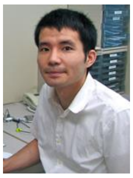

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