Spatial Concepts: Sensitivity to Changes in Geometric Properties in Environmental and Figural Perception

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Abstract. This study examined spatial concepts in environment perception, by looking at people's reaction to changes in shape, scale, orientation, and topology while navigating in a virtual environment, as contrasted to the case of figural perception. Although people attended to changes in shape, they were most sensitive to a topological relation and discriminated it qualitatively from other transformations. In environment perception, compared to figural perception, the property of similarity did not have great cognitive prominence. Mental-rotation ability affected spatial perception, with high-spatial people discriminating between different transformations more clearly and low-spatial people attending more to topological relations.

Keywords: Spatial thinking, Spatial cognition, Spatial ability, Scale, Environmental exploration, Geometric transformations.

1 Introduction

The fact that humans live and act in space seems rather obvious, but has profound implications for their everyday reasoning and behavior; and thus the issues of human spatial cognition and behavior have attracted theoretical and practical attention from researchers in various disciplines. In particular, the characteristics of large-scale spaces, or the *environment*, and their effects on the cognition of space (environment perception) have been discussed in the context of knowledge development, as contrasted with the perception of objects (object perception). Importantly, Ittelson (1973) contended that the environment is larger than and surrounds the human body, and thus it cannot be perceived in its entirety from a single viewpoint. To do that, a person needs to explore the environment (not simply view it as an external observer) and integrate the views at different locations into a coherent mental image of the environment. It makes the task of acquiring knowledge about the environment (or "cognitive mapping") very difficult for some people, especially people with a poor sense of direction (Hegarty et al., 2002; Kozlowski & Bryant, 1977).

In relation to the distinction between environment and object perceptions, an issue that has been extensively discussed is *scale*. Montello (1993) discussed different types of spaces in terms of spatial scale, and notably distinguished *environmental* and *figural*

C. Freksa et al. (Eds.): Spatial Cognition 2014, LNAI 8684, pp. 338–353, 2014.

spaces. The two spaces differ in the size compared to the human body (the former being larger and the latter smaller than the body) and in the requirement for the viewer to move around in the space to acquire the knowledge; thus mapping onto the environment-object distinction discussed above (also see Hegarty et al., 2006). One exception to this distinction is when a map is used: viewing a map that represents an environmental space renders the task of learning about the environment a learning about a figural space (e.g., Thorndyke & Hayes-Roth, 1982).

The issue of spatial knowledge and learning has also been recently discussed from a slightly different perspective, in terms of *spatial thinking* (National Research Council, 2006), corresponding to the recognition that spatial thinking plays critical roles in the STEM disciplines (science, technology, engineering, and mathematics) and in everyday life (e.g., Keehner et al., 2004; Kozhevnikov, Motes, & Hegarty, 2007; Newcombe, 2010; Uttal & Cohen, 2012). Particularly in the literature of geoscience learning and education, researchers have discussed the concepts of spatial thinking. For example, Golledge, Marsh, and Battersby (2008) proposed that spatial concepts can be classified into spatial primitives (identity, location, magnitude, and space-time) and derivatives at higher levels (e.g., arrangement, distribution, distance, adjacency, connectivity, scale, and projection). Similar classifications were proposed by Gersmehl and Gersmehl (2007), Janelle and Goodchild (2009), and Kuhn (2012).

The present study aims to extend the discussions of spatial concepts further, particularly by examining the perception of various spatial concepts in the scale of environmental space. Specifically, it is of interest to see, in the case of environment perception, if people perceive different spatial concepts as being different from each other and whether people perceive some concepts as more salient than others. In fact, the term spatial thinking has not been clearly defined (National Research Council, 2006) and other terms such as spatial ability are often used interchangeably to discuss its meaning (Hegarty, 2010; Ishikawa, 2013a; Lee & Bednarz, 2012).

Motivated by that interest, Ishikawa (2013b) examined spatial concepts in the case of figural perception, by extending the traditional arguments of geometric properties in the cognitive and mathematical literatures. Cognitively, an understanding of geometries has been discussed in terms of a progression of topological, projective, and Euclidean geometries (Piaget & Inhelder, 1948/1967) and scrutinized in the context of K-12 learning and education (e.g., Kidder, 1976; Mandler, 1983, 2012; Martin, 1976). Mathematically, geometries are defined in terms of properties that are preserved through a group of transformations (Gans, 1969). For example, topological transformations preserve openness, interior, order, and connectedness. In addition to these properties, projective transformations preserve collinearity and cross-ratios; similarity transformations (scaling) preserve angle-size; and Euclidean transformations (rigid motions, i.e., translation, rotation, and reflection) preserve length.

Ishikawa (2013b) presented figural configurations that were deformed (i.e., the shapes of which were changed) to different degrees and transformed through rotation, scaling, and reflection to participants, and asked them to judge the dissimilarity between the original and the deformed or transformed configurations. The results showed that participants were sensitive to the changes in shape, but their sensitivity to rotation, scaling, and reflection differed depending on the degree of deformation. Also, people with a low spatial ability were more sensitive to rotation and reflection than those with a high spatial ability, whose responses were more aligned with the mathematical classification of transformations. In sum, the study pointed to the difference in cognitive and mathematical classifications of spatial properties, and the effects of spatial ability on people's spatial conception.

The major objective of the present study is to examine the cognitive classifications of different spatial concepts in environment perception, because, as the aforementioned importance of scale in spatial cognition suggests, spatial concepts in environment perception and figural perception may differ. Therefore this study looks into the difference between cognitive and mathematical classifications of geometric properties while navigating in a virtual environment, taking differences in the level of spatial abilities into consideration. Methodologically it extends the experiment conducted by Ishikawa (2013b) for figural perception to the case of environment perception, and examines people's responses (or "sensitivity") to the changes in shape, orientation, size, and topology caused by various geometric transformations (deformation, rotation, scaling, and reflection).

2 Method

2.1 Participants

A total of 57 students (32 men and 25 women) participated in the experiment. They were undergraduate students in various disciplines including law, economics, literature, sociology, physics, chemistry, engineering, and architecture. Their ages ranged from 18 to 29, with a mean of 19.6 years.

2.2 Materials

Virtual Environments with Different Geometric Configurations. As experimental stimuli, three-dimensional views of virtual cities consisting of three "landmarks" (a traffic sign pole, a tree, and a cylindrical building) and paths connecting them, projected on a screen, were used (Figure 1). No two landmarks were visible simultaneously, being screened by the walls. The two-dimensional or configurational arrangements of the three landmarks matched the 36 geometric configurations of three dots examined in the Ishikawa (2013b) study (see Figure 2).

Fig. 1. Views from the virtual environments at the three landmarks: a traffic sigh pole (*left*), a tree (*middle*), and a cylindrical building (*right*).

The configurations varied with respect to the degree of *deformation* and the types of transformations applied. For deformation, an original configuration of an equilateral triangle was deformed into eight configurations, with the lengths and angles among the three landmarks being changed with the constraint that the scale factor was fixed at 1 (Figure 2, panels #2-9). The degree of deformation was varied on the basis of bidimensional regression coefficients computed between the coordinates for randomly generated three dots and those for the three landmarks in the original configuration (Tobler, 1994). Since bidimensional regression attempts to maximize the correspondence between two configurations to be compared through translation, rotation, and scaling, values for bidimensional regression coefficients do not become too small, for example down to 0, even when coordinates are randomly generated. In the present case of three dots, the values ranged from .73 to 1 (shown in Figure 2).

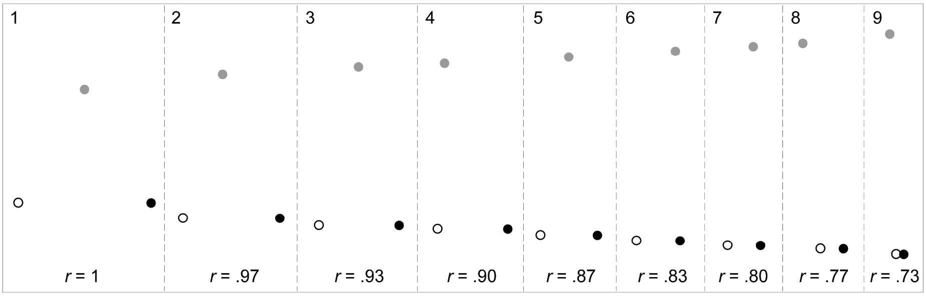


Fig. 2. Nine two-dimensional configurations (#1-9) that were deformed to different degrees. The leftmost panel shows the original configuration. Values for *r* indicate the bidimensional regression coefficients between the original (#1) and deformed (#2-9) configurations. The grey dot corresponds to the landmark of a traffic sigh pole, the white dot a tree, and the black dot a cylindrical building. In the experiment, participants looked at three-dimensional views as shown in Figure 1, not the two-dimensional plans shown in this figure. Reproduced by permission of Springer from Ishikawa 2013b, fig. 1.

To these nine configurations, three different types of transformations were applied, to yield three more sets of nine configurations: a *rotation* (half the configurations, which were chosen randomly, were rotated 90° to the right, and the other half were rotated 90° to the left), a *scaling* (half the configurations were scaled by a factor of 2, and the other half by a factor of 0.5), and a *reflection* (the nine configurations were flipped over). With the reflection, the cyclic order of the three landmarks is altered and thus it can be conceived as breaking the topology of the three landmarks (i.e., ordered clockwise vs. counterclockwise); it was included to see if the changes caused by it are perceived as qualitatively different from the other transformations.

As examples, the three transformed configurations for the original configuration are shown in Figure 3. In the virtual environment, for the deformed, scaled, and reflected configurations, participants started at the traffic sign pole (denoted by a grey dot in Figures 2 and 3) and walked counterclockwise around the paths connecting the three landmarks. For the rotated configurations, they started either at the the tree (denoted by a white dot) when the configurations were rotated to the right or at the cylindrical building (denoted by a black dot) when rotated to the left. Participants walked along the paths that connected the three landmarks at a speed of 4 km/h. The original configuration was scaled in the virtual environment so that it took 30 s to walk around the three landmarks and return to the origin.

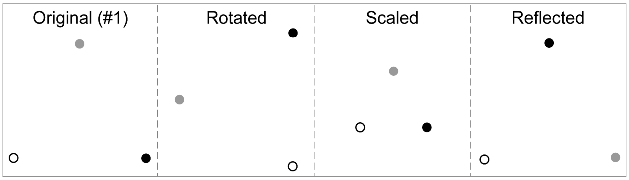


Fig. 3. Three transformations applied to the original configuration (#1, leftmost panel): rotation, scaling, and reflection (the second, third, and fourth panel from the left, respectively). Reproduced by permission of Springer from Ishikawa 2013b, fig. 2.

Card Rotations Test. Participants took the Card Rotations Test, which is a major spatial test assessing people's ability to rotate imagined pictures mentally (Ekstrom et al., 1976). In the test, participants viewed 20 items, each consisting of one card in a standard orientation and eight alternative cards, and answered whether the alternative cards were the same as the standard (i.e., rotated into different orientations) or different from the standard (i.e., flipped over). They received one point for each correctly identified card and lost one point for each wrongly identified card. Participants were allowed 6 min to complete this test. Mental-rotation ability correlates with the understanding and use of maps in the field (e.g., Liben & Downs, 1993), and so it was assessed in this study as a possible correlate with the perception of differences in geometric properties.

Sense-of-Direction Scale. Participants filled out the Santa Barbara Sense-of-Direction (SBSOD) scale, which consists of fifteen 7-point Likert-type questions about navigational abilities or preferences (Hegarty et al., 2002). It is scored so that a higher score indicates a better SOD, ranging in value from 1 to 7. People having higher SOD scores tend to do better on configurational understanding of environmental spaces, so the scale was used in this study to see whether the trait relates to the characteristics of spatial concepts in environment perception.

2.3 Design and Procedure

Participants viewed the scenes of walking through the 36 virtual environments in random order. The stimulus environments were always presented on the screen paired with the environment with the original configuration (the two-dimensional plan of panel #1 in Figure 2), which was shown half the times to the left of the screen and the other half to the right. In both of the paired environments, the navigator started at the same time. After viewing each pair of the scenes, participants answered whether they thought the configurations or arrangements of the three landmarks in the pair of cities were spatially the same or different on a 7-point scale (1 = *same*; 7 = *different*). Namely, the responses indicated a perceived degree of dissimilarity of the transformed configuration to the original configuration. This is an extension of the method used by Ishikawa (2013b) to the case of environmental exploration, which was originally based on the method used by Levinson (1996) to study the use of spatial frames of reference.

After completing all 36 scenes, participants filled out the SBSOD scale and took the Card Rotations Test. They finished all these tasks within 45 min on average.

2.4 Hypotheses and Possible Results

About the responses to changes in geometric properties in environment perception for this study, hypotheses similar to the ones examined by Ishikawa (2013b) for figural perception are constructed. Concerning the effects of the degree of deformation, participants would perceive the deformed configurations as more dissimilar to the original configuration as the degree of deformation becomes larger (i.e., the regression line of perceived dissimilarity on bidimensional regression coefficients would have a negative slope).

Concerning the effects of different types of transformations, one possibility is that participants would respond in line with the mathematical classification of geometric transformations. If participants' perception shares characteristics with Euclidean transformations, their responses would not change with rotation or reflection, because these transformations preserve Euclidean properties. Their responses to scaled configurations, however, would differ, because scaling does not preserve the Euclidean property of length. If participants' perception shares characteristics with similarity transformations, regression lines for rotated, reflected, and scaled configurations would coincide that for deformed configurations, as rotation, reflection, and scaling preserve angle-size. By contrast, if participants "live" in the world of topology, they would perceive all configurations as the same, and the regression lines would have a slope of 0; except that they would respond to reflected configurations differently as long as they regard reflection as breaking topology.

Another possibility is that participants' responses do not conform to the mathematical classification of transformations. Then, rotation, scaling, and reflection would change participants' perception, and so the regression lines for these three transformations would deviate from that for deformation. And in that case, there are two further possibilities. If the effects of rotation, scaling, and reflection are independent of the degree of deformation, the four regression lines would be parallel. Or, if the effects differ depending on the degree of deformation, the slopes for the four regression lines would be different.

As well as examining these hypotheses, this study also compares the responses in the case of environment perception (this study) to those in figural perception (Ishikawa, 2013b), particularly paying attention to the possible effects of experiencing the configurations in a horizontal perspective and not in their entirety. One issue of interest is whether the property of similarity (which is preserved by scaling) is as noticeable as in figural perception. Another issue is whether the cognitive importance of sequential or topological knowledge about the space (i.e., "route" knowledge) is greater in environment perception than in figural perception. If so, reflection, which breaks the cyclic order of the landmarks, would be perceived as qualitatively different from other transformations, and to a greater extent than in figural perception. And rotation, which preserves the topology of the landmarks, might be discriminated less sensitively than in figural perception.

With these hypotheses in mind, the present study examines the size and the equivalence of slopes for regression lines for the four sets of configurations and compares them between environment and figural perceptions.

3 Results

3.1 Effects of the Types of Transformations and the Degree of Deformation

Participants' responses were examined through a repeated measures analysis of variance (ANOVA), with the degree of deformation (the nine panels in Figure 1) and the types of transformations (deformation, rotation, scaling, and reflection) as within-subject variables. Following the general recommendation (Girden, 1992), univariate and multivariate tests were conducted at the .025 level each (when both tests are significant, statistics for the univariate test are reported).

There were significant main effects of degree of deformation and type of transformation, $F(8, 376) = 57.22$, $p < .001$; $F(3, 141) = 34.77$, $p < .001$, respectively; and a significant interaction between the two variables, $F(24, 1128) = 8.17$, $p < .001$. The existence of a significant interaction shows that although participants discriminated between the four types of transformations, their sensitivity to rotation, scaling, and reflection differed depending on the degree of deformation.

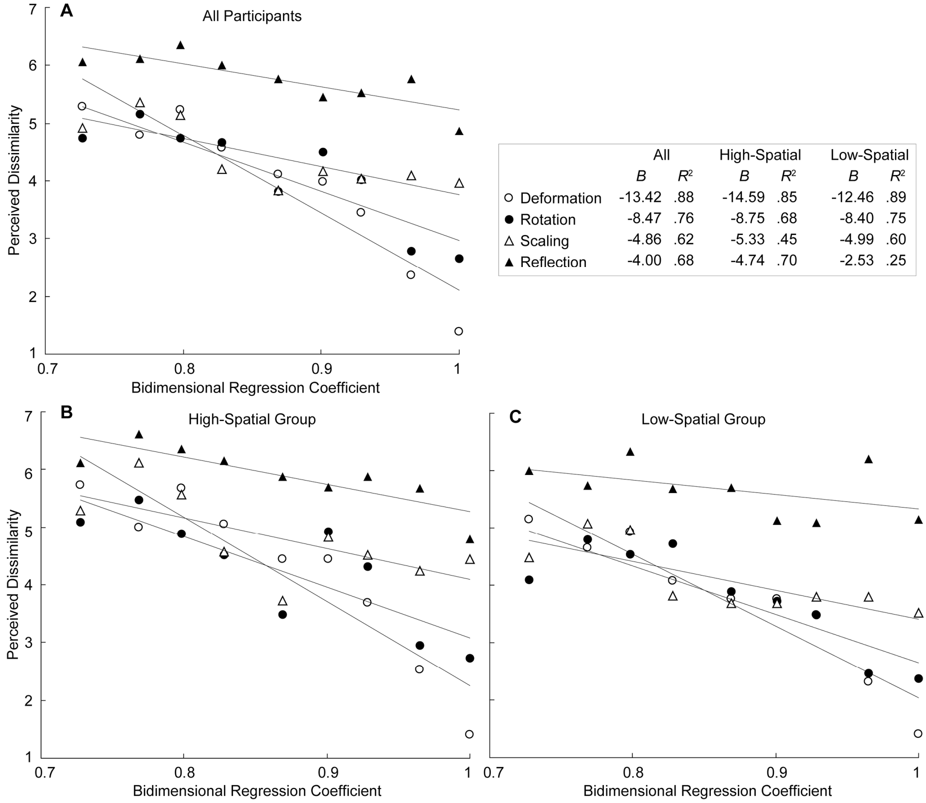
3.2 Regression for Deformation, Rotation, Scaling, and Reflection

The effects of the degree of deformation and the types of transformations were further examined through regression analysis, with participants' responses being regressed on the degree of deformation for each type of transformation separately (Figure 4A).

The slopes for regression lines are significantly different between deformation and scaling and between deformation and reflection, $t(14) = 4.41$ and 5.32, respectively, $p < .001$ (Bonferroni, $\alpha = .05/6$). All regression lines have a negative slope, showing that participants perceived the configurations as more dissimilar to the original configuration as the degree of deformation increased (or the value for r became smaller).

At the bidimensional regression value of $r = 1$ (the original configuration and its transformed images), participants' responses to the four configurations were significantly different from each other, $t(51) = 5.17$, $t(53) = 10.48$, $t(50) = 11.84$, $t(53) = 4.01$, $t(50) = 5.55$, $t(56) = 5.56$, p's $< .001$. At the value of $r = .73$ (the most greatly deformed configuration and its transformed images), the perceived dissimilarity value for the reflected configuration was significantly larger than that for the deformed, rotated, and scaled configurations, *t*(50) = −3.65, *t*(52) = −4.06, *t*(56) = −4.48, respectively, *p*'s < .001.

These findings about the differences in slopes and the distances between the regression lines along the vertical axis show that the effects of the three transformations on perceived dissimilarity differed depending both on the degree of deformation and on the types of transformations. When the degree of deformation was small, participants perceived rotated, scaled, or reflected configurations as dissimilar to the original, with the reflected configuration being most dissimilar, and then the scaled configuration, and then the rotated configuration. When the degree of deformation became large, participants did not discriminate between deformed, rotated, and scaled configurations, but still perceived reflected configurations as dissimilar to the other configurations.



	All		High-Spatial		Low-Spatial	
	B	*R*²	*B*	*R*²	*B*	*R*²
○ Deformation	-13.42	.88	-14.59	.85	-12.46	.89
● Rotation	-8.47	.76	-8.75	.68	-8.40	.75
△ Scaling	-4.86	.62	-5.33	.45	-4.99	.60
▲ Reflection	-4.00	.68	-4.74	.70	-2.53	.25

Fig. 4. Relationships between perceived dissimilarity and the degree of deformation for all participants (A), the high-spatial group (B), and the low-spatial group (C). Lines depict linear regression lines. *B* = unstandardized regression coefficient; R^2 = coefficient of determination.

3.3 Effects of Spatial Aptitudes

Mental-Rotation Ability. Effects of spatial ability on participants' responses were examined through an analysis of covariance (ANCOVA), with their scores on the Card Rotations Test being entered as a covariate into the repeated measures ANOVA conducted in section 3.1. A significant main effect of mental-rotation ability was observed, $F(1, 40) = 11.09$, $p < .01$, indicating that participants with a higher mental-rotation ability tended to perceive deformed and transformed configurations as more dissimilar (or to discriminate between them more sensitively). In light of the significance of spatial ability, the effects of the degree of deformation and the types of transformations on perceived dissimilarity are examined in the next section through separate regression analyses for high- and low-spatial groups of participants.

Sense of Direction. Effects of sense of direction were examined through an ANCOVA with participants' scores on the SBSOD scale being entered as a covariate. No significant main or interaction effects were observed for the SBSOD scores.

3.4 Regression for the High- and Low-Spatial Groups

Since the main effect of mental-rotation ability was found to be significant, participants' responses were further examined through regression analysis for participants with a high and low mental-rotation ability. To do that, participants were classified into two groups ($n = 25$ each) by a median split of their scores on the Card Rotations Test ($Mdn = 122.5$). Mean scores for the high- and low-spatial groups were 144.2 ($SD = 11.1$) and 106.4 ($SD = 10.0$), respectively. The two means were significantly different from each other, $t(48) = 12.63$, $p < .001$. (Similar mean values were observed in the Ishikawa, 2013b, study for its high- and low-spatial groups, *M*s = 151.8 and 114.7, respectively.)

As seen in Figures 4B and 4C, perceived dissimilarity values for deformed and transformed configurations by the high-spatial group were larger than those by the low-spatial group; that is, the high-spatial group discriminated between the configurations more sensitively than the low-spatial group did. Both groups perceived reflected configurations as most dissimilar, but the slope for reflection is not significantly different from 0 for the low-spatial group, showing that the low-spatial group discriminated reflection from other transformations to a greater extent than did the high-spatial group.

3.5 Multidimensional Scaling of Responses by High- and Low-Spatial People

As in the Ishikawa (2013b) study, the effects of mental-rotation ability was examined in more detail through multidimensional scaling (MDS) analysis of the high- and low-spatial groups' responses. In ordinal MDS with the PROXSCAL method, a three-dimensional solution and a four-dimensional solution yielded a stress value indicating a fair fit, .09, for the high- and low-spatial groups, respectively (Kruskal, 1964). For illustration, a two-dimensional solution for each group is shown in Figure 5.

The three- and four-dimensional coordinates were further examined through cluster analysis, with three clusters being identified for each group (see Clusters I-III and the dendrogram shown in Figure 5).

For the high-spatial group, Cluster I mainly consists of the configurations to which small degrees of deformation were applied (panels #1 and #2 in Figure 2) and their rotated images. Cluster II consists of configurations to which medium degrees of deformation were applied (panels #3, #4, and #5) and scaled configurations. Cluster III consists of greatly deformed configurations and their rotated and scaled images, and the reflected configurations. For the low-spatial group, Cluster I mainly consists of configurations to which small degrees of deformation were applied (panels #1 and #2) and most of the rotated configurations. Cluster II consists of configurations to which medium to large degrees of deformation were applied (panels #3-9) and most of the scaled configurations, and Cluster III consists of the reflected configurations.

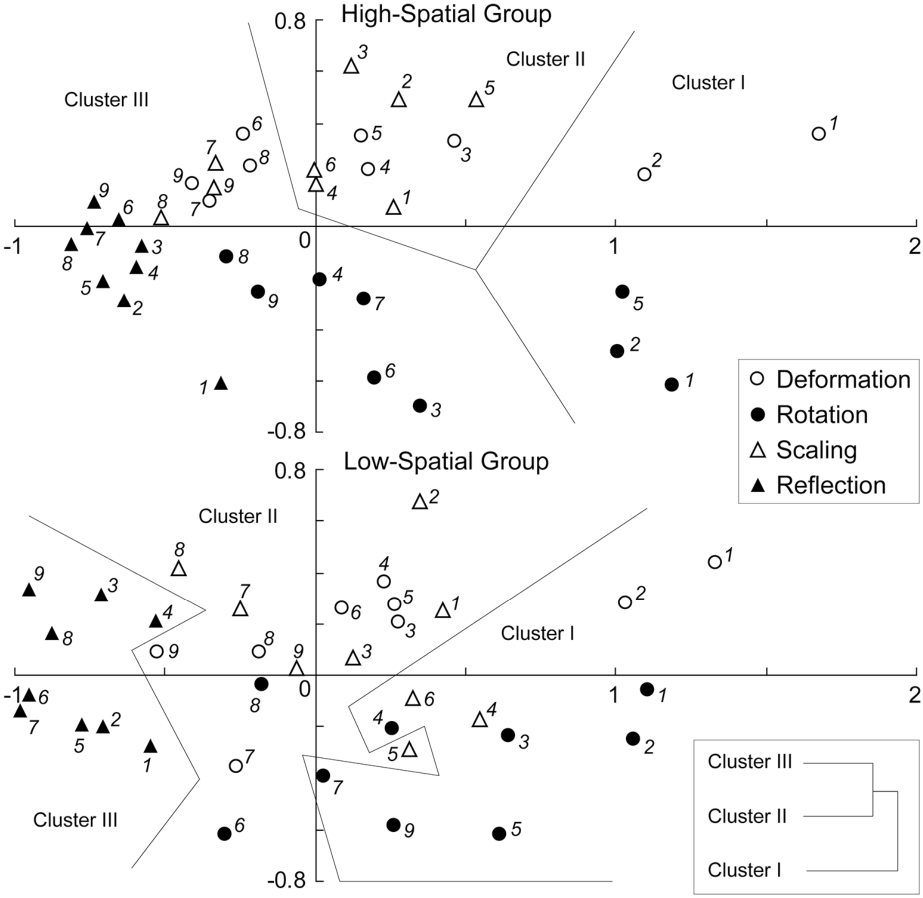
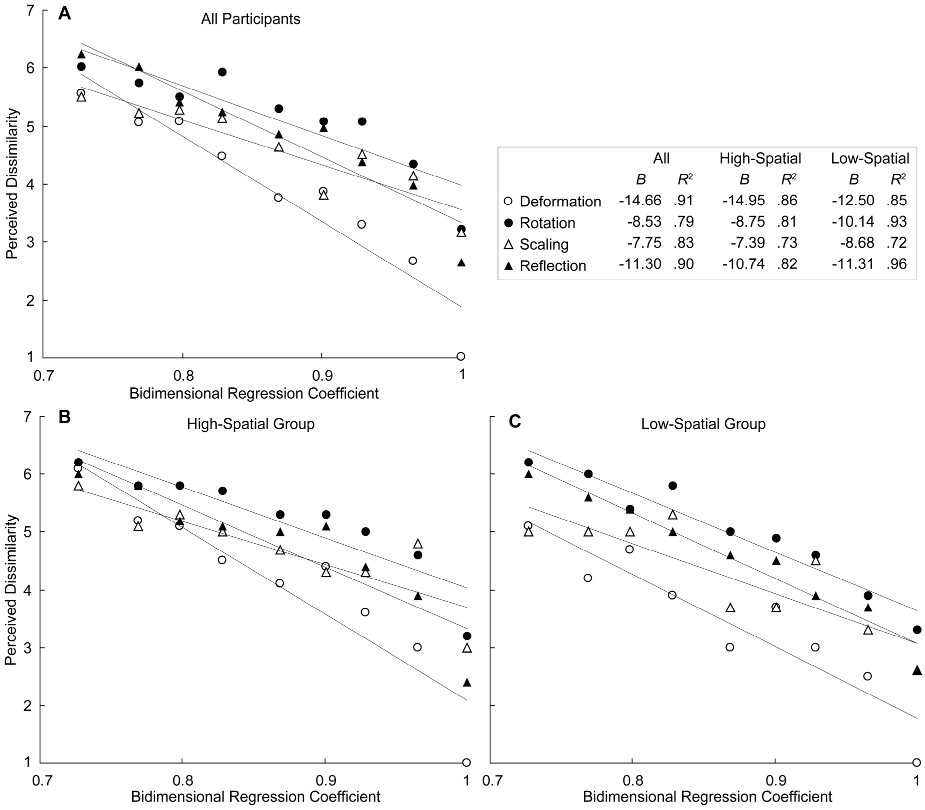


Fig. 5. MDS solutions (2D) for the high-spatial (*top*) and low-spatial (*bottom*) groups. Numbers in italics correspond to the panel numbers in Figure 2 and indicate the degree of deformation.

Compared to the low-spatial group, Clusters II and III for the high-spatial group are more tightly clustered and separated from Cluster I. Importantly, the clustering of scaling (similarity) and rotation and reflection (rigid motions) was clearer for the high-spatial group. It shows that their conception was more similar to the mathematical classification of geometries than the low-spatial group's.

3.6 Comparison between Environment and Figural Perceptions

To examine the differences in the responses to geometric properties in environment perception (this study) and figural perception (Ishikawa, 2013b), the regression lines and MDS solutions obtained in the two studies were compared. The regression and MDS results from Ishikawa (2013b) are shown in Figures 6 and 7.



	All		High-Spatial		Low-Spatial	
	B	R^2	*B*	R^2	*B*	R^2
○ Deformation	-14.66	.91	-14.95	.86	-12.50	.85
● Rotation	-8.53	.79	-8.75	.81	-10.14	.93
△ Scaling	-7.75	.83	-7.39	.73	-8.68	.72
▲ Reflection	-11.30	.90	-10.74	.82	-11.31	.96

Fig. 6. Relationships between perceived dissimilarity and the degree of deformation in figural perception, for all participants (A), the high-spatial group (B), and the low-spatial group (C). Reproduced by permission of Springer from Ishikawa 2013b, fig. 3.

Between the two studies, reflection has significantly different slopes, $t(14) = 4.04$, $p < .01$, with the slope for environment perception being less steeper negatively than that for figural perception ($B = -4.00$ vs. -11.30). At the bidimensional regression value of $r = 1$, perceived dissimilarity values for scaling and reflection were larger in environment perception than in figural perception, $t(105) = 2.38$, $p < .05$, and $t(105) = 6.37$, $p < .001$, respectively. At the value of $r = .73$, perceived dissimilarity values for rotation and scaling were smaller in environment perception than in figural perception, $t(105) = -4.34$, $p < .001$, and $t(105) = -2.13$, $p < .05$, respectively. Notably in environment perception, scaled configurations were perceived as more dissimilar when the degree of deformation was small, and reflection (which breaks topology) was perceived as causing a greater difference, than in figural perception.

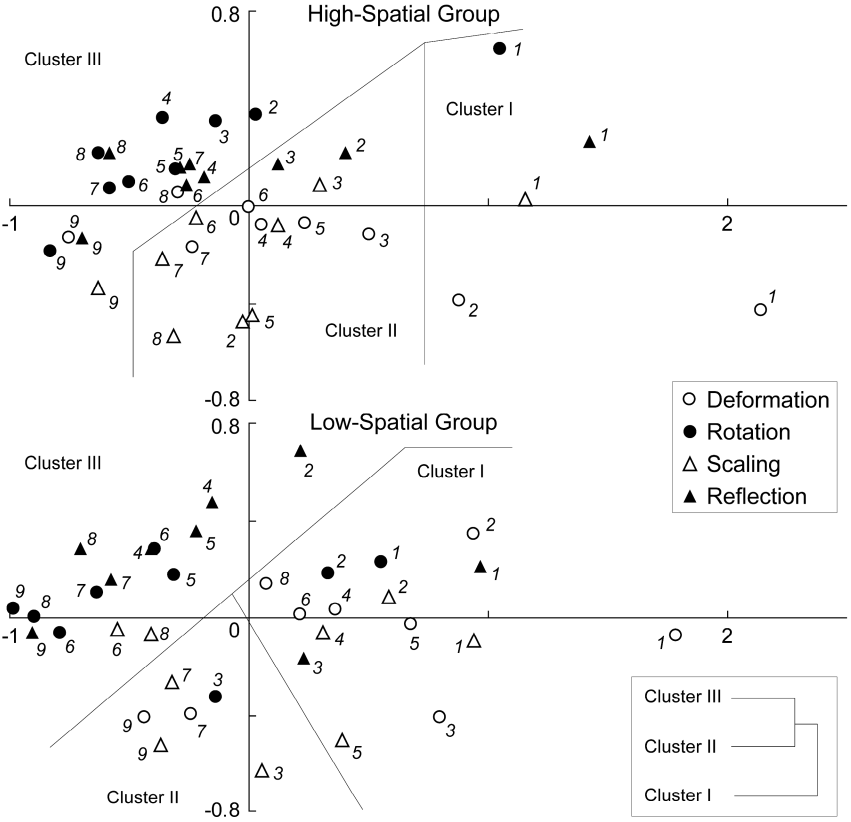


Fig. 7. MDS solutions in figural perception for the high-spatial (*top*) and low-spatial (*bottom*) groups. Reproduced by permission of Springer from Ishikawa 2013b, fig. 4.

As seen in Figures 4 and 6, perceived dissimilarity among rotation, scaling, and reflection (or the vertical distances between the three regression lines) was smaller in figural perception, suggesting that the three transformations were considered in figural perception more similar, in light of the properties of congruence and similarity. In environment perception, reflection is discriminated from the others to a greater extent, and its regression slope is less steep, than in figural perception, indicating a constant sensitivity to topological properties. Also in environment perception, the perceived dissimilarity value for rotation was smaller than in figural perception, suggesting that the fact that rotation preserves topology (or "routes") affects the judgment of configurational similarity more greatly in environment perception. By contrast, as shown above, scaled configurations were perceived as more dissimilar in environment perception, suggesting that viewing the paths horizontally, not from above, makes the property of similarity less prominent cognitively in environment perception.

As seen in Figures 5 and 7, in figural perception a clear separation was made between the cluster of scaling and the cluster of rotation and reflection, with the former constituting similarity transformations and the latter rigid motions. In contrast, in environment perception, rotation and reflection were separated (especially so for the low-spatial group), pointing to the greater prominence of topological relations.

4 Discussion

This study examined how people respond to the changes in geometric properties when perceiving them in a horizontal perspective in virtual environments, compared to when viewing two-dimensional figures. As found by Ishikawa (2013b) for figural perception, the present results show that people are sensitive to the changes in shape while navigating in environmental spaces. Moreover, as seen in Figures 4 and 6, the patterns of reaction or sensitivity to the changes in shape are similar in environment and figural perceptions. This sensitivity to metric properties, although topology (sequential information, or routes) has cognitive importance in environment perception as discussed below, indicates that the simple argument of spatial knowledge acquisition in terms of a progression of landmark-route-survey knowledge with respect to metricity is not viable empirically (Ishikawa & Montello, 2006).

Also similar to the case of figural perception, the regression lines for the four types of transformations do not coincide or parallel each other, contrary to the inference based on the mathematical classification of geometric transformations. Thus, in environment perception, cognitive and mathematical classifications of spatial properties are different. Furthermore, peoples' sensitivity to rotation, scaling, and reflection differs depending on the degree of deformation. When the degree of deformation is small, people perceive reflected configurations most dissimilar to deformed configurations, then scaled configurations, and then rotated configurations. They become less sensitive and do not discriminate rotated and scaled configurations from deformed configurations. In contrast to figural perception, in environmental perception people discriminate reflection from others constantly across different degrees of deformation, which points to the importance and qualitative distinction of topological information in environment perception.

In figural perception, the transformations of scaling, rotation, and reflection are considered relatively similar, compared to the case of environment perception, with a cognitive separation between scaling (similarity transformation) and rotation and reflection (rigid motions, resulting in congruence). By contrast, in environment perception, scaled configurations are considered dissimilar to deformed configurations, and reflection is discriminated from other transformations qualitatively. It points to the lesser cognitive prominence of similarity and the greater prominence of topology in environment perception, in which landmarks and paths need to be experienced in a horizontal perspective, not seen from above.

Concerning the effect of spatial aptitudes, people with a high mental-rotation ability discriminate between different configurations more sensitively, and in a way more aligned with the mathematical classification of geometries, than people with a low mental-rotation ability do. The extent to which reflected configurations are considered qualitatively different is greater for the low-spatial group, pointing to a greater tendency for them to attend to the property of topological relations, or to understand environments at the level of route knowledge.

In summary, the present results reveal the characteristics of spatial concepts perceived in large-scale environments, as contrasted by spatial concepts in figural perception. In particular, the results provide insights about the difference between cognitive and mathematical ways of classifying geometric properties, cognitive salience of different geometric properties and interaction among them, and the effects of spatial ability on the conception of spatial properties. Also, this study looked into the issue of environment perception from a different perspective than the existing studies, which examined the accuracy of mentally represented environments (e.g., Ishikawa & Montello, 2006) or analyzed relative positioning of landmarks in mental representations through MDS (e.g., Golledge & Hubert, 1982). Thus it exemplifies a novel attempt at investigating environmental perception and cognition from the perspective of spatial thinking.

Further issues to consider include the method for comparing the configurations of two virtual environments. In this study, participants viewed deformed and transformed configurations always paired with the original configuration, which may have been easier than comparing two environments from memory. Also, the effects of semantic or contextual factors need to be inspected, as they were found to affect the perception of spatio-temporal concepts such as topological relations represented by geometric figures (e.g., Klippel, 2012).

As a possible application of the present results, knowledge about the relationship between physical and perceived configurations may be applied to the design of city structures. As the symbol size on graduate circle maps can be varied referring to the relationship between physical and perceived dot size, the regression lines obtained in this study might be used to predict, for example, the shape of a neighborhood that is deformed to a degree that stimulates excitement of walking without disorienting the traveler. Finally, the results also provide pedagogical implications. Knowing that cognitive and mathematical classifications and environmental and figural spatial concepts differ, effective instruction of environmental learning and navigation could be developed, especially targeted to low-spatial people.

Acknowledgments. I thank HueYen Yang for his assistance in developing the virtual environments.

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