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SPATIO-TEMPORAL CUBE FOR VISUALIZING CULTURAL COLLECTIONS: EXPLORING A USER-FRIENDLY ROTATIONAL REPRESENTATION WITH DIFFERENT SPATIAL ABILITY

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Abstract

In this study, we compared two rotational representations of a spatio-temporal cube displaying a cultural collection data to determine which was more useful for information search. While the horizontal data plane of the cube represented a geographical map, the vertical axis showed time as an upward spatial dimension. Users manipulated the cube to find the country and time period in which artworks with the characteristics specified in the questions were most used. In the viewpoint rotation condition, the background flowed in conjunction with a horizontal rotation as if the users moving around the stationary cube. In the cube rotation condition, the cube was rotated in front of the user's eyes, and the background did not change. The users were able to search information more accurately when using the viewpoint rotation than the cube rotation. This was true for both users with high and low spatial abilities. This finding is discussed in terms of how the environmental reference frame supports users' spatial cognition.

Keywords: *Data visualization, cultural collection, spatio-temporal cube, rotational representation, spatial ability.*

1. Introduction

One way to visually capture the period of artworks and their geographical relationships is to represent it in three-dimensional (3D) spatio-temporal space (Windhager et al., 2020). These 3D visualization system is expected to represent complex relationships in a visually comprehensible way, sometimes encouraging users to make discoveries they did not intend to make. However, while presenting information in a three-dimensional space can integrate a variety of information, there is a possible risk that users who do not have a high spatial ability will not benefit from it. This is because spatial abilities not only compensate for the lack of spatial information in 2D representations, but are also necessary for learning in 3D representations (Krüger & Bodemer, 2021). For example, if users lose track of which direction they are looking from when manipulating the cube, there will be more errors and misunderstandings in searching spatial information, such as mistaking the bias of the east-west distribution of artworks for the north-south bias. Therefore, it is important to create a system that reduces the burden on the spatial ability of users and improves the convenience of using 3D visualization system.

From this point of view, we focuses on two types of rotational representations of cubes in a 3D visualization system. There are at least two ways to represent the rotation of the cube in which the information is placed. One is "cube rotation", which is a representation of cube rotating in front of the user's eyes against a fixed background. The other is "viewpoint rotation", an expression in which the user's viewpoint rotates around the cube and the background changes. Both representations do not differ in the visual change of the rotating cube itself, but according to the spatial reference frames theory, they may have different effects on the user's information search. McNamara et al. (Mou & McNamara, 2002; Rump & McNamara, 2006) classifies the criteria for specifying locations and directions into two types: egocentric and environmental (allocentric) reference frame. Egocentric reference frame is those defines the location with respect to the observer, whereas environmental reference frame defines the location relative to objects other than observer. The point here is that we can use the external objects that make up the environment as directional cues to indicate the location of something.

In both the viewpoint rotation and cube rotation conditions, the relationship between the user and the cube changes during operation of the system. However, under the viewpoint rotation condition, the relationship between the cube and the background objects is maintained. For example, taking Figure 5 (b) as an example, we can see that the spatial relationship between the door and the cube is always constant even if the cube rotates and changes its orientation. Therefore, under viewpoint rotation conditions, it is predicted that users will be able to use the background environment as a stable orientation cue to correctly understand the spatial state of the cube and to search for information. However, this hypothesis has not yet been tested. It is also an open question whether, if viewpoint rotation supports users' information search, it is true for both users with high and low spatial abilities or only for one of the two groups. This study investigates which of the two rotation representation methods, cube rotation and viewpoint rotation, facilitates users' information search using 3D visualization system, and whether it is related to individual differences in users' spatial ability.

2. Method

2.1. Users

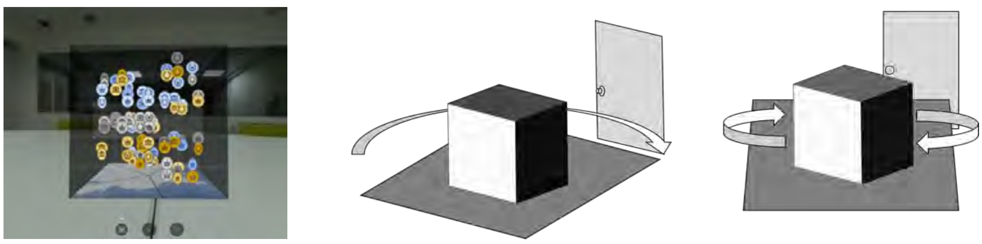
Twenty four students in Hiroshima international university participated in the experiments (12 men, 12 women). As a reward, they received a 1,000 yen quo card as a reward, which can be used at various stores in japan.

2.2. Materials and design

Search task Images of fictional artworks, coins and potteries, were used. FOCUS IN CUBE 3D created by DNP (see Figure 1 (a)) was used to represent the fictional artwork. Users were able to view the artworks by interactively switching their viewpoints, for example, from the outside of the cube to get a bird's-eye view of the entire artworks, or from the inside of the cube to look at the local area in detail. The horizontal and depth axes of the cube were used as the coordinate axes to express the production location of the artworks. On the bottom of the cube composed of these two axes, a square map divided into five countries by border lines were presented. The time axis is divided into five periods by lines drawn horizontally along the sides of the cube. The images of the fictional artworks were displayed inside the cube according to the spatial and temporal coordinates assigned to each image in advance. The cube was operated on a 20-inch, 4K touch panel; tracing the cube with one finger rotated the cube in the direction of the finger traced. When two fingers touched the screen, expanding the space between the fingers brought the cube closer (expansion), and contracting it brought it further away (contraction). The cube had a highlight function that made only groups of artworks that were in line with the characteristics of the theme of interest emit light and stand out. Each side of the cube had a translucent rectangular label, which contained the name of the theme (motifs, textures, colors, and shapes) in Japanese and a circular button. By pressing the button in the label, the display on the side of the cube switched from a main category showing the theme to a subcategory showing the features of the selected theme. When the users rotated the element they wanted to filter to the front, the artworks that matched that feature emitted light in the color. Behind the cube, a picture of the room taken by a 360°camera was displayed. In the viewpoint rotation condition (see Figure 1 (b)), the cube was displayed on a pedestal fixed to the desk in the room. When the cube was rotated in this condition, the background changed accordingly, visually expressing the user's movement around the cube placed on the desk. In the cube rotation condition, there was no pedestal, and the cube was displayed directly on the desk (see Figure 1 (c)). Under this condition, the background did not change when the cube was rotated, and the cube rotating in front of the user was expressed.

In the search task, the users searched for the country or period of artworks with specific characteristics using the filtering function of (i.e., by rotating) the cube. For the country-attribute question, the users were shown a chronological sheet with a target period out of the five was painted gray, and asked to "Check the country in which [pottery or coin] with ［particular feature] was used the most in the target period", and required to check the appropriate country on the map with check box. For the period-attribute question, the users were shown a country map with a target country out of the five was painted gray, and asked to "Check the period in which [pottery or coin] with ［particular feature] was used the most in the target country", and required to check the appropriate period on the chronological sheet with check box.

Figure 1. Example of FOCUS IN CUBE 3D used in each of the cube rotation and viewpoint rotation conditions, a schematic diagram of each rotation, and layout of the room.



(a) FOCUS IN CUBE 3D (b) Viewpoint rotation (c) Cube rotation

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Mental rotation test (MRT) We used the mental rotation test (MRT) to assess an individual's spatial ability; the MRT is a test that requires imagining the movement or form of an object (e.g., Cooper, 1975; Shepard & Metzler, 1971) and is used specifically to measure an individual's mental transformation ability (Kung & Hamm, 2010; Searle & Hamm, 2017). Images of the letters F and R were used. The experimental program for the MRT was created with the programming tool Hot soup processer and displayed on a 13-inch touch screen (Microsoft surface pro 8). In the task, the fixation point (+) was displayed on the screen for 2 seconds, and the normal or mirror image of F or R was presented at an orientation rotated from 0° to 315° (relative to upright direction) in 45° increments. At the bottom of the screen, there were rectangular buttons on the left and right corners, with the left button labeled "Normal (正立)" and the right button labeled "Mirror (鏡映) " in Japanese. When either button was pressed, the response time and whether the answer was correct or incorrect were recorded, and the fixation point was displayed again for the next trial (see Figure 3). The task was completed after 32 trials (letter: 2 x angle: 8 x normal/mirror: 2).

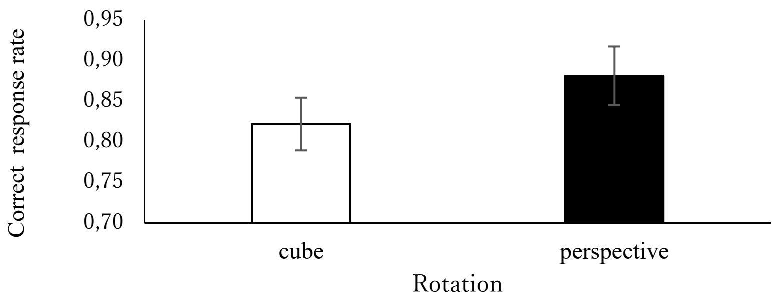
2.3. Procedure

The experiment was conducted on each user. Users performed in the following order: practice operating the touch panel, practice and main trials of the search task, and MRT.

3. Results

For each user, the correct response time and correct response rate for the search task and the MRT were calculated. For MRT, the values for each angle from 0° to 315° were replaced by the average value from 0° to 180° (the original value was used for 0° only). The slope of the approximate line for the increase of the correct response time for each angle was calculated for each individual. Three users whose correct response rate was below the chance level in the four conditions consisting of the combination of rotation representation (viewpoint, cube) and attribute (country, period) in the search task, and one user whose number of correct responses in the MRT was below the chance level were excluded from the subsequent analyses. The measures of the search task were analyzed in a two-factor repeated measures ANOVA with rotation (viewpoint, cube) × attribute (country, period). Only for the correct response rate, the main effect of rotation was significant, and the correct response rate was higher for viewpoint rotation than for cube rotation ($F(1,18)=5.82$, $p=.027$, see Figure2). Users were able to search more accurately when rotating the viewpoint than when rotating the cube.

Figure 2. Correct response rates between cube and viewpoint rotation in search task.



3.1. Effects of users' spatial ability on the search task

The correct response time and the correct response rate for each angle from 0° to 315° were calculated by replacing the average of 0° to 180° (the original values were used only for 0°). As the angle increased, the correct response time increased and the correct response rate decreased. These trends were confirmed by ANOVA in the correct response time. The main effect of rotation was significant ($F(4,76)=29.4$, $p<.001$). Multiple comparisons showed that correct response time was significantly longer as the angle increased between all conditions ($t(19)>4.00$) with the exception between 0° and 45° , and 90° and 135° ($t(19)<0.36$). The main effect of rotation was also significant for the correct response rate ($F(4,76)=2.58$ $p<.001$), but the results of multiple comparisons did not show significant differences between any of the angles ($t(19)<0.01$).

To assess spatial ability, the mean correct response time, the mean correct response rate, and the slope of the change in mean correct response time per angle were determined for each user. In analyzing the effect of spatial ability on the search task, it was concerned that the effect of the order in which the rotation conditions were implemented in the search task might be confounded with the effect of spatial ability. This is because the results of the search task showed a strong order effect, especially in correct response time, with all users answering the task correctly faster in the later rotation condition than in the earlier one. Therefore, the order of implementation of the two rotation conditions was counterbalanced in the high and low spatial ability groups, respectively. That is, of the users who performed the cube rotation condition first and those who performed the viewpoint rotation condition first, the top five MRT performers each, for a total of 10, were classified as the high spatial ability group, and the bottom five MRT performers each, for a total of 10, were classified as the low spatial ability group. This classification was done for the MRT's response time and correct response rate, correct response time sloop, respectively. There was no difference in the degree of interest in art between the low and high spatial ability groups, as asked in the post-questionnaire.

The correct response time and the correct response rate in search task were analyzed in a three-factor mixed model ANOVA with rotation (viewpoint, cube) × attribute (country, period)×spatial ability (high, low). When spatial ability was classified based on MRT's correct response rate, the main effect of spatial ability was significant on the correct response rate of search task, showing that the high spatial ability group searched more accurately than the low spatial ability group ($F(1,18)=6.26$, $p=.022$, see Figure 3). Furthermore, when spatial ability was classified based on MRT's correct response time slope, attribute × spatial ability interaction was significant for correct response time ($F(1,18)=9.84$, $p=.006$), and for country attribute search, the high spatial ability group was able to search for the correct answer in less time than the low spatial ability group ($t(18)=3.23$, $p=.022$). In the period attribute search, however, there was no significant difference in the correct response time by spatial ability (see Figure 4).

Figure 3. Correct response rate between low and high spatial ability users in search task. Spatial ability was classified based on the correct response rate (CRR) in MRT.

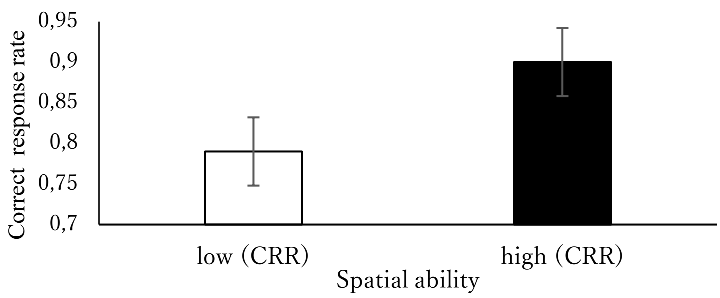
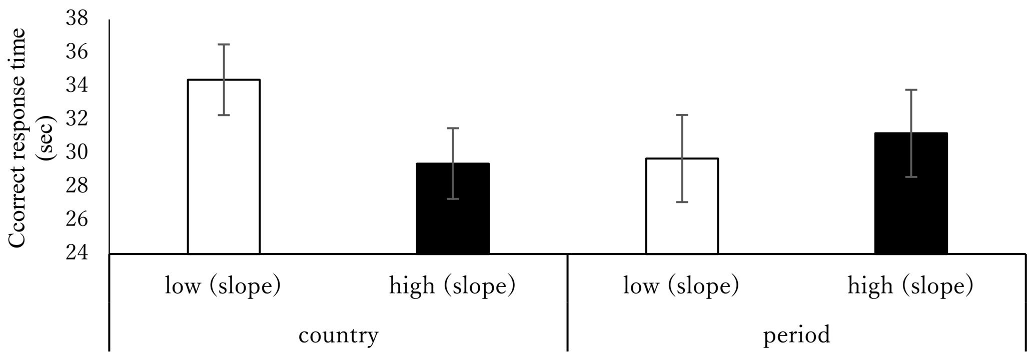


Figure 4. Correct response rate between low and high spatial ability users in search task. Spatial ability was classified based on the correct response time slope in MRT.



4. Discussion

The purpose of this study was to compare two different ways of representing cube rotation and to test which one facilitates the search of information using the 3D visualization system. The result showed that the accuracy of the search task was higher in the "viewpoint rotation" condition, in which the user's viewpoint moved around the cube, than in the "cube rotation" condition, in which the cube itself rotated in front of the users (Figure 2). The cause of this difference can be interpreted from spatial reference frame theory as follows. Under both conditions, the relationship between the users and the cube changes while the cube is being manipulated. However, in the viewpoint rotation condition, the relationship between the cube and the background object is maintained. Therefore, in the viewpoint rotation condition, using the background environment as a stable directional cue, users were able to correctly identify the placement of artworks in the cube without misunderstanding from which side they were viewing the artworks. On the other hand, in the cube rotation condition, the background room did not change when the cube was rotated, so the users could not use the visual change of the room to understand which side of the cube they were looking at. This has led to an increase in the number of cases where users misunderstood which side they were looking at the artworks from, and thus incorrectly grasped the placement of the artworks in the cube.

In this experiment, regardless of the user's spatial ability, information search was more accurate in the viewpoint rotation condition than in the cube rotation condition. This suggests that the presentation of an environmental reference frame using a viewpoint rotation representation can support information search and spatial thinking using cubes for users with low to high spatial ability. In spite of it, even when the 3D visualization system presented the environmental reference frame, there were still differences in the performance of information retrieval based on the user's spatial ability. However, from an educational point of view, while it is important for educational tools to bridge the ability gap among students, it is more desirable for them to be able to support the abilities within all students. Therefore, the introduction of visual representations with environmental reference frame in 3D visualization system is essential in aiming for educational tools that improve the abilities of all students.

The perspective of this study is a synthesis of two hypotheses about the impact of 3D visualization on learning that have been proposed in previous studies: the ability-as-compensator hypothesis and the ability-as-enhancer hypothesis (Höffler & Leutner, 2011; Huk, 2006). The ability-as-compensator hypothesis predicts that people with low spatial ability who have difficulty visualizing will benefit more from graphic representations. On the other hand, the ability-as-enhancer hypothesis predicts that people with higher spatial ability who have sufficient working memory capacity to handle 3D models will benefit more from 3D models. We believe that by reducing the spatial cognitive load of the visualization system, people with low spatial ability will be able to benefit from it without overloading their capacity, while people with high spatial ability will have more capacity, allowing for more accurate and deeper understanding.

The range of application of FOCUS IN CUBE 3D is wide, and it is expected to have creative effects, such as discovering new relationships between information that was overlooked by visualizing data. Therefore, it remains to be seen to what extent the suggestions obtained using relatively simple tasks such as information search can be applied to more complex tasks. However, given that human cognitive resources (working memory) are finite, we can expect that reducing the cognitive load on lower-order tasks will allow more time to focus attention and thought on higher-order creative tasks, thereby increasing productivity in higher-order tasks. Further verification of this is awaited.

References

Cooper, L. A. (1975). Mental rotation of random two-dimensional shapes. *Cognitive Psychology, 7*(1), 20-43. doi:https://doi.org/10.1016/0010-0285(75)90003-1

Höffler, T., & Leutner, D. (2011). The role of spatial ability in learning from instructional animations - Evidence for an ability-as-compensator hypothesis. *Computers in Human Behavior, 27*, 209-216. doi:10.1016/j.chb.2010.07.042

Huk, T. (2006). Erratum: Who benefits from learning with 3D models? The case of spatial ability (Journal of Computer Assisted Learning (2006) 22 (392-404)). *J. Comp. Assisted Learning, 22*, 392-404. doi:10.1111/j.1365-2729.2006.00180.x

Krüger, J., & Bodemer, D. (2021). *Space, a Central Frontier - The Role of Spatial Abilities When Learning the Structure of 3D AR Objects*.

Kung, E., & Hamm, J. P. (2010). A model of rotated mirror/normal letter discriminations. *Mem Cognit, 38*(2), 206-220. doi:10.3758/mc.38.2.206

Mou, W., & McNamara, T. P. (2002). Intrinsic frames of reference in spatial memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 28*(1), 162.

Rump, B., & McNamara, T. P. (2006, September). Updating in models of spatial memory. In *International Conference on Spatial Cognition* (pp. 249-269). Springer, Berlin, Heidelberg.

Searle, J. A., & Hamm, J. P. (2017). Mental rotation: an examination of assumptions. *Wiley interdisciplinary reviews. Cognitive science, 86*.

Shepard, R. N., & Metzler, J. (1971). Mental rotation of three-dimensional objects. *Science, 171*(3972), 701-703. doi:10.1126/science.171.3972.701

Windhager, F., Salisu, S., Leite, R. A., Filipov, V. A., Miksch, S., Schreder, G., & Mayr, E. (2020). Many Views Are Not Enough: Designing for Synoptic Insights in Cultural Collections. *IEEE Computer Graphics and Applications, 40*(3), 58-71.