Chapter #22

EFFECTS OF ROTATIONAL REPRESENTATION OF SPATIO-TEMPORAL CUBES AND SPATIAL ABILITY ON INFORMATION SEARCH

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ABSTRACT
The purpose of this study was to explore which rotational representation, viewpoint rotation or object rotation, is more useful in search task where perceptual interaction with the data being manipulated exists using a spatio-temporal cube displaying cultural collection data. The horizontal data plane of the cube represented a geographical map, and the vertical axis represented time as an upward spatial dimension. Users manipulated the cube to identify the country and time period in which certain artworks with the characteristics specified in question items, i.e., coins or pottery, were most commonly used. In the viewpoint rotation condition, the background flowed along with a horizontal rotation, as if the users were moving around a stationary cube. In the cube rotation condition, the cube was rotated in front of the user's eyes, and the background did not change. Using spatial reference frame theory, we predicted that the advantage of viewpoint rotation, as described in imagery studies, holds true for the use of a visualization system in which the trajectory of the cube's rotation during manipulation was visible. Users were able to locate information more accurately when using viewpoint rotation. This was true for both users with high and low spatial abilities.

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

1. INTRODUCTION

The digitization of cultural collections allows artworks that are difficult to display available to the public while maintaining their preservation and to obtain access to information on them at any time and any place. Digitization has also created novel means of showing works that were not previously possible to display. One example of this is a visualization system that visually presents each artwork and its relationships to other pieces.

To support the development of an integrated visualization system for understanding vast digital cultural collections, Windhager et al. (2020) devised a polycube framework to map information by means of 3D space-time cubes. These polycubes have a data plane that consists of horizontal and depth axes, as well as a time axis in the vertical direction. Using the cube system, time and space information, which is presented in different chronological notations and maps in 2D visualization systems, can be displayed as a visually integrated cohesion of data points inside a space-time cube. One of the authors of this chapter works with Dai Nippon Printing Co., Ltd. (DNP), which is developing a digital tool, using a cube-shaped interface termed as FOCUS IN CUBE 3D. In this interface, cultural assets and artworks are mapped inside a cube, where the bottom represents spatial information, such as the place of creation, and the vertical axis represents temporal information such as the time of creation. In addition, the theme is described on the side of the cube. Rotating the cube horizontally and switching the side of the theme that faces the user allows works that match the theme to be illuminated and filtered. FOCUS IN CUBE 3D can represent complex relationships in a visually comprehensible way, sometimes encouraging users to make discoveries they did not intend to make. FOCUS IN CUBE 3D is designed as a general-purpose system that can represent information in various genres in multiple dimensions without being limited to art. Therefore, the cube, a three-dimensional structure with clear axes for mapping information and without the figurative nature of a museum, was chosen for this system.

However, while a variety of information can be integrated into a three-dimensional space, there is the risk that users who do not have a sufficient spatial ability cannot benefit from this. This is because spatial abilities not only compensate for a lack of spatial information in 2D representations but are also necessary for learning in 3D representations (Krüger & Bodemer, 2021). For example, Bogomolova et al. (2021) reported that surgical residents with high spatial ability benefited more from a 3D educational video than an alternate 2D one for learning spatially complex surgical procedures, but those with low spatial ability did not have an advantage when using 3D videos. This significant disparity may appear where users with low spatial ability run over capacity trying to process rich spatial information. The same concern applies to the use of 3D visualization systems.

From this point of view, this study focuses on two types of rotational representations of cubes in a 3D visualization system. There are at least two ways of representing the rotation of the cube in which the information is placed. One of these is cube rotation, a representation of cube rotating before the user’s eyes against a fixed background. The other is viewpoint rotation, in which the user’s viewpoint rotates around the cube and the background changes. Neither representation differs in the visual change of the rotating cube itself, but according to the spatial frame of reference theory, they may have different effects on the user’s information search.

With reference to the spatial reference frame, McNamara et al. (Mou & McNamara, 2002; Rump & McNamara, 2007) classified the criteria for specifying locations and directions into two groups: egocentric and environmental (allocentric) reference frames. Egocentric reference frames define the location with respect to the observer, but the environmental reference frame defines the location relative to objects other than the observer. For example, a wall clock in a room can be identified and described in two ways: on the observer’s right side or on the left side of a bookshelf. The relative position defined by the egocentric reference frame changes with the position of the observer, but the position defined by the environmental reference frame is independent of the observer.

In the viewpoint rotation approach, the spatial relationship between the user and the cube changes as the viewpoint rotates around the cube, but the relationship between the cube and the background objects is maintained. That is, the cube rotates relative to the egocentric reference frame but not relative to the environmental reference frame. Thus, the user can use the background environment as a stable directional cue to understand the current state of the cube. However, in cube rotation, the cube rotates independently from its surroundings, so that the relative orientation of the cube changes with respect to both the user and the background objects. Here, the user must keep track of the rotational direction and the angle of the cube relative to their own bodies, the background environment, or both. This means that the user cannot use a stable directional cue to reference to identify the spatial state of the cube in either reference frame. Consequently, we expect that viewpoint rotation will be easier for the user to orient the cube, using an environmental reference frame to establish cube rotation and to aid in the exploration of a visual dataset mapped inside it.

In relation to the rotation of visuospatial mental image, Zacks, Vettel, and Michelon (2003) proposed multiple system frameworks in which different neural structures are responsible for viewpoint and object-based spatial transformations. This theory indicates that these structures are shaped by natural selection and lifelong learning to capture regularities existing in the environment. The use of multiple systems is supported by the findings of several neuroimaging studies (Lambrey, Doeller, Berthoz, & Burgess, 2012; Wraga, Shephard, Church, Inati, & Kosslyn, 2005; Zacks et al., 2003). These studies report results that suggest that the two types of visuospatial mental transformations depend on different resources for neural processing. Behavioral studies of mental imagery have also shown that it is generally faster and more accurate to imagine viewpoint rotation than imagining object or array rotation (Creem, Wraga & Proffitt, 2001; Wraga, Creem, & Proffitt, 2000; Wraga, Creem-Regehr, & Proffitt, 2004). Thus, we predict that a 3D visualization system with viewpoint rotation will be more effective for users to mentally transform the depicted cube or a visual dataset inside it than a system with cube rotation.

Therefore, the advantage of viewpoint rotation has been demonstrated in studies of mental imagery using imagined arrays. However, visualization systems, such as FOCUS IN CUBE 3D, do not explicitly require the use of imagery, as the trajectory of the cube rotation associated with the manipulation can be perceived. Whether the advantage of viewpoint rotation is also demonstrated in such task situations where perceptual interaction exists has not been fully tested, compared to the wealth of findings in imagery studies. We consider that viewpoint rotation allows users to employ the background as an environmental reference frame to capture the orientation of a cube and the layout of cultural objects inside it. Thus, viewpoint rotation representation is expected to reduce the spatial burden on the user and reduce misunderstandings of the information mapped inside the cube relative to cube rotation.

It also remains an open question whether, if viewpoint rotation supports users' search for information, this is true for both users with higher and lower spatial abilities or only for one of the two groups. Prior research focusing on the impact of 3D visualization models on learning has proposed two contrasting hypotheses: the ability-as-compensator hypothesis and the ability-as-enhancer hypothesis (Höffler & Leutner, 2011; Huk, 2007). The ability-as-compensator hypothesis predicts that people with low spatial ability who have difficulty visualizing will benefit more from graphic representations. By contrast, the ability-as-enhancer hypothesis predicts that people with higher spatial ability and sufficient working memory capacity to handle 3D models will benefit more from such models. Thus, the two models clearly differ in terms of the groups for which the 3D model has a positive effect, indicating that the low-spatial ability group would benefit according to the ability-as-compensator hypothesis and the high-spatial ability group would benefit from viewpoint rotation according to the ability-as-enhancer hypothesis. Hypothetical conflicts of this type indicate that no comprehensive theory has yet been established. Therefore, we thought it is necessary to conduct a new study involving the two types of rotation methods and the user's spatial ability. From the theoretical framework for our research, based on the spatial reference frame theory, we consider that viewpoint rotation will help participants with low spatial ability to grasp the visualized data and search for required information by reducing the spatial cognitive load of searching for information using a visualization system. In addition, the process of information search using a visualization system requires not only spatial understanding of the visualized data but also consideration of its meaning (e.g., what kind of distributional bias or characteristics the visual data shows). Therefore, the reduction of the cognitive load required for spatial cognition through viewpoint rotation could have a positive effect by giving high-spatial-ability individuals more room to comprehend the visualized information more accurately. These predictions can be inferred by examining how differences in participant performance due to spatial ability appear when they perform information search using the visualization system under the two rotation conditions. If viewpoint rotation primarily assists low-spatial-ability individuals, then the performance difference due to spatial ability should be smaller in the viewpoint rotation condition than in the cube rotation condition. Conversely, if viewpoint rotation primarily assists high spatial performers, then the performance difference according to spatial ability should be larger in the viewpoint rotation condition than in the cube rotation condition. Following these explanations, the difference in performance with the visualization system due to differences in spatial ability should be shown as an interaction of spatial ability × rotation. Conversely, if viewpoint rotation is effective for low and high spatial ability users, as described as a possibility in this study, then the difference in performance due to spatial ability would be expected to be equal for cube and viewpoint rotation. Following this explanation, differences in performance with the visualization system due to differences in spatial ability would be observed as a main effect of spatial ability.

Overall, this study investigates which of the two rotation representation methods better facilitates users' information search with the use of 3D visualization systems and whether it is related to individual differences in users' spatial ability. We used the Mental Rotation Test (MRT) to measure participants' spatial ability. In this test, participants are asked whether the rotated block is the same shape as the block paired with it or whether the rotated alphanumeric character is normal or a mirror image. Response times in these tests generally increase as the shortest angular difference between the paired block or displayed letter and the original block or upright letter increases in the range 0°–180° (Cooper & Shepard, 1973; Shepard & Metzler, 1971). The mechanism behind this has been assumed to be a mental manipulation, i.e., analogous to the process of physical rotation (Cooper, 1975). Hamm and colleagues (Kung & Hamm, 2010; Searle & Hamm, 2012) discovered that in two-dimensional stimuli using the alphabet letters, participants were more likely to use nonrotational (nonspatial) strategies and that mixing them with rotational strategies led to deviation from linear performance. This tendency becomes more pronounced as the angular difference from the upright decreases. Therefore, Kung and Hamm (2010) proposed that the difference between 180°, where mental rotation is most needed, and 0°, where mental rotation is not needed at all, divided by 180, provides the best estimate of an individual's mental rotation rate, i.e., the time required to rotate an image by 1°. In this study, mental rotation rate calculated based on the letter-based MRT was used as a measure of participants' spatial ability, particularly mental manipulative ability.

2. METHODS

2.1. Participants

24 college students (12 men and 12 women) majoring in psychology participated in the experiment. Each received a 1,000 yen Quo card as a reward, which can be used at a range of shops in Japan.

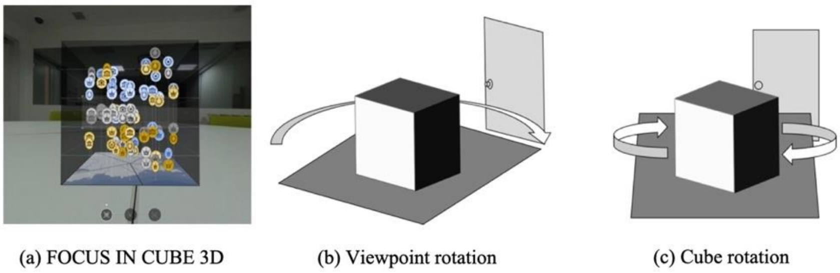
2.2. Materials and Design

2.2.1. Search Task

Images of fictional artworks, namely, coins and pottery, were used. FOCUS IN CUBE 3D, which was created by DNP (Figure 1 (a)), was used to represent these fictional artworks. The participants were able to view the artworks by interactively switching their viewpoints, for example, looking from the outside of the cube to obtain a bird's-eye view of the entire artworks or from the inside of the cube at the local area in detail. The horizontal and depth axes of the cube were used as coordinate axes to express the production location of the artworks. On the bottom of the cube, a square map along these axes was presented that was divided into five countries using border lines. The time axis was divided into five periods, using lines drawn horizontally along the sides of the cube. Images of the fictional artworks were displayed inside of the cube, according to the spatial and temporal coordinates that were assigned to each image in advance. The cube was manipulated using a 20-inch, 4K-resolution touch panel; tracing the cube with one finger rotated the cube in the direction of the finger's motion. When two fingers touch the screen, expanding the space between the fingers brought the cube closer (expansion), and contracting it moved it further away (contraction). The cube exhibited 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 showed a translucent rectangular label containing the name of the theme (motifs, textures, colors, and shapes) in Japanese, along with a circular button. When the button in the label was pressed, the display on the side of the cube switched from a main category showing the theme to a subcategory with the features of the selected theme. After rotating the element they wanted to filter to the front, the participants were shown artworks that matched that feature emitting light in the given color. Behind the cube, a 360° camera image of the room was displayed. In the viewpoint rotation condition (Figure 1 (b)), the cube was displayed on a pedestal fixed to a desk in the room. When the cube was rotated in this condition, the background changed in response, visually expressing the participant's movement around the cube. There was no pedestal in the cube rotation condition, and the cube was displayed directly on the desk (Figure 1 (c)). Under this condition, the background did not change when the cube was rotated, and the cube rotating in front of the participant was expressed.

In the search task, the participants searched for a country or period of artworks with specific characteristics using the filtering function, that is, by rotating the cube. For the country attribute question, the participants were shown a chronological sheet where one target period out of the five was colored gray and were asked to "Check the country in which [pottery or coin] with [particular feature] was used the most in the target period." The participants were to select the appropriate country on the map. For the period attribute question, the participants were shown a country map on which one target country out of the five was painted gray and were asked to "Check the period in which [pottery or coin] with [particular feature] was used the most in the target country." The participants were to select the appropriate period from the chronological sheet.

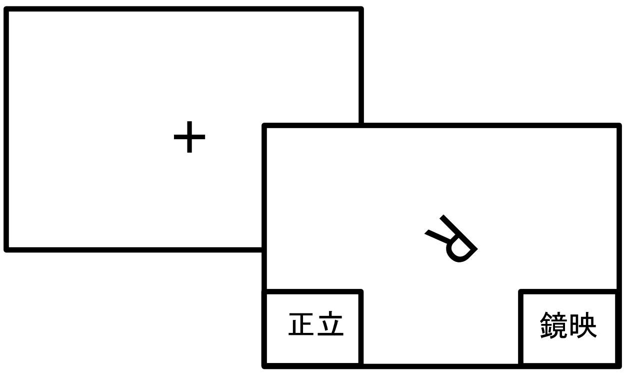
Figure 1.
Example of FOCUS IN CUBE 3D used in the cube rotation and viewpoint rotation conditions, a schematic diagram of each rotation, and depiction of the layout of the room.



2.2.2. Mental Rotation Test

We used MRT to assess spatial ability. Images of the letters F and R were used. The experimental program for the MRT was created using the programming tool Hot Soup Processer and displayed on a 13-inch touch screen (a Microsoft Surface Pro 8). For this task, a 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 the upright direction) in 45° increments. At the bottom of the screen, there were rectangular buttons at 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 the correctness of the answer were recorded, and the fixation point was displayed again for the next trial (Figure 2). The task was completed after 32 trials (letter: 2 × angle: 8 × normal/mirror: 2).

Figure 2.
A schematic time course of a single trial in the MRT. Each trial began with the presentation of a fixation point for 2 seconds. Then, the normal or mirror image of F or R was presented at an orientation that was rotated from 0° to 315° in 45° increments. At the bottom of the screen were rectangular buttons at the left and right corners, with the left button labeled in Japanese “Normal” (正立) and the right button labeled “Mirror” (鏡映).



2.3. Procedure

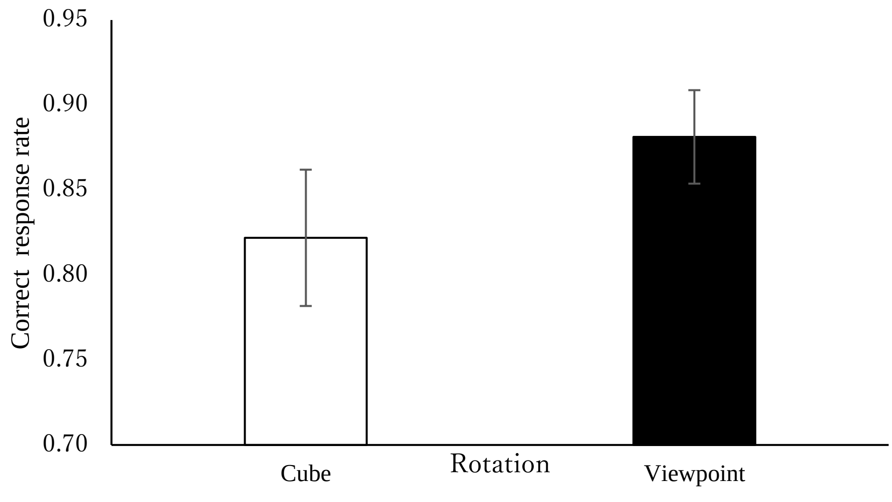
The experiment was conducted on each participant. Participants performed the experiment in the following order: practice operating the touch panel, practice and main trials of the search task, and conduct the MRT.

3. RESULTS

For each participant, the correct response time and correct response rate were calculated for the search task. The rate rather than the number of correct responses was used as a measure because a few participants' data included trials with missing records. Correct response rate was subjected to angular transformation to stabilize variance (arcsine square root percentage transformation) before statistical analysis. The correct response time was calculated for the MRT. The values for each angle from 0° to 315° were replaced by an average value from 0° to 180° (the original value was used for 0° only). Three participants whose correct response rate was below the level of chance in the four conditions, consisting of a combination of rotation representation (viewpoint, cube) and attribute (country, period) in the search task, and one participant whose number of correct responses in the MRT was below the level of chance were excluded from the subsequent analyses.

The measures for the search task were analyzed in a two-factor repeated measures analysis of variance (ANOVA) with rotation (viewpoint, cube) × attribute (country, period). 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 Figure 3). The participants were able to search more accurately when rotating the viewpoint than when rotating the cube.

Figure 3.
Correct response rates between cube and viewpoint rotation in a search task.



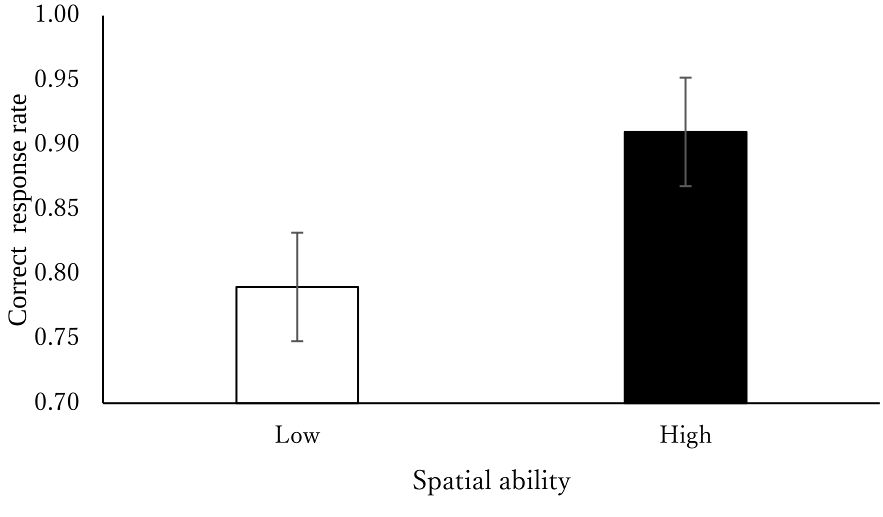
3.1. Effects of Participants' Spatial Abilities on the Search Task

As the angle increased, the correct response time increased. These trends were confirmed by ANOVA. The main effect of rotation was significant ($F(4, 76) = 29.4$, $p < .001$). Multiple comparisons showed that correct response times were significantly longer as the angle increased between all conditions (t(19) > 4.00), with an exception between 0° and 45° and between 90° and 135° (t(19) < 0.36).

To assess spatial ability, the difference in MRT's correct response time between 180° and 0° for each participant was divided by 180° and calculate mental rotation speed. In the analysis of the effects of spatial ability on the search task, it was a concern that the order in which the rotation conditions were applied in the search task could produce confounding effects with spatial ability. This is because the results of the search task showed a strong order effect, especially in terms of correct response time, with all participants providing correct answers more rapidly in the later rotation condition than in the earlier one. Therefore, the order of implementation of the two rotation conditions was counterbalanced for between the high and low spatial ability groups. That is, of the participants who performed the cube rotation condition first and those who performed the viewpoint rotation condition first, the top 5 MRT performers from each group, for a total of 10 participants, were classified as the high spatial ability group, and the bottom 5 performers each, for a total of 10, were classified as the low spatial ability group. There was no difference in the degree of interest in art between the low and high spatial ability groups, as identified in the post-questionnaire.

The correct response time and the correct response rate for the search tasks analyzed in a three-factor mixed model ANOVA with rotation (viewpoint, cube) × attribute (country, period) × spatial ability (high, low). In addition to the aforementioned main effect of rotation, a main effect of spatial ability was significant in the correct response rate, indicating that the high spatial ability group provide more accurate searchers than the low spatial ability group (F(1, 18) = 4.49, p =.048; Figure 4).

Figure 4.
Correct response rate between low and high spatial ability participants in a search task.



4. DISCUSSION

This study compared two different methods of representing cube rotation and to tested which of the two better facilitated an information search 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 user. The cause of this difference can be understood in the terms of spatial reference frame theory, as follows. Under both conditions, the relationship between the user 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, the users could correctly identify the placement of artworks in the cube without misunderstanding the side from which they viewed the artworks. In contrast, in the cube rotation condition, the background room did not alter when the cube was rotated, so the users could not use any visual change in the room to track which side of the cube they were observing. This led to an increase in the number of cases where users misunderstood which side they were seeing the artworks from, enabling them to incorrectly grasp the placement of the artworks in the cube.

The findings of this study are also consistent with views regarding spatial imagery research. Several studies have suggested that viewpoint rotation is easier to image than object rotation (Creem et al., 2001; Wraga et al., 2000, 2004). A multiple systems framework assumes that the two types of mental spatial transformations have evolved to solve different types of problems (Zacks et al. 2003). On this view, object-based transformations are oriented toward the planning of actions with physically manipulable objects, but viewpoint transformations are oriented toward planning for possible self-movements and social interactions. The advantage of viewpoint rotation thus would not be surprising, given that we are mobile organisms and cannot survive without being able to acutely predict changes in spatial relationships between our moving selves and the objects around us. In search tasks, users may have used imagery corresponding to the two types of rotational representations to plan means of manipulating the cube or predicting the outcome of a manipulation. Therefore, it is assumed that users can make better use of the imagery in the viewpoint rotation condition than in the cube rotation condition, which leads to more efficient data searches. The advantage of viewpoint-rotated imagery would thus be enhanced through the use of more complex tasks requiring more spatial thinking than the search task.

The finding indicates that an environmental reference frame supports the search for information using 3D visualization system. However, it remains to be learned why the difference in rotation condition alters the accuracy of the search not only in country identifications but also in period identifications. For the user, the position of the period category does not change with rotation, so period attribute searches should not need the support of an environmental reference frame. This may be because users needed to focus on a specific country before identifying the period. In the viewpoint rotation condition, the presence of an environmental reference frame made it easier to identify the specified country within the cube, which reduced the possibility of misidentifying the period by focusing on the wrong country.

Further, regardless of the user's spatial ability, information search was more accurate in viewpoint rotation than in cube rotation. Therefore, the introduction of visual representations with environmental reference frames in the 3D visualization system is essential for developing educational tools that improve the abilities of all students.

This study synthesizes two hypotheses on the impact of 3D visualization on learning from previous studies: the ability-as-compensator hypothesis and the ability-as-enhancer hypothesis (Höffler & Leutner, 2011; Huk, 2007). The present study exhibits the advantage of viewpoint rotation in information search using the visualization system for high- and low-spatial-ability participants. The difference in search performance due to high and low spatial ability observed in the object rotation condition was neither significantly reduced nor increased in the viewpoint rotation condition. Therefore, we believe that by reducing the spatial cognitive load of the visualization system, people with low spatial ability can benefit from it without overloading their capacity, while people with high spatial ability have more capacity, allowing for greater accuracy and deeper understanding.

Previous studies have shown that spatial reference frames can influence the memory of location relations. Although memory-based search was not performed in this study, the environmental reference frame will likely also contribute to the user's accurate memory of information by supporting the accurate perception of information during searches using a 3D visualization system. Therefore, viewpoint rotation representation can be effective, even in memory learning, such as in learning the history of an artwork by manipulating the 3D visualization system.

The use of viewpoint rotation in the visual representation of the operation of FOCUS IN CUBE 3D improves the accuracy of information searches. If the visual symmetry of the data displayed inside the cube is high, it may be difficult for the users to identify the side from which they are observing the cube. Adding a background to the cube that indicates a change in viewpoint may help users properly grasp the three-dimensionally arranged data and prevent search errors. Viewpoint rotation is also expected to be effective, not only for users with low spatial ability but also for those with high spatial ability. Regarding education and usability, it is important to reduce the burden on users with low ability, but it is more desirable to support all users with different abilities. Therefore, it is necessary to introduce viewpoint rotation into a 3D visualization system, such as FOCUS IN CUBE 3D, to make it a useful tool for all users. On the other hand, the range of applications in FOCUS IN CUBE 3D is wide, and it is expected that it will have creative effects, such as discovering new relationships between information overlooked by visualizing data. Therefore, the extent to which the suggestions obtained with relatively simple tasks such as information searches can be applied to more complex tasks remains to be seen. However, as human cognitive resources are finite, we believe that reducing cognitive loads in lower-order tasks will make attention resources available for higher-order creative tasks, increasing productivity in these.

Further research is needed to confirm the above. In this study, we classified the spatial abilities of the participants posteriorly, making it difficult to open up ability differences. In future studies, it would be worthwhile to investigate the extent of the contribution of a visualization system with viewpoint rotation among participants with more extreme ability differences according to a priori classification. In particular, it is important to know whether people with spatial ability problems (disabilities) can also be assisted in using visualization systems through viewpoint rotation representation. We think that the results of this study have significant practical application because they would stimulate further research to motivate the expansion or show the limitations of the people who can expect to be cognitively assisted by viewpoint rotation representations.

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