Influence of 3D images and 3D-printed objects on spatial reasoning

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Abstract

In this study, we experimentally investigated the influence of a three-dimensional (3D) graphic image and a 3D-printed object on a spatial reasoning task in which participants were required to infer cross sections of a liver in a situation where liver resection surgery was presupposed. The results of the study indicated that using a 3D-printed object produced more accurate task performance and faster mental model construction of a liver structure than a 3D image. During the task, using a 3D-printed object was assumed to reduce cognitive load and information accessing cost more than using a 3D image.

Keywords: External representation; 3D print; Spatial reasoning; Mental model

Introduction

Spatial reasoning and external representations

Spatial reasoning refers to inferring an object's shape and structure and the physical relationship between objects using spatial information (e.g., Byrne & Johnson-Laird, 1989). Spatial reasoning is ubiquitous in daily activities such as planning routes, inferring a road's slope angle, or arranging furniture in a room.

External representations such as figures, tables, and graphs are often used for spatial reasoning (Hegarty, 2011). Many studies on distributed cognition theory demonstrated the effects of using external representations on cognitive activity (e.g., Zhang & Norman, 1994). External representations can store information externally and reduce working memory load (Zhang & Norman, 1994). Physically manipulating external representations allows people to save mental rotation efforts (Kirsh & Maglio, 1994). Furthermore, spatially organized information on external representations could allow the offloading of cognitive processes onto perceptual processes (Scaife & Rogers, 1996).

Many studies on spatial reasoning have shown that different external representations of the same information have different effects on spatial reasoning (e.g., Hegarty, 2011). John, Cowen, Smallman, and Oonk (2001) experimentally investigated the effects of using two-dimensional (2D) and three-dimensional (3D) graphic images of the same spatial information for spatial reasoning and found that 3D images were more effective than 2D images in providing an understanding of shapes and layouts; 3D images integrate the multiple perspectives expressed by 2D images into a single perspective, provide supplementary depth cues, and display object features that would be invisible in 2D images. In contrast, they also found that 2D images were more useful than 3D images for an understanding of relative positions because 2D images display only necessary information and allow people to focus on it.

Other studies have shown that 3D images are more useful than 2D images only for people with high spatial ability (Hegarty, Keehner, Cohen, Montello, & Lippa, 2007; Nguyen, Nelson, & Wilson, 2011). Spatial ability is the ability to mentally store and manipulate spatial representations accurately (Hegarty & Waller, 2005). High spatial ability individuals can infer a structure's internal representation, whereas low spatial ability individuals cannot accurately construct a structure's internal representation and tend to depend on external representations (Kali & Orion, 1996). Because people with high spatial ability can recognize the complex spatial information in a 3D image with less difficulty, they can better take advantage of the information (Nguyen et al., 2011).

3D-printed objects

The recent prevalence of 3D printers has made it possible for people to replicate objects. 3D printers give people a totally new and unprecedented way of displaying information and have been used in various fields such as education, industrial manufacturing, and medicine. However, very few studies have investigated the influence of 3D-printed objects on spatial reasoning.

Some studies experimentally investigated human understanding of molecular structures using concrete models (Barrett, Stull, Hsu, & Hegarty, 2015; Stull, Barrett, & Hegarty, 2013). In their experimental tasks, participants learned molecular structures using 3D images or concrete models. After their learning the structures, they were required to orient the 3D images or concrete models in the same directions as the molecular structures depicted on paper. The results of these experiments demonstrated no difference in task accuracy between the use of 3D images and concrete models. However, the task completion time was shorter with the use of 3D images than with concrete models. Based on these results, they concluded that a 3D image was more useful than a concrete model for understanding physical structures. However, in their experiments, task accuracy rate was very high. Therefore, further investigations that consider situations requiring people to understand more complex structures with physical object models are necessary.

Furthermore, Maehigashi et al. (2015) investigated, using an ethnographic method, the influence of using a 3D-printed liver model on doctors during liver resection surgery. Protocol analyses results revealed that using 3D-printed models helped doctors elaborate their mental models of a patient's liver, mentally simulate the liver resection accurately, and share a similar mental model with other doctors. They also suggested the possibility that a 3D-printed model enhances mental model elaboration more than a 3D image.

In this study, we experimentally investigated the influence of 3D images and 3D-printed objects on a spatial reasoning task in which participants were to infer cross sections of a liver in a situation where liver resection surgery was presupposed. We tested the following two hypotheses: (1) spatial reasoning would be more accurate when a 3D-printed object was used than when a 3D image was used and (2) the learning time for constructing a mental model would be shorter when a 3D-printed object was used than when a 3D image was used.

Experiment

Participants memorized or referred to a liver's internal structure displayed by a 3D image or a 3D-printed object and inferred the locations of veins on a certain cross section of a liver and a tumor in the liver.

Method

Participants Forty-eight university students participated in this experiment.

Factorial design The experiment had a two-factor mixed design. The factors were (1) external representation (image and object) between participants and (2) task situation (memory and reference) within participants.

Material Two desks, a primary and a secondary desk, were used in the experiment. The primary desk (representing an operating table in a surgical setting) was set in front of a participant, and the secondary desk (representing a tool stand in a surgical setting) was set on the participant's right side. Three boxes were placed on the primary desk. Each box contained a 3D-printed model of a liver (target) (representing a patient's liver) and an answer sheet. On the secondary desk was either a computer on which a liver's 3D image was displayed or a box containing a liver's 3D-printed object created using the same manufacturing method as the 3D-printed model of the liver used for surgery. Figure 1 shows a 3D image, a 3D-printed object, and a target.

(a) 3D image (b) 3D-printed object (c) Target

Figure 1: (a) 3D image, (b) 3D-printed object, and (c) target

The 3D image was created with Pluto, a computer-aided diagnosis system developed at Nagoya University's Graduate School of Information Science, using data from a patient's liver measured by computed tomography (CT) (Figure 1a). In the 3D image, the thickest vein, an inferior vena cava (IVC), and five veins branching from the IVC were represented in blue, and a tumor was represented in white. The participants could rotate, zoom in on, and zoom out of the image using a mouse.

The 3D-printed object and the three targets were created with a 3D printer using the same CT liver data as the 3D image (Figure 1b, 1c). In particular, a 0.02-mm thick layer of acrylic resin was laid down in approximately 4,000 layers to produce the 3D-printed object and the target. The extra resin was then melted and removed, and the surface of the printed liver was polished. The 3D-printed object shows a liver's inside structure. In the 3D-printed object, the IVC, the five veins, and the tumor had the same relative scale and color as those in the 3D image. In contrast, the liver's inside structure was invisible in the target as the inside structure of a patient's liver is invisible during surgery. The target's surface was colored light gray. A line was drawn around each of the three targets created from the same CT liver data. Each line was drawn at a different location. Furthermore, on each target, the letters "A" and "B" were represented and indicated the two separated areas based on the drawn line. Two sets of 3D images, a 3D-printed object, and three targets were created from different CT liver datum.

Experimental task The experiment employed a spatial reasoning task in which participants were required to take a vein and a tumor location test for each target after examining a 3D image or a 3D-printed object. In the vein location test, participants were required to indicate the locations of the veins that appeared on the cross section resulting from cutting the target along the drawn line. In particular, participants were required to mark "O" for the IVC and "X" for the branching vein on the cross section's outer contour that was printed on the answer sheet (Figure 2). There were three types of cross sections: one with no IVC and two branching veins, another with one IVC and two branching veins, and the last with one IVC and three branching veins. In the tumor location test, the participants were to identify the area in the liver, A or B, where the tumor occurred.

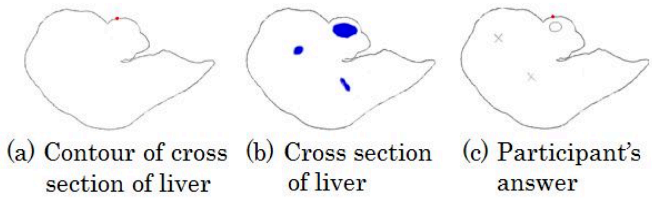

Figure 2: Figure 2: Vein location test. (a) Contour of cross section of liver, (b) cross section of liver, and (c) participant's answer. (a) shows the outer contour of a liver's cross section printed on the answer sheet. (b) shows an actual cross section of a liver. (c) shows a participant's answer, which provides the number of IVCs, O, and the branching veins, Xs, (drawn correctly here).

Procedure

Twenty-four participants were randomly assigned to the image condition where they conducted the experimental task with the 3D image, and the other participants were assigned to the object condition where they conducted the task with the 3D-printed object. First, the participants took anatomical and spatial ability tests. The anatomical test comprised five questions on the names of the liver's regions and veins. The spatial ability test was produced by Guay and McDaniels (1976) and comprised 24 questions requiring mental rotations. The participants were required to answer as many questions as possible in three minutes. Next, all the participants performed a practice task in the memory and reference task situations. In the practice task, the 3D image or the 3D-printed object representing one IVC and three branching veins were used. During the learning period, the participants used the 3D image or the 3D-printed object for one to three minutes to memorize the inside structure in a memory task situation and observe it in a reference task situation. After that, they took the vein and tumor location tests for one target.

After the practice, all participants conducted the experimental task in the memory and reference task situations. During the learning period, participants memorized the inner liver structure in the memory task situation and observed it in the reference task condition for three to five minutes using the 3D image or the 3D-printed object. When the participants had judged themselves prepared for the tests after at least three minutes had passed, or when five minutes had passed, the tests began. Participants took out the target and the answer sheet from one of three boxes on the primary desk and attempted the vein and tumor location tests. In the memory task situation, the computer display was switched off in the image condition, and the 3D-printed object was put into a box on the secondary desk in the object condition. In the reference task situation, the computer display stayed switched on in the image condition and the 3D-printed object remained on the secondary desk in the object condition. The participants could refer to the 3D image or the 3D-printed object freely while taking the tests in the reference task situation. Moreover, for the memory and reference task situations, different 3D images or 3D-printed objects created from the different CT liver datum were used.

The answer sheet provided for the vein and tumor location tests and two questionnaires. In the questionnaires, the participants rated their confidence toward their answers in the vein and the tumor location tests on a 7-point scale from (1) not confident at all to (7) extremely confident. After the participants completed the tests and questionnaires for one target, they returned the target and answer sheet to the box and took another set from another box. One of the two task situations was completed when they completed the tests and questionnaires for all three targets. A five-minute break was given between the task situations.

The order of the task situations was counterbalanced between the participants. The combinations of CT liver datum and task situations were also counterbalanced between the participants. Three sets of targets and answer sheets were randomly placed in the boxes on the primary desk. Participants were instructed to perform the tasks as accurately as possible. Furthermore, removing the target from the primary desk was forbidden during the experiment because it would be impossible for doctors to remove a patient's liver from the operating table during surgery. However, removing the 3D-printed object from the secondary desk was permitted in the object condition because doctors can place a liver's 3D-printed model right beside a patient's liver to confirm the interior structure of the liver during surgery (Maehigashi et al., 2015).

Results

None of the participants answered any of the questions on the anatomical test correctly, and no significant difference emerged between the image ($M = 9.08$) and the object ($M = 7.88$) conditions in the spatial ability test ($t(46) = 1.01, p = .32$). These results confirmed the homogeneity of the participants' anatomical knowledge and the homogeneity of spatial abilities between the conditions.

Next, we conducted 2(External representation: image and object) $\times$ 2(Task situation: memory and reference) analysis of variance (ANOVA) on the following dependent variables. First, the analysis was conducted on the learning time. The learning time was the mean time used by the participants to memorize or observe the inner structure of the 3D image or the 3D-printed object before attempting the tests in each condition (Figure 3). Results showed no significant interaction ($F(1,46) = 0.14, p = .71$). There was a significant main effect on the external representation factor, indicating that the learning time was shorter for the object condition than for the image condition ($F(1,46) = 7.72, p < .01$). The task situation factor also showed a significant main effect, indicating that the learning time was shorter for the reference condition than for the memory condition ($F(1,46) = 23.35, p < .001$).

Moreover, as the vein location test score, we calculated the mean absolute difference value between the correct number of veins and the number of drawn veins on the answer sheet in each condition for the IVC and the branching veins respec-

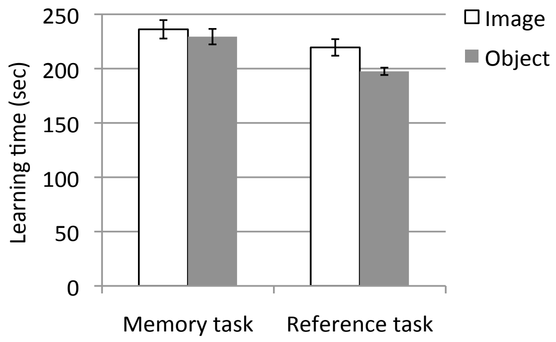

Figure 3: Learning time. The error bars indicate the standard error.

tively; the closer to zero the score, the more accurate the number of the drawn veins. First, for the IVC, analysis results showed no significant interaction ($F(1,46) = 1.73, p = .19$). There was no significant main effect on the external representation factor ($F(1,46) = 0.50, p = .48$). There was a marginally significant main effect on the task situation factor ($F(1,46) = 3.08, p = .09$). Next, for the branching veins, there was no significant interaction ($F(1,46) = 0.09, p = .77$) (Figure 4). There was no significant main effect on the task situation factor ($F(1,46) = 2.19, p = .15$). However, there was a significant main effect on the external representation factor, indicating that the the number of the veins was more accurately drawn for the object condition than for the image condition ($F(1,46) = 8.30, p < .001$).

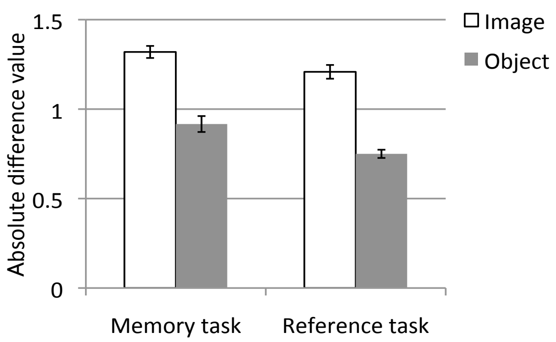

Figure 4: Absolute difference value for branching veins. The error bars indicate the standard error.

Furthermore, in each tumor location test, if the tumor location was correctly answered, a score of one was assigned. The tumor location test score was the mean total score of the tests for the three targets in each condition (Figure 5), meaning that the higher the score, the more accurate the answer. This analysis found a significant interaction ($F(1,46) = 18.98, p < .001$). Next, we conducted a simple main effect test on the external representation factor and found a marginally significant difference for the memory condition ($F(1,92) = 3.38, p = .07$) and a significant difference for the reference condition ($F(1,92) = 21.15, p < .001$), thus indicating higher scores in the object condition than in the image condition. We also conducted a simple main effect test on the task situation factor and found a marginally significant difference for the image condition, indicating that the score was lower in the reference condition than in the memory condition ($F(1,46) = 2.85, p = .10$). In contrast, no significant difference was observed for the object condition ($F(1,46) = 1.46, p = .23$). A significant main effect was observed on the external representation factor ($F(1,46) = 18.98, p < .001$), but not on the task situation factor ($F(1,46) = 0.12, p = .73$).

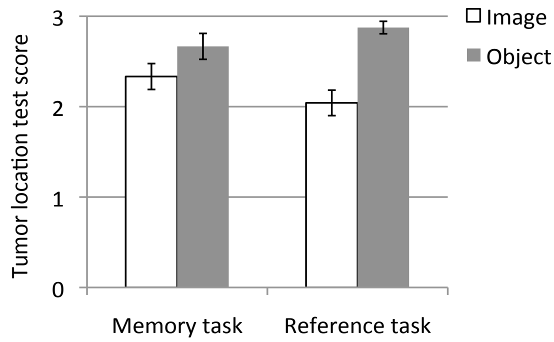

Figure 5: Tumor location test scores. The error bars indicate the standard error.

In addition, the analysis was conducted on the confidence ratings for the vein and the tumor location tests. No interaction was found in the rating for the vein location test ($F(1,46) = 1.34, p = .25$). No main effect was observed on the external representation factor ($F(1,46) = 0.40, p = .53$), but a significant main effect was observed on the task situation factor, indicating higher confidence ratings in the reference condition than in the memory condition ($F(1,46) = 47.06, p < .001$). Moreover, no interaction was found in the rating for the tumor location test ($F(1,46) = 1.13, p = .29$). No main effect was found on the external representation factor ($F(1,46) = 0.44, p = .51$), but a significant main effect was found on the task situation factor, thus indicating that the confidence rating was higher in the reference condition than in the memory condition ($F(1,46) = 36.27, p < .001$).

Finally, we conducted a correlation analysis on the relations between the spatial ability test score and the task performance, the learning time, and the vein and tumor location test scores in each condition (Table 1). In the memory task situation's object condition, a positive correlation was found between the spatial ability test score and the learning time. A negative correlation between the spatial ability test score and the vein location test score was also found for the branching veins. These results showed that participants with higher spatial ability tended to memorize the liver's inner structure more slowly and draw the number of branching veins accurately with the 3D image.

Table 1: Correlation matrices showing correlations between the spatial ability test score and the task performance, the learning time, and the vein and tumor location test scores in each condition. Values are correlation coefficients (r).

		Learning time	Vein location test score		Tumor location test score
			IVC	Branching vein	
Image	Memory task	.45**	-.14	-.44*	.30
	Reference task	-.22	-.19	-.13	-.19
Object	Memory task	.08	-.03	-.04	-.30
	Reference task	.17	.21	-.05	.18

$* \, p < .05$, $** \, p < .01$

Discussion

Accuracy of spatial reasoning

The vein and the tumor location test results indicated that the liver's inner structure was more accurately inferred when the 3D-printed object was used than when the 3D image was used, especially for the branching veins' structure in the vein location test. This result supported hypothesis 1 that stated that spatial reasoning would be more accurate with use of a 3D-printed object than with a 3D image.

It is possible that the participants in the object condition had a smaller cognitive load than those in the image condition. People perceive depth information in the real world more accurately than in the virtual 3D environment because the real world offers more depth cues (Kemeny & Panerai, 2003). This indicates that depth information is also missing from 3D images. Therefore, participants in the image condition might have to mentally complement or modify the 3D image's spatial information, temporarily storing this information in their memory and mentally resizing it to map the information to the target. Participants in the object condition, in contrast, were assumed to store the spatial information temporarily in their memory as they perceived it and map this information from the 3D-printed object directly to the target without internally complementing, modifying, or resizing it. Thus, participants in the object condition were assumed to have a smaller cognitive load and fewer errors from the internal manipulation of spatial information.

Moreover, it is also possible that the participants in the object condition incurred a lower information accessing cost than those in the image condition. Information accessing cost is incurred from acquiring information (Gray, Sims, Fu, & Schoelles, 2006). Participants in the image condition had to manipulate a computer mouse to acquire the required information, but participants in the object condition only had to pick up and physically rotate a 3D-printed object. Accessing information with a 3D-printed object was thus considered easier and less prone to errors or omissions than doing so with a 3D image.

In addition, in the vein location test, no difference was found between inferring the IVC's structure with the 3D image and the 3D-printed object. As the scores were very close to zero in all conditions, the test was considered easy and a ceiling effect was observed. Also, inferring the liver's inner structure was more accurate in the reference task situation than in the memory task situation. The participants in the memory task situation had to take the test using mental models constructed during the learning period. Participants in the reference task situation, in contrast, could continue updating their mental models and thus sustain more accurate models while attempting the test. As a result, the difference in the test score between the task situations was considered to be observed.

Furthermore, in the tumor location test, inference using the 3D image was more accurate in the memory task situation than in the reference task situation. This is because during problem solving, people tend to depend more on inaccurate memory with its low cost of accessing information than on seeking accurate external information, which has a higher cost (Gray & Fu, 2004). In our experiment, participants in the reference task situation using a 3D image might have avoided using the image because of the high cost of accessing information, depending instead on inaccurate memories, thus leading to lower test scores. The fact that the tumor location test was easier than the vein location test was also assumed to lead them to rely more on their inaccurate memory.

Learning time for mental model construction

Analysis of the learning time showed that the learning time was shorter when a 3D-printed object was used than when a 3D image was used. This result supported hypothesis 2 that stated that the learning time for constructing a mental model would be shorter when a 3D-printed object was used than when a 3D image was used.

This result could also be explained by the reduced cognitive load and information accessing cost when a 3D-printed object is used. Using the 3D image presumably required participants to mentally complement or modify the 3D image's spatial information. However, such internal manipulation was unnecessary when the 3D-printed object was used. Moreover, manipulating a computer mouse could involve more cost to access the required information than picking up and rotating a 3D-printed object. This could explain why learning times were shorter when a 3D-printed object was used than when a 3D image was used.

Moreover, the learning time was shorter in the reference task situation than in the memory task situation. In the memory task situation, participants had to construct mental models as accurately as possible during the learning period because they were not allowed to refer to the external representations during the tests. In the reference task situation, however, participants could refer to external representations during the tests, so they did not have to construct elaborate mental models during the learning period.

Effect of spatial ability and confidence on spatial reasoning

Participants with higher spatial ability tended to take a longer learning time and draw the number of branching veins accurately only when the 3D image was used in the memory task situation. Inferring the branching vein structure was the most difficult task in this experiment. Therefore, the effects of one's spatial ability were considered to be observed in the test score for the branching veins. Also, in the memory task situation, the participants had to construct mental models as accurately as possible and attempt the test without referring to any of the external representations. Therefore, the effects of one's ability to store and manipulate the spatial representation were considered to be prominent in the memory task situation. Because participants with higher spatial ability could store and manipulate the complex spatial representation, they were assumed to tend to take longer learning time to elaborate mental models and inferred the liver's inner structure accurately. Moreover, it is also possible that using a 3D-printed object might cancel the effect of using one's spatial ability to infer a physical structure, particularly raising the performance of participants with lower spatial ability, although we did not acquire sufficient data to support it in this experiment.

At last, the confidence ratings for the vein and tumor location tests showed an effect of the task situation and no effect of external representation. As people are sensitive to a task's cognitive load (Chandler & Sweller, 1991), participants reported themselves less confident in the memory task situation, which required a higher cognitive load than in the reference task situation. People are also sensitive to the cost of manipulating external representations (Gray et al., 2006). However, this cost is usually evaluated unconsciously (Walsh & Anderson, 2009). Therefore, the costs and effects of using external representations are considered difficult to be evaluated subjectively.

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