Investigation on Using 3D Printed Liver during Surgery

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Abstract

In this study based on ethnographic methods, we investigated how using a three-dimensional (3D) printed liver influenced doctors during liver resection surgery. Results of the analyses implied that using the 3D printed liver enhanced the construction of elaborate mental models of patients' livers, the mental simulation of liver resections, and the construction of shared mental models of patients' livers among doctors. Based on these results, we compared the advantages of using a 3D printed liver over a two-dimensional (2D) and a 3D image during surgery.

Keywords: External resources; Mental model; 3D print; Ethnography

Introduction

External resources

In cognitive science, many studies have investigated external resources and revealed that methods of displaying information greatly impact cognitive activities. In recent years, computer graphic technology has allowed people to generate two-dimensional (2D) and three-dimensional (3D) images. More recently, 3D printers which allow the creation of physical models have become popular. Presumably, information displayed by a 3D printed model produces a different effect on cognitive activities than a 2D or 3D image. In this study, we investigated how using a 3D printed liver influenced doctors in liver resection surgery for the removal of a portion of the liver.

2D image In 2D images used as external resources, information search and recognition is easier when information is displayed as a figure rather than as text (Larkin & Simon, 1987) and as graphs rather than as numerical data (Shah, 1997). People can take advantage of the spatial locations of figures and graphs to easily search for and recognize information.

Moreover, external resources allow people to share the same information and enhance the construction of common understanding (Kirsh, 2010). Alac (2005) showed the construction process for the common understanding of structural information in a 2D brain image. First in the process, interlocutors direct their attention to the same information through utterances and gestures such as pointing. Next, they perform and embody actions such as gestures and body movements to express and explain the depth information of the 2D brain image. Finally, interlocutors construct a common understanding of the brain's structural information. The performative and embodied actions that complement the depth information of the 2D image have been shown to be important for the common understanding of structural information.

3D image Although 2D images are inadequate for depth information, in recent years, newly developed technology, such as virtual reality, clearly displays 3D structural information. Keehner, Hegarty, Cohen, Khooshabeh, and Montello (2008) revealed that people understand structural information better when they refer to 3D images rather than 2D images.

Moreover, de Jong, Kolloffel, van der Meijden, Staarman, and Janssen (2005) experimentally showed that when participants created 3D art with others, they actively shared and confirmed their ideas and comments through messages posted on the internet. This result implies that 3D images allow people to share structural information without performative and embodied actions to complement depth information as shown in Alac (2005). In other words, 3D images enhance the construction of the common understanding of structural information more than 2D images.

3D printed model More recently, owing to the prevalence of 3D printers, people can replicate objects. The industrial impact of 3D printing is huge; indeed, some countries, e.g., the United States, China, and Japan, promote 3D printers as a national strategy. However, only a few studies have investigated how using 3D printed models influences cognitive activities.

Some previous studies have experimentally compared the human structural understanding of a 2D image with and without a physical 3D model (Stull, Hegarty, Dixon, & Stieff, 2012). The result showed that the structural understanding was better when the physical 3D model was used. It is stated that the 3D model allowed the participants to rotate the model externally, reduced their mental rotations, and enhanced their focus on understanding structural information. In addition, Kemeny and Panerai (2003) indicated that human perception of the depth information in the real world is more accurate than in the virtual 3D environment because the real world contains more depth cues. Results of previous studies predict that because 3D printed models help people focus on understanding structural information and show more depth cues than virtual 3D environments, 3D printed models would enhance the accurate understanding and sharing of structural information better than 3D computed images.

In this study based on ethnographic methods, we observed and recorded liver resection surgeries in which 3D printed livers were used as models of actual patients' livers. Liver resection requires surgical accuracy in a tense life or death situation. In such situations, we investigated how the use of a 3D printed liver influenced doctors.

Mental model

A mental model is an internal representation of some domain or situation (Gentner, 2002). Presumably, using the 3D printed liver during surgery influences doctors' mental models of a patient's liver in at least three ways.

The first influence is the elaboration of mental models. Mental models are updated with new information and are elaborated when accurate information is acquired (Chi, DeLeeuw, Chiu, & Lavancher, 1994; Vosniadou & Brewer, 1994). Therefore, using the 3D printed liver during surgery would likely help doctors refer to accurate spatial locations of liver regions and enhance the elaboration of their mental models of the liver.

The second influence is mental simulation. Mental models simulate actions and predict the results of those action (Trickett & Trafton, 2007). In a liver resection surgery, doctors can not visually confirm the spatial locations of veins and tumors on a patient's liver. However, the 3D printed liver replicates and visualizes the real liver's exact physical information. Therefore, the 3D printed liver would likely allow doctors to simulate resection accurately, in the same way as in the actual resection.

The third influence is sharing mental models with others. In collaborative work settings, individuals often have a similar mental model, called a shared mental model or a team mental mode (Jeong & Chi, 2007; Mathiue, Heffiner, Goodwin, Sala, & Cannon-Bowers, 2000). Because a 3D printed liver allows doctors to perceive the same structural information, it should enhance sharing mental models of a liver and constructing common understanding of resection plans.

In this study, we investigated these three influences on doctors' mental models of the liver, based on recorded protocols and body movements during surgery.

Method

Liver resection surgery

In this study, three surgeries performed at Nagoya University Hospital were observed and recorded with the hospital and patients' approval. These surgeries were resections of liver tumors. The patients were one female and two males in their seventies. The doctors—the surgeon, the first assistant, and the second assistant—performed the surgeries. Also, two anesthesiologists and two to three nurses participated in each surgery.

For recording the surgeries, three cameras and two microphones were placed in the operating room as shown in Figure 1. One camera and two microphones were mounted above the doctors' heads. Another camera was placed behind the first and second assistants, and a cameraperson held the third camera, changing his position in the operating room to record the surgeries. Finally, the patient lay between the surgeon and the assistants.

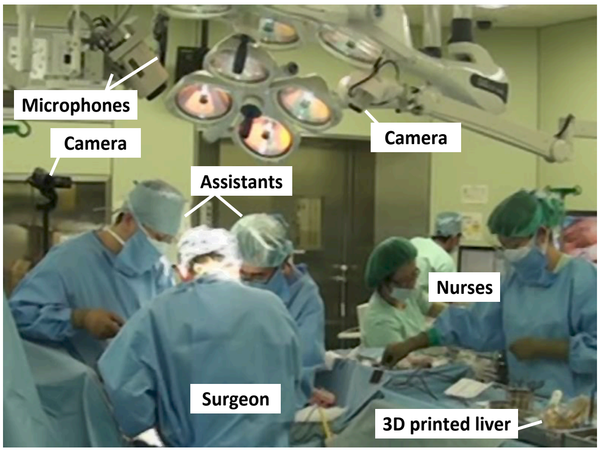

Figure 1: Placement of the recording equipment in the operating room. This figure is a still from a video recording with a handheld camera.

3D printed liver

Because the size, shape, and structure of each patient's liver differed, a 3D printed liver was created based on data from each liver. First, the patient's liver was measured by computed tomography (CT). Next, based on the CT liver data, a 3D printed liver was created with a 3D printer. In particular, one 0.02-mm thick layer of acrylic resin was laid down in approximately 4,000 layers to produce a 3D printed liver. Subsequently, the extra resin was melted and removed, and the surface of the printed liver was polished. A 3D printed liver displays the structural information inside a liver so that the veins and tumors can be perceived visually. Figure 2 shows a 3D printed liver, in which the portal veins were painted whitish, the hepatic veins blue, and the tumors clear white.

Results

Coding

We conducted a protocol analysis of the recorded video images and sounds. First, we defined a conversation as serial speech acts by the doctors before, during, and after using the 3D printed liver. Next, in each conversation, the doctors' utterances and body movements were segmented according

Figure 2: 3D printed liver

to a pause or breath as one utterance unit in each conversation. Then, body movements without utterances were also segmented according to one serial action. Finally, each segment was coded in terms of three categories as follows: an utterer, utterance point, or utterance content.

With regard to coding, for the utterer, the person who uttered was coded. Most segments were assigned to two subcategories, the surgeon and the first assistant. The others were assigned to the second assistant, the nurses, and the anesthesiologists. Next, for the utterance point, the origination of where the utterance occurred on the real liver or the 3D printed liver was coded. Although most segments were assigned to two subcategories, the real liver or the 3D printed liver, some segments were assigned to neither the real liver nor the 3D printed liver.

Moreover, for the utterance content, what the utterance was about was coded. Most segments were assigned to three subcategories: (1) confirmation of fact, (2) confirmation of plan, and (3) prediction/presumption. First, confirmation of fact was defined as an utterance verifying a position, size, or length of a liver region. Second, confirmation of plan was defined as an utterance verifying resection regions of a liver or resection lines on a liver. Third, prediction/presumption was defined as the prediction of a result produced after an action was taken or the presumption of an unconfirmed position, size, or length of a liver region. The other segments were assigned to a surgeon's task request to assistants (e.g., "pull it" and "hold it"), the ease of a task (e.g., "it is hard to do" and "it is hard to see"), a task procedure (e.g., "we will take pictures" and "let's see with an echo"), and body movements without utterances.

Analysis

A total of 44 conversations were observed using the 3D printed livers, 17 in the first surgery, 10 in the second, and 17 in the third. The total number of segments in the 44 conversations was 721. The mean number of segments in one conversation was 16.39. The mean time of one conversation was 60.25 seconds.

To focus on how using the 3D printed liver for a liver resection influences doctors, we conducted an analysis only on the segments assigned to the following subcategories for each category: the surgeon or the first assistant for the utterer, the real liver or the 3D printed liver for the utterance point, and confirmation of fact, confirmation of plan, or prediction/presumption for the utterance content. In addition, with regard to the utterer, although the second assistant was also a doctor, his utterances were extremely few (10 segments). Therefore, we eliminated those data and thus used 427 segments for analysis.

First, for the utterer, the result of the binomial test showed that the surgeon (282 segments) significantly uttered more than the first assistant (145 segments) ($p < .001$). Next, for the utterance point, the binomial test result showed that more utterances occurred on the real liver (237 segments) than on the 3D printed model (190 segments) ($p < .05$). Moreover, for the utterance content, chi-square test results showed a significant difference in the number of utterances among the three subcategories, confirmation of fact (237 segments), confirmation of plan (190 segments), and prediction/presumption (37 segments) ($x2(2) = 141.73, p < .01$). The result of a multiple comparison test showed that confirmation of fact utterances occurred more frequently than confirmation of plan utterances and prediction/presumption utterances ($ps < .001$). Last, confirmation of plan utterances occurred more than prediction/presumption utterances ($p < .001$).

Because confirmation of fact and confirmation of plan utterances predominated during surgery, we conducted a following analysis of data based on those utterances and investigated how the 3D printed liver was used.

Confirmation of fact

Recordings of the surgeries revealed that some utterances occurred along with tactile confirmation, i.e., by lightly squeezing the real liver. Some utterances also occurred with visual confirmation on the 3D printed liver. Therefore, for confirmation of fact, we conducted an analysis focused on tactile and visual confirmation. In particular, based on the 237 segments assigned to confirmation of fact, for tactile confirmation, we counted segments in which touch was mentioned (e.g., "it is stiff" or "from the tactile feeling"), and utterances that occurred with a squeezing action. Moreover, for representative visual confirmation, we counted segments in which the distance (e.g., "3 cm" or "this width") and the positional relation (e.g., "it is behind this vein" or "it is above this region") were mentioned.

Table 1 shows the number of segments in which tactile and visual confirmation occurred on the real and 3D printed livers. The result of Fisher's exact test shows that a significant difference in the proportion ($p < .001$) and increase of utterances regarding visual confirmation on the 3D printed liver was prominent.

Case example The following indicates one complete conversation as a case example, revealing the typical utterance pattern of confirmation of fact. In each segment, the utterer and the utterance point were indicated. For the utterer, "S" is the surgeon and "A" is the first assistant. For the utterance

Table 1: Number of segments in which tactile and visual confirmation occurred on real and 3D printed livers

	Tactile	Visual
Real liver	21	14
3D printed liver	0	34

point, "R" is the real liver, "3D" is the 3D printed liver, and "N" is neither the real liver nor the 3D printed liver. Underlining indicates the bodily movements of the utterers.

1	A/N：	Can you give me that, used a while ago?
2	S/N：	Can you give me the 3D printed model, the model?
3	A/R：	There is something hard in here. He lightly squeezed the real liver.
4	S/R：	Yes, here it is. He lightly squeezed the real liver.
5	A/R：	Here it is. He lightly squeezed the real liver.
6	A/N：	He received the 3D printed liver from the nurse.
7	S/3D：	Here, or more precisely, here. He traced the 3D printed liver with his index finger and indicated a location on the 3D printed liver.
8	A/R：	Here it is. He indicated a location on the real liver.
9	S/R：	Yes. He indicated a location on the real liver.
10	S/3D：	The top, the top is here. He indicated a location on the 3D printed liver.
11	A/3D：	Yes, it is.
12	A/N：	He passed the 3D printed liver to the nurse.

In segments 1 and 2, the surgeon and the first assistant asked the nurse to hand them the 3D printed liver. From segments 3 to 5, tactile confirmation was performed on the real liver. In segment 7, visual confirmation was performed on the 3D printed liver. In segments 8 and 9, confirmation of the location of a liver region was performed on the real liver. Last, in segments 10 and 11, visual confirmation was performed on the 3D printed liver. From the serial utterance pattern, the following process was verified for the confirmation of fact: (1) tactile confirmation of a liver region was performed on the real liver, (2) visual confirmation of the liver region was performed on the 3D printed liver, and (3) confirmation of the location of the liver region was performed on the real liver.

Confirmation of plan

Based on the 153 segments assigned to confirmation of plan, we analyzed segments in which resection regions or resection lines were mentioned. We counted segments where resection regions (e.g., "cut this vein" or "leave this vein") and resection lines (e.g., "cut on this line" or "cut along this") were mentioned. Table 2 shows the number of segments in which the resection regions and lines were mentioned on the real and the 3D printed livers. The result of Fisher's exact test revealed that there was a significant difference in the proportion ($p < .005$), and the increase of the utterances regarding resection regions on the 3D printed liver was prominent.

Table 2: Number of segments in which resection regions and lines were mentioned on real and 3D printed livers

	Regions	Lines
Real liver	16	33
3D printed liver	22	9

Case example The following indicates one complete conversation as a case example for the typical utterance pattern of confirmation of plan.

1	S/R：	Should it be left?
2	A/R：	The one in the back?
3	S/N：	He lifted up the 3D printed liver.
4	S/3D：	Here in the back. Right here. Here in the back. He put the 3D printed liver right beside the incision and pointed to a location on the 3D printed liver.
5	A/3D：	Would it be left?
6	S/3D：	No, it wouldn't because it's 8 (indicating a liver region).
7	A/3D：	Ah
8	S/3D：	Here. Right here beside this tumor. He indicated a location on the 3D printed liver.
9	A/3D：	Ah
10	S/3D：	This vein, this vein.
11	A/3D：	Here, it's buried in like this.
12	S/N：	He put the 3D printed liver at the corner of the operating table.
13	S/R：	As I thought, 8 would be
14	A/R：	Would the total resection be necessary?
15	S/R：	Yes, cutting along the curve is necessary.

In segments 1 and 2, the surgeon and the first assistant confirmed the resection region on the real liver. In segments 5 and 6, they confirmed the resection region on the 3D printed liver. Finally, they confirmed the resection region on the real liver in segment 14 and the resection line on the real liver in segment 15. From the serial utterance pattern, the following process was verified for the confirmation of plan: (1) the resection region was confirmed on the real liver, (2) the resection region was confirmed on the 3D printed liver, and (3) the resection line was confirmed on the real liver.

Communication

Last, we investigated the influence of using the 3D printed liver from a viewpoint of communication between doctors. Based on the 427 segments assigned to the three categories—the utterer, the utterance point, and the utterance content—, we counted segments in which demonstratives (e.g., "this" or "that") and the name of a liver region (e.g., "tumor" or "hepatic vein") were mentioned. Results showed multiple demonstratives or names of liver regions in each segment. Therefore, all utterances in the 427 segments were decomposed into phrases using a standard Japanese morphological analysis system, MeCab (Kudo, Yamamoto, & Matsumoto, 2005), and we counted the number of phrases in which demonstratives and names of liver regions were mentioned on the real and the 3D printed livers, as shown in Table 3. The result of Fisher's exact test revealed a significant difference in the proportion ($p < .05$), and demonstratives were used more with the 3D printed liver than with the real liver.

Table 3: Number of phrases in which demonstratives and names of liver regions were mentioned on real and 3D printed livers

	Demonstrative	Name of liver region
Real liver	102	64
3D printed liver	147	56

General Discussion

Elaborate mental model of liver

An analysis for the confirmation of fact revealed the prominence of utterances of doctors about visual confirmation on the 3D printed liver. The case example of confirmation of fact verified a certain process in which (1) tactile confirmation of a liver region was performed on the real liver, (2) visual confirmation of a liver region was performed on the 3D printed liver, and (3) confirmation of the location of a liver region was performed on the real liver. We concluded that in the process, (1) doctors confirmed the spatial location of a liver region by touching the real liver, (2) doctors' mental models of the liver were updated through visual confirmation from the 3D printed liver's information, and (3) doctors mapped structural information from their updated mental models to the real liver. Therefore, using the 3D printed liver likely enhanced the elaboration of doctors' mental models of the patient's liver and their understanding of the precise locations of the liver regions during surgery.

Some studies showed that a 2D image needs to be mentally complemented and translated to an internal 3D representation to understand the structural information (Alac, 2005; Stull, Hegarty, Stieff, & Dixon, 2010). Moreover, the previous study that compared the visual perception in the real world with that in the virtual 3D environment showed that people perceive depth information in the real world more accurately because it offers more depth cues (Kemeny & Panerai, 2003). This result implies that the depth information of 3D images also needs to be mentally complemented with additional depth information. The 3D printed liver used in this study was a real object, and presumably, having the 3D printed liver allowed doctors to position it right beside the real liver and to directly map the structural information from it to the real liver without internal complementation or translation.

Furthermore, Barrett, Stull, Hsu, and Hegarty (2015) experimentally compared structural understanding when physical 3D models were used with when virtual 3D images were used and revealed no prominent difference in understanding. However, in their study, structural understanding was measured by rotating 3D models or images to match the orientation and conformation shown by 2D images in a situation where internal translation of the structure were necessary. Compared to the previous study, this study investigated the influence of using a 3D printed liver during surgery when doctors treated a real liver. In this situation, using the 3D printed liver that allows doctors to directly map information to the real liver is likely more effective than using a virtual 3D image.

Moreover, Gray, Sims, Fu, and Schoelles (2006) demonstrated information access cost, that is, the expense of access to certain computer information such as input of commands or manipulation of a mouse. They experimentally showed that people are sensitive to such costs, and the cost influences human decisions to act. The information access cost of using the 3D printed liver could be lifting it or rotating it. Such information access would be easy and rarely missed. Therefore, using a 3D printed liver is likely more efficient than using a computer image from the viewpoint of information access as well.

Mental simulation of resection

The analysis for the confirmation of plan revealed the increase of doctors' utterances about resection regions to be prominent on the 3D printed liver. Furthermore, the case example of the confirmation of plan verified a certain process, in which (1) a resection region was confirmed on the real liver, (2) the resection region was confirmed on the 3D printed liver, and (3) the resection line was confirmed on the real liver. We concluded that in this process, (1) doctors confirmed a resection region on the real liver, (2) doctors mentally simulated the resection on the 3D printed liver, and (3) doctors also mentally simulated the resection on the real liver. Therefore, using the 3D printed liver likely enhanced the understanding of resection regions and accurately simulated the resection.

Previous studies showed that when mental simulation generated incorrect predictions, the mental model would be modified, and the simulation would be conducted again based on the modified model (Trickett & Trafton, 2007). In addition, when people try to understand the behavior of a complex system, physical manipulation of the system would be efficient in reducing the cost of mental simulation and in observing the manipulation's accurate results (Hegarty, 2000). In the liver resection surgery, incorrect prediction by mental simulation or a tentative action could lead to a fatal accident. The 3D printed liver had the same structural information of the real liver and accurately replicated the information as a physical object. Therefore, we hypothesize that the doctors could accurately simulate the resection on the 3D printed liver in the same way as the actual resection on the real liver.

Shared mental model among doctors

Analysis of communication among doctors showed an increase in doctors' utterances of demonstratives on the 3D printed liver. Clark, Schreuder, and Buttrick (1983) experimentally investigated the understanding of demonstratives and showed that when demonstratives are uttered at some physical object, the listener assumes the demonstrative object based on visual salience. In this study, the 3D printed liver replicated the physical structure inside the real liver, and liver regions important for the resection were emphasized with color. Because the doctors clearly perceived and shared visual saliences of the 3D printed liver, they might be able to frequently use demonstratives on the 3D printed liver and then accurately share structural information.

Moreover, Pylyshyn (2000) stated that demonstratives indicate the relation among the utterer, the listener, and the demonstrative object so that using demonstratives allows interlocutors to avoid processing other information. In this study, the 3D printed liver accurately replicated the internal structure of the real liver, and structural information could be shared by uttering demonstratives. Therefore, there is a possibility that the 3D printed liver allowed doctors to concentrate on sharing structural information, enhanced the construction of a shared mental model of the real liver, and enhanced common understanding of operational plans among doctors.

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