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RESEARCH ARTICLE

Representations of microgeometric tactile information during object recognition

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Abstract
Object recognition through tactile perception involves two elements: the shape of the object (macrogeometric properties) and the material of the object (microgeometric properties). Here we sought to determine the characteristics of microgeometric tactile representations regarding object recognition through tactile perception. Participants were directed to recognize objects with different surface materials using either tactile information or visual information. With a quantitative analysis of the cognitive process regarding object recognition, Experiment 1 confirmed the same eight concepts (composed of rules defining distinct cognitive processes) commonly generated in both tactile and visual perceptions to accomplish the task, although an additional concept was generated during the visual task. Experiment 2 focused only on tactile perception. Three tactile objects with different surface materials (plastic, cloth and sandpaper) were used for the object recognition task. The participants answered a questionnaire regarding the process leading to their answers (which was designed based on the results obtained in Experiment 1) and to provide ratings on the vividness, familiarity and affective valence. We used these experimental data to investigate whether changes in material attributes (tactile information) change the characteristics of tactile representation. The observation showed that differences in tactile information resulted in differences in cognitive processes, vividness, familiarity and emotionality. These two experiments collectively indicated that microgeometric tactile information contributes to object recognition by recruiting various cognitive processes including episodic memory and emotion, similar to the case of object recognition by visual information.

Keywords Tactile perception · Microgeometric properties · Tactile representation · Semantic memory · Episodic memory

Introduction

Humans can immediately and accurately recognize many objects in the external world through tactile perception. Klatzky et al. (1985) randomly presented 100 types of objects (e.g., book, carrot, egg, hammer, button and candle) to subjects with blocked visual perception and asked for identification through tactile perception. The accuracy exceeded 90%, and the response times before answering were ≤ 5 s. This finding showed that humans can easily recognize typical three-dimensional objects through tactile perception. Object recognition through tactile perception involves collecting and processing two elements, i.e., the shape of the object (macrogeometric properties such as size and form) and the material (microgeometric properties such as texture and hardness), with a haptic system that incorporates sensory information from the skin (tactile perception) and from joints, muscles and tendons (kinesthetic perception) (Loomis and Lederman 1986) and ends with object identification determined by matching an internal representation of integrated sensory information with memory representations and semantic representations in the central nervous system (Endo et al. 1992; Gibson 1969; Klatzky and Lederman 2008).

There have been many studies of object recognition by tactile perception, involving the low-level processing of tactile information by hands and fingers, which are engaged in a tactile search of elements comprising an object (e.g., form, curvature, coarseness and temperature) (Connor et al. 1990;

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Ho and Jones 2006; Hollins et al. 2001; Miyaoka et al. 1999; Smith et al. 2010; Srinivasan and LaMotte 1995). When the characteristics of tactile perception regarding macrogeometric and microgeometric properties were compared with those of visual perception, visual perception was found to be strongly related to macrogeometric properties, whereas tactile perception was strongly related to microgeometric properties (Klatzky and Lederman 1987; Klatzky et al. 1993; Lederman and Klatzky 1997; Lederman et al. 1996; Srinivasan and LaMotte 1995). Therefore, tactile perception can process microgeometric properties more efficiently compared with macrogeometric properties.

In addition, tactile perception can gather a limited amount of information at once, and this information is processed sequentially and therefore slowly. However, tactile perception is thought to be superb at perceiving shapes with a very fine surface (Baumgartner et al. 2013; Whitaker et al. 2008). It thus appears that a series of perceptual information obtained from each sensory receptor (such as skin) activates various tactile representations during the object recognition by tactile perception.

However, Ballesteros et al. (1999) showed that a good naming percentage is achieved when a glove is worn, although they observed differences in naming percentages and reaction times. Therefore, high-level processing, rather than low-level processing (such as receptor sensitivity), is likely to significantly affect object recognition by tactile perception. Brain function imaging has shown that the cerebral processing of macrogeometric and microgeometric properties differs. For example, regarding the intracerebral region where the tactile processing of objects is carried out, processing of the form is related to the lateral occipital cortex, whereas the surface material is processed at regions active in semantic processing and at the secondary somatosensory area and insular cortex, which are related to long-term memory of tactile perception (Bonda et al. 1996; Kitada et al. 2005; Newman et al. 2005; Roland et al. 1998; Stilla and Sathian 2008).

Studies of high-level object recognition through tactile perception showed that recognition is enhanced when the visual image from a past visual experience is linked to the tactile representation (Amedi et al. 2001, 2002; James et al. 2002; Klatzky et al. 1991; Lederman et al. 1990; Sathian 2005; Sathian and Zangaladze 2001, 2002; Sathian et al. 1997; Zhang et al. 2004). Moreover, the possibility that perceptual representation in object recognition is shared between visual and tactile perceptions has been indicated by cross-modal priming research (Easton et al. 1997a, b; Reales and Ballesteros 1999).

There are also some insights suggesting a relationship between tactile and visual recognition regarding perceptual representation in object recognition. However, most of the research mentioned above used familiar or unfamiliar three-dimensional objects or two-dimensional descriptions such as diagrams. The focus was mainly on macrogeometric properties, especially the shape. Few studies focused on microgeometric properties such as texture and roughness. In other words, there has not been a consensus as to how tactile representations are characterized for the microgeometric properties of material elements that tactile perception predominantly processes and that are associated with the perceptual representation memory system that leads to the naming of an object (Gallace and Spence 2009). Additionally, few investigations have addressed questions related to episodic memory, such as where participants are explicitly asked to recollect information regarding their previous life experiences with tactile stimuli.

In the present study, we therefore focused on microgeometric properties among object properties, especially material attributes, and we investigated how tactile representation is related to long-term memory (semantic and episodic memory). Semantic memory is memory regarding general information, and it is knowledge of a world independent of personal experience (Tulving and Donaldson 1972). A ‘concept’ is defined as systematic knowledge that includes individual examples. For instance, the concept of a ‘chair’ includes knowledge of various types and uses of chairs. Such concepts cannot exist independently, and humans retain multiple related concepts. Multiple models have been proposed to explain this relationship, such as the semantic network model and the spreading activation model (Collins and Loftus 1975; Collins and Quillian 1969). These models represent concepts as nodes and express the relationship by connecting nodes with links. A shorter link means that nodes are deeply related, and the activation of one node is propagated to other nodes through links. This is equivalent to the association process of knowledge where one concept that attracts attention leads to the extraction of other ideas in the order of relevance from high to low (Collins and Loftus 1975).

Naming a pictured object is a complex process. It involves a number of relatively distinct, mental representations and cognitive processes. DeLeon et al. (2007) provided evidence that a network of brain regions supports naming, but separate components of this network are differentially required for distinct cognitive processes or representations underlying the complex task of naming pictures. Axelrod et al. (2017) showed that our mental experience is mediated by a combination of activities of multiple cognitive processes. In terms of data analysis procedures, to provide a rich picture of the cognitive processes, we analyzed the qualitative data based on the modified grounded theory approach (Kinoshita 2003). This approach is a systematic qualitative research methodology, whose basic procedures are naming, categorizing and describing phenomena found in the text. In this study, to test the hypothesis that changes in material attributes recruit distinct cognitive processes in object recognition, we used an item association task in which items were associated using material attributes as stimuli and performed the systematic qualitative data analysis.

Experiment 1

Experiment 1 focused on the relationships between responses (reaction words) obtained from material attributes and perceptual information during item association tasks. The previous studies involving association tasks were conducted using visual and auditory perceptions but not tactile perception. Here we displayed material attributes as visual and tactile perceptual information, and we attempted to identify cognitive processes (thought processes) from the reception of the perceptual information until the naming of the object through a semi-structured interview. We also qualitatively analyzed the differences between visual and tactile perceptions.

Methods

Participants

The participants were 13 college students without visual and tactile functional disorders or special tactile skills who agreed to participate after the experimental outline was explained to them. Their mean ± SD age was 19.8 ± 1.2 years; there were eight males and five females. Twelve were right-handed and one was left-handed, as assessed using the scale developed by Chapman and Chapman (1987). Japanese was the language of all 13 participants.

Stimuli

The stimulus material was three objects with different surface textures: smooth paper, sandpaper (#120) and cloth (mixed cotton and hemp). The color of all three materials was blackish brown.

Procedures

A total of six tasks, based on tactile (T-task) and visual (V-task) information from the three stimulus materials, were randomly presented in a different order to all participants to remove the effect of order. Regarding the experimental environment and presentation methods, each participant was seated at a table, and a stimulus material was placed approx. 40 cm in front of the participant. In the T-task, a curtain was placed between the participant and the presented stimulus material in order to screen the field of vision near the participant's hand. A gap in the curtain where the participant's hand could pass through was made at the center of the curtain. The participant was instructed to place his or her dominant hand through the curtain and actively touch the stimulus material with the fingertip of the index finger. In the V-task, the curtain was removed and the stimulus material had been placed under a panel with a cutout circle with a radius of 8 cm, such that the entire image of the stimulus material was not visible. The stimulus material was presented at the start of the task. Each experiment was carried out individually in a private room.

The experimental procedure was adopted mainly from Seitz and Beilin (1987). Step 1: The participant was instructed to touch or look at the stimulus material and was asked to give one answer on what item the participant was touching or seeing. Step 2: The participant was instructed to touch or look at the same stimulus material again after Step 1 and was asked to answer, as many times as possible, what item the participant may be touching or seeing. The time limit was 3 min. Step 3: A semi-structured interview was carried out concerning Steps 1 and 2. The main questions in the interview were (1) how was your judgment made? And (2) what were you careful about? The interview was conducted regarding all items that the participant answered during the tasks, and the cognitive process leading to the answers was determined. The contents of the interview were recorded by an IC recorder [ICR-S290RM(S), Sanyo] after permission was obtained.

The contents of the interviews in Step 3 were analyzed. The analysis was based on a word-for-word recording from the recorded data, using the modified grounded theory approach (Kinoshita 2003). The characteristics of this analysis include: (1) it aims to generate theories; (2) it excels in explaining and hypothesizing target phenomena; and (3) its method is clear, and it enables a researcher to elicit well-explained results from a profound interpretation of qualitative data. The modified grounded theory approach also requires a target group and a theme of the analysis. For Experiment 1, the target group was healthy adults, and the theme was 'thought process from the perception until the response.' We divided the data into those of the T-tasks and V-tasks and then analyzed these data sets separately.

During the analysis, an analysis worksheet (one concept on one sheet) was used. A focus was placed on the content that was associated with the theme mentioned above, and the word-for-word recording obtained from the interviews was analyzed. From the recording, an example was elicited and interpreted, a definition was given, and a concept was generated. This process was repeated while continuously focusing on the content of the data. The analysis yielded similar and opposite examples from which the previous concept was elaborated, and/or a new concept was generated.

At the same time, memos were taken on the interpretation and the thought process and written in the section 'memos for theory' of the worksheet as examples were elicited and categorized. Next, each of the generated concepts was analyzed against other concepts until the conceptualization required no further addition or modification (theoretical saturation). Finally, the relationships between the generated concepts and categories were examined, and a figure with the results was developed. Table 1 is an example of an analysis worksheet.

Results

The participants' comments relating to the object cognitive processes varied to some extent depending on the participant. For example, some participants gave a very simple description, whereas others gave more detail, so that their comments were related to more than one concept and were categorized into both concepts. As shown in Table 2, eight concepts were generated during the object cognitive process in the T-task and the V-task. It should be noted that this is not an exhaustive list. It is the list of concepts generated from the participants in this study, and there may be items missing. We reorganized all of the worksheets into five categories: 'intuitive judgment,' 'judgment by memory recall,' 'exploratory judgment,' 'judgment by association' and 'functional adherence.' In addition, 'judgment by tactile image' occurred during the V-task.

'Intuitive judgment' consists of the concept (definition) that includes answering the item from perception or identifying an object in a familiar environment from perception. This implies that an intuitively recalled item from perception is answered without any consideration. An example of a T-task answer could be, 'I touched it, and, oh, it was like plastic.' In a V-task, an answer could be, 'The sandpaper was, well, it was evident from the look it easily popped into my mind.'

'Judgment by memory recall' consists of three concepts: the recalling of an item used in the past, the recalling of a scene in daily life and the recalling of an event scene from the past. This is because perception recalls past experience and scenes in daily life, leading to the answering of the recalled item. Moreover, items that were used to answer tasks for other materials may be reused for another answer. An example of an answer in a T-task is, 'The touch is like something I used in elementary school art class.' In a V-task, an example answer is, 'The frying pan I am actually using right now is black. I look at it frequently, and based on that, this looks like inside that frying pan.'

'Exploratory judgment' consists of the concept of the use of an item in the current situation (the experimental room). The concept concerns the search for something related to the perceived item, and an answer is reached by comparing and matching the searched item with the item that is currently perceived. An example answer for a T-task is, 'A curtain would feel like cloth when I touch it, and I saw a curtain when I abruptly looked forward, so I felt that the feel of touch would be similar.' An example answer in a V-task is, 'It looks similar to cardboard boxes placed around, so it would be paper.'

Table 1 Example of analysis worksheet

Concept	Recalling a scene in daily life
Definition	An item is recalled from a scene in daily life
Variables	No. 1 (tactile: smooth paper) P12: 'I was looking for something similar for a while. The feeling. And, I pictured inside the house. First, a TV showed up. Walls reminded me of school, but a TV and then a post appeared. I looked for something else. Then, all of a sudden, a refrigerator came in my mind. Then, I was thinking that a refrigerator was similar but thought telephone was better than refrigerator' No. 8 (tactile: smooth paper) P6, 15–16: (P6) 'I thought about everything that came in my mind from my past memory. Then, a dog with a short hair, a creature appeared. I thought about a dog, rather.' (omission) (T15: Did the dog appear when you were trying to search your past? Was the thing that came in your mind suddenly the dog you had seen before?) (P15) 'The former. I was thinking about something similar, and then the dog appeared.' (T16: At that time, did an actual dog appear or did a situation or a scene surrounding the dog appear?) (P16) 'The dog was sleeping. I was petting the dog while he was sleeping' No. 8 (tactile: sandpaper) P20–25: (P20) 'There will be a tool if you move across this field. It feels like a rusty part of the post.' (T21: Did it feel like it spread from the field?) (P 21) 'Yes.' (T22: Did the scene change from the field to the tool?) (P22) 'That's right.' (T23: The rusty tool didn't come from the feeling of rough surface, but the roughness reminded me of the field, and the rusty tool appeared from the field. Then, I compared, I think.) (P23) 'I looked for roughness within the field.' (T24: You said roughness of the field. Is it true that from there, you searched the inside of school for roughness?) (P24) 'That's right.' (T25: Then, a tool appeared. Are you comparing the feeling of the object that you're touching right now and the feeling of the tool that you have in mind?) (P25) 'That's right'
Memos for theory	This concept differs from the already generated concept (answering an item intuitively) in that an item is recalled by using a strategy in an attempt to think back to a scene in daily life.

Sentences within '' are the participant's statements. Sentences within () are the interviewer's comments. No. is a participant's case number. Numbers after P and T are paragraph numbers from the transcription

P participant. *T* interviewer

Table 2 Categories, concepts and definitions of the cognitive processes leading to object recognition

Category	Concept	Definition	Task
Intuitive judgment	Answering an item intuitively or an item in a familiar environment from perception	An item is intuitively answered without any consideration	T·V
Judgment by memory recall	Recalling an item used in the past	An item used in the past is recalled	T·V
	Recalling a scene in daily life	An item is recalled from a scene in daily life	
	Recalling an event scene from the past	An item is recalled from a past event scene	
Exploratory judgment	Using an item in the current situation (experimental room)	A searched item in the current situation (experimental room) is answered by comparing and matching the searched item with the item that is currently perceived	T·V
Judgment by association	Generating an item associated with an answered item	An item associated with an item that was already answered in a task is answered	T·V
	Generating an associated item through a situation or scene related to an answered item	An associated item is answered through a situation or scene related to an answered item	
Functional adherence	Persisting the state	Only an item that was already answered regarding a perceived item can be recalled in the persisting state. In this case, no answer can be generated, because the item that is already answered is recalled after all attempts	T·V
Judgment by tactile image	Answering a tactile perceptual image generated and recalled through visual information	An image of tactile perception is recalled through visual information or by comparing and matching the image generated through visual information with the tactile representation in memory	Only V

T, item association task based on tactile information

V, item association task based on visual information

'Judgment by association' consists of two concepts that include generation through an answered item and generation through a situation or scene related to an answered item. This suggests that the participant was recalling and answering something similar to an item that was already answered in a task, and was also answering something recalled from past experience regarding the item. An example of a T-task answer may be, 'I was thinking something like cloth, and, well, cheap and thin jeans may feel like this.' One example of an answer in a V-task is, 'I was thinking about cloth. I was thinking about where else cloth exists; shoes came out and I answered it.'

'Functional adherence' consists of the concept of the persisting state. Only something that was already answered regarding a perceived item can be recalled in the persisting state. In this case, no answer can be generated, because something that is already answered is recalled after all attempts. An example in a T-task is, 'I tried to think of something else, but, what I think is cloth, and cloth.' A V-task example is, 'I can only think of this as cloth.'

'Judgment by tactile image,' which is generated only in a V-task, consists of the concept of answering based on an item generated and recalled from a tactile perceptual image. This implies that the participant, when answering, recalled an image of tactile perception through visual information or by comparing and matching an item generated through visual information with the tactile representation in memory. Examples include the following: 'For the curtain, I remembered the feel when I am touching it. Imagined, rather than remembered. But, a black curtain can't exist. So I neglected the color, and thought about the image when I touched it and the look of the surface,' and 'My feeling when I touched was the hard feeling and apparent roughness, so I recalled a file.'

Figure 1 shows the hypothesized flow of the cognitive perceptual processes from elementary sensory reception to object identification.

Experiment 2

Experiment 1 showed that the characteristics of cognitive perceptual processes are similar between visual and tactile perceptions. This suggested that peculiar problems do not happen in an association task using tactile information as the stimulus material.

Therefore, Experiment 2 focused only on tactile information, and we thus designed a task similar to Experiment 1. We asked the participants to describe their cognitive process leading to object recognition and to provide ratings of the vividness of tactile object perception, the participant's familiarity with the object and the affective valence of the object during item association for each answer (item) in the task. We designed a questionnaire based on the concepts obtained in Experiment 1 to assess the cognitive strategy

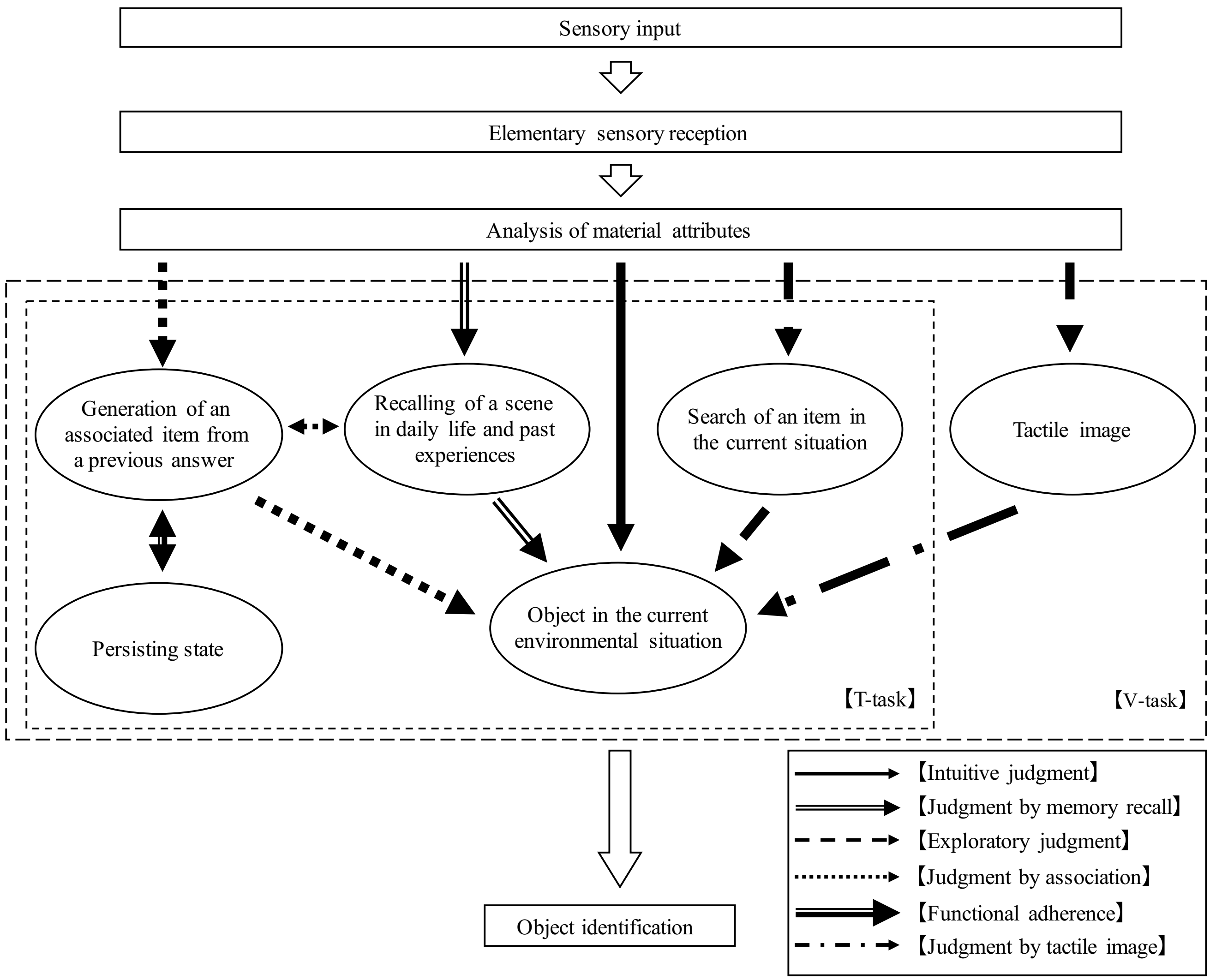

Fig. 1 Hypothesized flow of the cognitive processes from elementary sensory reception to object identification

(Table 3). We used the results to investigate whether there are differences in tactile representations with a difference in tactile information (i.e., the material).

Methods

Participants

The participants in Experiment 2 were 83 college students without tactile functional disorders or special tactile skills. Their mean ± SD age was 22.7 ± 4.8 years; 59 males, 24 females; 80 were right-handed, two were left-handed and one was both-handed as assessed using the scale developed by Chapman and Chapman (1987). We randomly assigned the participants for the analysis of one material out of three materials. Japanese was the language of all 83 participants.

Stimuli

Three tactile materials were used: plastic (polypropylene), cloth (100% cotton) and sandpaper (#120). All three materials were 28 cm long by 23 cm wide.

Regarding the experimental environment, the participant sat at a table, and the stimulus material was placed near the fingertips of his or her dominant hand. The participant was asked to actively touch the stimulus material with the fingertip of the index finger. The material had been placed at the bottom of a box (length 24.5 cm, width 36 cm and height 20 cm) in order to screen the hand (material surface). The participant used earplugs to limit the noise during contact (Fig. 2).

Table 3 Cognitive strategy questionnaire

Name of Participant (Identification Number)：______________________________ No.__________

Associative word：________________________

What kind of cognitive strategy did you use from touching the stimulus until the above-mentioned associative word of the answer? Please select the one that applies to your strategy from the following numbers and circle the number.

1. Chokkanteki ni kaito o eta
   I gave an intuitive answer.

2. Kako ni shiyo shita koto ga aru buppin o omoidashite kaito o eta
   I gave an answer by recalling an item used in the past.

3. Nichijo no seikatsu bamen o omoidashite sono bamen kara atehamarisona mono o mitsuke kaito o eta
   I gave an answer by recalling a scene in daily life and finding something similar in the scene.

4. Mukashi no dekigoto ya bamen o omoidashite soko kara atehamarisona mono o mitsuke kaito o eta
   I gave an answer by recalling an event scene from the past and finding something similar in the event scene.

5. Gen jokyo (kono heya) no bamen kara atehamarisona mono o mitsuke kaito o eta
   I gave an answer by finding something similar in the current situation (experimental room).

6. Ichido kotaeta renso-go (buppin-mei) kara soreto kankei suru buppin o renso sa sete kaito o eta
   I gave an answer by generating an item associated with an answered item.

7. Ichido kotaeta renso-go (buppin-mei) kara soreto kankei suru jokyo ya bamen o omoidashi sono naka kara atehamari-sona mono o mitsuke kaito o eta
   I gave an answer by generating an associated item through a situation or scene related to an answered item.

8. Sonohoka no hoho de kaito o eta
   I gave an answer in other ways.

Please describe your strategy in details.

(Note) The numbers from 1 to 7 correspond to the numbers of the cognitive strategies from 1 to 7, respectively. The participants were not aware of this information.

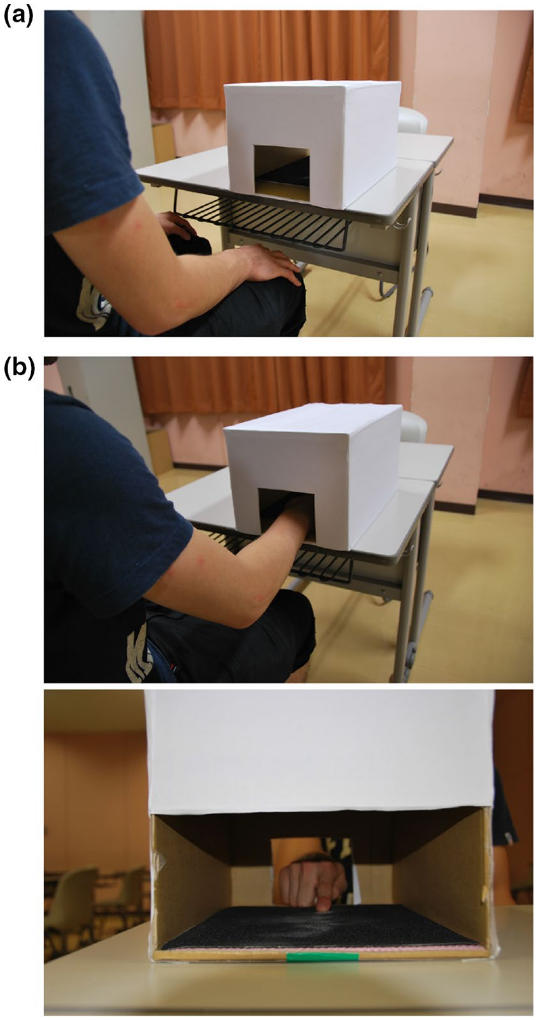

Fig. 2 Experimental environment **a** scene before the experiment, **b** scene during the experiment

Procedure

The experiment was carried out in an individual private room. The outline of the experiment and how the task was to be carried out were explained to the participant before he or she began the task. The participant was informed of the following regarding the task: (1) the participant must answer as often as possible what item the participant may be touching based on the tactile perception during the test (contact), (2) the duration of the task will be 3 min, (3) there will be a questionnaire after the task is finished and (4) this task is not a test, and therefore, there is no right or wrong answer.

Next, a practice task, using material other than one used in the experimental task (the tactile perception of a cardboard surface), was carried out so that the participant could better understand the test without knowing questionnaire contents.

The experiment was then initiated. The participant was supplied with one questionnaire for each item to be answered. The questionnaire consisted of four topics: (1) cognitive process, (2) vividness, (3) familiarity and (4) affective valence.

For the cognitive process, the participant was asked to describe one cognitive process that led to answering of the item during the task, among the following eight strategies. Strategy 1: The answer was intuitively obtained. Strategy 2: The answer was obtained while recalling an item the participant had used in the past. Strategy 3: The answer was obtained by recalling a scene in daily life, finding an item that may fit from the scene and then obtaining the answer. Strategy 4: The answer was obtained by recalling an event scene from the past, finding an item that may fit from the scene and then obtaining the answer. Strategy 5: The answer was obtained by finding an item that may fit from the current situation (this room) and then obtaining the answer. Strategy 6: The answer was obtained by associating an item from an associated word (item) from a previous answer. Strategy 7: The answer was obtained by remembering a situation or scene related to an associated word (item) from a previous answer, by finding an item that may fit from this situation/scene and by then obtaining the answer. Strategy 8: The answer was obtained by another method. The participant was asked to freely write down the other method.

Regarding vividness, the participant was instructed to use the following rating: 1 = vague, 2 = not vivid, 3 = moderately vivid and 4 = extremely vivid. Regarding familiarity, or how frequently did the participant touch the test item, the participant was instructed to use the following rating: 1 = never, 2 = a few times, 3 = sometimes, 4 = often and 5 = very frequently.

Regarding the affective valence, i.e., what emotion the participant felt about the test item, the participants were instructed to use the following rating: 1 = unpleasant, 2 = unpleasant than pleasant, 3 = neither pleasant nor unpleasant, 4 = pleasant than unpleasant and 5 = pleasant.

Results

Table 4 shows a concise summary of the concepts and associative words that emerged across the participants for each material.

The difference in the number of words used for the items among the three materials

The number of words used for the items identified in the tasks for each material was as follows: plastic, 194 words ($M = 6.9$, SD = 4.2), cloth, 164 words ($M = 5.9$, SD = 2.4) and sandpaper, 158 words ($M = 5.9$, SD = 3.3) (Table 5). A one-way analysis of variance (ANOVA) showed no significant

Table 4 A concise summary of the concepts and associative words that emerged across the participants for each material

Concept (cognitive strategy)	Associative word		
	Plastic	Cloth	Sandpaper
1 Intuition	'desk pad,' 'glass,' 'desk'	'cloth,' 'cotton,' 'hair'	'sandpaper,' 'board,' 'paper'
2 Recall of items	'desk pad,' 'tablecloth,' 'board'	'carpet,' 'cloth,' 'felt'	'sandpaper,' 'board,' 'sand'
3 Recall of everyday scenes	'glass,' 'desk,' 'tile'	'carpet,' 'clothes,' 'towel'	'nail clippers,' 'wall,' 'shoes'
4 Recall of past event scenes	'stone,' 'tablecloth,' 'door'	'animal's hair,' 'carpet,' 'cloth'	'board,' 'sand,' 'glass'
5 Exploration	'desk,' 'whiteboard,' 'floor'	'chair,' 'board,' 'paper'	'desk'
6 Association between items	'book,' 'plastic,' 'desk pad'	'cloth,' 'clothes,' 'towel'	'board,' 'sand,' 'shoes'
7 Association of items with situations or scenes	'aluminum,' 'concrete,' 'tile'	'clothes,' 'carpet,' 'cushion'	'leather,' 'shoes,' 'floor'

Table 5 Differences in the cognitive strategy, vividness, familiarity and affective valence among the three materials

	Plastic ($n=194$)		Cloth ($n=164$)		Sandpaper ($n=158$)	
	n (%)	Adjusted residual	*n* (%)	Adjusted residual	*n* (%)	Adjusted residual
Cognitive strategy[a]						
1	38 (19.6)	−1.3	29 (17.7)	−1.8	49 (31.4)	3.2**
2	26 (13.4)	−2.9**	40 (24.4)	1.8	36 (23.1)	1.2
3	75 (38.7)	4.9**	32 (19.5)	−2.4*	29 (18.6)	−2.7**
4	10 (5.2)	−2.9**	26 (15.9)	3.0**	16 (10.3)	0.1
5	22 (11.3)	4.4**	6 (3.7)	−1.3	1 (0.6)	−3.2**
6	15 (7.7)	−1.5	17 (10.4)	0.0	21 (13.5)	1.6
7	8 (4.1)	−0.8	14 (8.5)	2.5*	4 (2.6)	−1.7
Vividness[b]						
Vague	6 (3.1)	−0.4	1 (0.6)	−2.4*	11 (7.0)	2.9**
Not vivid	18 (9.3)	−4.1**	46 (28.0)	3.9**	30 (19.0)	0.3
Moderately vivid	59 (30.4)	−1.2	67 (40.9)	2.3*	48 (30.4)	−1.1
Extremely vivid	111 (57.2)	4.5**	50 (30.5)	−4.4**	69 (43.7)	−0.3
Familiarity[c]						
Low	30 (15.5)	−4.4**	54 (32.9)	2.2*	53 (33.5)	2.4*
Medium	43 (22.2)	−0.5	41 (25.0)	0.6	37 (23.4)	0.0
High	121 (62.4)	4.4**	69 (42.1)	−2.5*	68 (43.0)	−2.1*
Affective valence[d]						
Negative	9 (4.6)	−2.3*	7 (4.3)	−2.2*	26 (16.5)	4.6**
Neutral	99 (51.0)	−2.0*	91 (55.5)	−0.4	103 (65.2)	2.6**
Positive	86 (44.3)	3.4**	66 (40.2)	1.7	29 (18.4)	−5.3**

Chi-squared test [a]$\chi^2(12)=70.26$, $p<0.001$; [b]$\chi^2(6)=44.62$, $p<0.001$; [c]$\chi^2(4)=24.23$, $p<0.001$; [d]$\chi^2(4)=41.09$, $p<0.001$

Residual analysis $**p<0.01$; $*p<0.05$

difference in the number of answers for each material [$F(2,80)=0.932$, $p=0.398$].

The difference in the frequency of use of each cognitive strategy, and the vividness, familiarity and affective valence ratings for the three materials

One participant used the cognitive strategy 8 for two responses to sandpaper, whereas none of the participants used this strategy for plastic or cloth. We compiled cross-tabulation tables and used Chi-squared tests to evaluate the relationships between the frequency of the use of each cognitive strategy and the vividness, familiarity and affective valence ratings. When we identified a significant difference, the strategy that caused the significant difference was clarified through residual analyses.

Regarding the relationship between the frequency of the use of each cognitive strategy, there was a significant difference according to the Chi-squared test [$\chi^2(12)=70.26$, $p<0.001$]. Moreover, residual analyses showed that the frequency of use was significantly higher in Strategies 3 and 5 (scenes and situations in daily life) ($p < 0.01$) with plastic, in Strategies 4 and 7 (past experience and situations) ($p < 0.01$ and $p < 0.05$, respectively) with cloth, and in Strategy 1 (intuitive judgment) ($p < 0.01$) with sandpaper (Table 5). The frequency of use was significantly lower in Strategies 2 and 4 (past experience and situations) ($p < 0.01$) with plastic, Strategy 3 (scenes in daily life) ($p < 0.05$) with cloth, and Strategies 3 and 5 (situations in daily life) ($p < 0.01$) with sandpaper (Table 5).

A significant difference in vividness with the differences in materials was observed [$\chi^2(6) = 44.62$, $p < 0.001$]. Residual analyses showed that for plastic, the rating 'extremely vivid' was significantly higher ($p < 0.01$), and 'not vivid' was significantly lower ($p < 0.01$) (Table 5). For cloth, 'not vivid' and 'moderately vivid' were significantly higher ($p < 0.01$ and $p < 0.05$, respectively), while 'extremely vivid' and 'vague' were significantly lower ($p < 0.01$ and $p < 0.05$, respectively) (Table 5). 'Vague' was significantly higher ($p < 0.01$) for sandpaper (Table 5).

Regarding the differences in the participants' familiarity with the different materials, 20% had expected ratings < 5. We thus combined 'often' and 'very frequently' as 'high,' and we combined 'never' and 'a few times' as 'low.' 'Sometimes' was relabeled as 'medium.' A significant difference in familiarity was revealed according to the Chi-squared test [$\chi^2(4) = 24.23$, $p < 0.001$]. Residual analyses showed that for plastic, the rating 'high' was significantly higher ($p < 0.01$) and 'low' was significantly lower ($p < 0.01$), and that for cloth and sandpaper, 'low' was significantly higher ($p < 0.05$), and 'high' was significantly lower ($p < 0.05$) (Table 5).

Our analysis of the differences in the affective valence for the three materials, again, 20% provided expected scores of < 5. Therefore, 'pleasant than unpleasant' and 'pleasant' were combined as 'positive'; 'unpleasant' and 'unpleasant than pleasant' were combined as 'negative'; and 'neither pleasant nor unpleasant' was relabeled as 'neutral.' A significant difference in the affective valence was revealed according to the Chi-squared test [$\chi^2(4) = 41.09$, $p < 0.001$]. Residual analyses showed that for plastic, the 'positive' rating was significantly higher ($p < 0.01$) and 'negative' and 'neutral' were significantly lower ($p < 0.05$) (Table 5). For cloth, 'negative' was significantly lower ($p < 0.05$) (Table 5). For sandpaper, 'negative' and 'neutral' ratings were significantly higher ($p < 0.01$) and 'positive' was significantly lower ($p < 0.01$) (Table 5).

Discussion

With a qualitative analysis of the cognitive process regarding object recognition, using the modified grounded theory approach, we identified eight cognitive processes, each of which was based on the distinct concept. It should be noted that each concept was analyzed against other concepts until the conceptualization required no further addition or modification.

The results of Experiment 1 indicate that V-tasks and T-tasks are answered through a very similar cognitive process, although there is a partially different concept between visual and tactile information. A similar cognitive process is followed possibly because the brain regions that process visual and tactile information regarding material attributes are similar (Goodale and Milner 1992; Newman et al. 2005). It could also be that the task used drives the similarity. That is, an association task with such clear high-level processing specifications already suggests that the results will not be modality specific because the task does not tap into a perceptual-level response, but a cognitive-level response.

Experiment 2 was an item association task using different tactile information to investigate whether a difference in tactile information (here, the material) will result in changes in tactile representation. We determined the ratings regarding memory characteristics for the answered items. The results provided the first demonstration that differences in tactile information (material attributes) resulted in differences in cognitive processes, vividness, familiarity and affective valence.

The characteristics of the materials were compared as follows. Items related to plastic were represented while imagining scenes and situations related to daily life; the items having high vividness and familiarity had positive affective valences. In contrast, the items related to cloth were represented while imagining experiences and situations in the past. Therefore, the items were mostly 'moderately vivid' or 'not vivid,' and had low familiarity. The items related to sandpaper were mostly answered intuitively. With sandpaper, the appearances of the items were not included; there was little experience of tactile contact, and the affective valence contained more negative or neutral elements.

The experiments used tactile information as a clue to search items from his or her memory. In a general memory search process to answer an item, each memory has an activity value. Memories with higher activity values are likely to be remembered, and memories that are joined to the clue have high activity during a search. Finally, memories that become more active than a threshold are remembered one by one (Raaijmakers and Shiffrin 1981; Chappell and Humphreys 1994; Anderson et al. 1998). Katz (1989) suggested that tactile memory is related to the remnants of the part of the body involved in a touching action, and that the touching action is recalled while recalling the hand's fingers, which are most often used in touching material. Therefore, the memory characteristic of each tactile perception would reflect the position of that item, using the materials existing in the experience to contact the object.

Memories regarding plastic and cloth may be joined with episodic memory accompanying touching behavior. Moreover, the periods of joined memory are different between these materials. Sandpaper has more elements of intuitive answering and thus has more elements of linguistic knowledge in semantic memory. The results we observed for vividness suggest that the memory of plastic is closer to daily memory, and thus, the vividness of recalled objects is higher. Cloth is more related to memory of the past, which would lead to a vagueness of recalled items. In contrast, sandpaper is strongly related to semantic memory, and thus, no visual image of items was recalled, resulting in 'vague' vividness. Regarding familiarity, the plastic material's familiarity ratings were 'high' because many plastic items exist in daily life and are frequently operated by hand. However, familiarity was 'low' for cloth because, although cloth items exist (e.g., garments worn and carpets underfoot), the frequency in daily life that these items are touched or operated by hand is not that high. The familiarity of sandpaper was 'low,' possibly because there are few items in daily life with surfaces that are similarly rough.

Finally, our investigation of affective valence revealed a difference in the emotions induced by different materials. Contact with a tactile perception material was reported to cause an emotional change (Craig 2002; Ramachandran and Brang 2008). Another study found that the recalling of a memory (episode memory, in particular) can also cause a recall of emotional feelings joined to the memory (Conway and Pleydell-Pearce 2000). In the present study, therefore, we could determine whether the emotional changes that were observed in the experiments originated from the tactile perception material or were related to episode memory that occurred while recalling an item.

In summary, our study confirmed that memory associated with the type of tactile perception material, which is a material element, is associated with episode memory in addition to semantic memory as knowledge and concepts. The associated memory, knowledge and affective valence were also shown to differ by the material type.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical standard All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards. The experiment reported here was approved by the Ethical Committee of Kochi School of Allied Health and Medical Professions.

Informed consent Informed consent was obtained from all individual participants included in the study.

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