Behavioral and fMRI Studies on Visuotactile Roughness Perception

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(Doctor's Course)
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視触覚による粗さ知覚に関する行動学および fMRI 研究

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Chapter 1 Introduction

On the other hand, tactile recognition experiments have been carried out worldwide for years. When examining the state of human touch, due to a variety of complex tactile information input by touch, we determine by analyzing the shape and condition of the surface. When touching something in the shape of a character, we imagine and visualize the shape based on tactile information while matching its similar shape and character to the brain require an advanced network of brain.

Haptic and visual information contribute to our texture perception, lead human to recognize surface characteristics of objects by single glance or particular touch. In addition, we generally recognize object's texture by using multisensory inputs, combining both modalities to produce final judgement into understanding the texture. During the processes, how do those different modalities affects each other? Are they integrated or disconnect inside our brain?

Perception of textures can be divided into two; fine (spatial features smaller than 200μm) and coarse textures. Texture depends on spatial and temporal cues and is mediated by different tactile receptors in the skin. According to the duplex theory, the perception of a surface with element size lower than 100 μm is impaired in the absence of movement. In tactile texture perception, roughness is one of the most important characteristics of a textured surface and it is evident that, at least for fine surfaces, motion plays an important role in extracting roughness information from textured surfaces. Recent studies on the haptic perception of roughness have indicated that even temporal coding is involved in the haptic perception of a coarse surface (200 μm) and that encoded spatial properties are likely a key factor. Information about the roughness of a surface can be encoded not only through active exploration of that surface but also by the surface rubbing passively against one's skin.

Plenty of psychological studies investigating tactile texture perception have been conducted using artificial stimuli such as dot surfaces, grating patterns or abrasive papers. In addition, a lot of research has been devoted to tactile rough-ness, in particular with respect to the role of vibration cues and to the neural mechanisms. Visual roughness is likely a factor that contributes to the perception of visual gloss. To date, many studies investigated texture perception in separate visual and haptic paradigms and the effect of simultaneous visual and haptic exploration of textures has always been overlook. Overlap of visual and haptic texture may represent in some brain areas, but whether visual and haptic information interacts in these cortical regions is still subtle. Behavioral studies also indicate the existence of such cross modal interaction and matching effects in visuo-haptic tasks. It was shown that people consistently and absolutely match specific tactile vibration rates (simulating manual exploration of a textured surface) to visual spatial frequencies, indicating some kind of cross modal association effect in visual and haptic texture perception.

To differentiate a surface texture, human apply both visual and haptic information for the perception. We are focusing in roughness, one of significant domain in the perception of textures. In addition, we generally recognize object's texture by using multisensory inputs, combining both modalities to produce final judgement into understanding the texture. During the processes, how do those different modalities affects each other? Are they integrated or disconnect inside our brain? Cognition of surface roughness at the same time in the two senses (tactile and visual) is still undeclared, and how both effects on each other could be intriguing. Moreover, human sensations during roughness perception always involve in interaction, but a lot of brain's response during the interaction is still unknown. Additionally, the perception of roughness has been studied primarily in the haptic domain. Plenty of psychological studies investigating tactile texture perception have been conducted using artificial stimuli such as dot surfaces, grating patterns or abrasive papers. In addition, a lot of research has been devoted to tactile roughness, in particular with respect to the role of vibration cues and to the neural mechanisms. Visual roughness is likely a factor that contributes to the perception of visual gloss, mainly focusing on spatial factors This raises the question on how the temporal factors affect the roughness perception. Does the spatial factors are more significance than temporal? How do we code the temporal code in visual roughness?

This thesis is divided into five chapters. In the first chapter, literature review on texture perception is explained. The main objective of the first study in the second chapter was to explore how the two modalities influence each other during roughness perception of fine surface. We designed two unimodal tasks and four bimodal tasks within both modalities using six different fine surfaces and six different grayscale photos. In unimodal visual task (V-V), subjects were asked to judge rougher visual stimuli between two stimuli that were presented in sequential order. In bimodal visual task, (V-Vt), subjects needed to do the same visual roughness judgement while perceiving an interference tactile stimulus at the second order of the presented stimuli. We expected to measure the influence of each modality by considering how subjects were interrupted by the emergence of the tactile interference stimulus. Furthermore, bimodal visual task are divided into two tasks, which applied rough tactile interference stimulus (V-Vt-rough) and smooth one (V-Vt-smooth). Unimodal and bimodal tactile task (T-T, T-Tv-rough, and T-Tv-smooth) were the opposite, which subjects need to do tactile rough-ness judgement. We propose that the roughness of the interference stimulus from different modality may affects subjects judgment and different between the two types. We found that tactile sensory was dominant in the perception of roughness by fine surface. During cross modalities, visual information has almost no effects toward tactile sensory, but in the other hand tactile information had significance effects onto visual sensory. Furthermore, we found that stimuli with smaller particles bring more interference into subject's perception compared to bigger particles in fine surface. We suggest that particles sizes are as significant as the modalities in visual, tactile, or multisensory integration of both, in roughness perception of fine surface.

In the third chapter, we measured brain activity during pattern perception using functional magnetic resonance imaging (fMRI). Human sensations always involve in interaction, but a lot of brain's response during the interaction is still unknown. This study was designed to discover the unresolved part of the brain during performing visual and tactile interaction roughness recognition experiments. We designed four types of tasks: visual task (VV), tactile task (TT), visual - tactile task (VT), tactile - visual task (TV). The common area of each of the brain activation during each task was analyzed; and the results showed that activations located in the frontal and parietal, suggesting these regions were actively involved in the cross-modal processing. Specific activation for the information from the tactile and visual modality was seen in the frontal and parietal lobe, respectively, suggesting the particular activation in each at this region.

In the fourth chapter, we designed a visual base stimulation to investigate the temporal factors of roughness perception. Visual stimulation with regularity and irregularity of spatial spacing were used in this study. In the present study, we used computer-assembled gratings and scrambles images to define time characteristics of visual roughness. The parameters of the grating including pixels per cycle, spatial frequency, and visible size were calculated and one single static grating image was generated. The actual sine grating and drift speed (in cycles per second) were then computed and the amount of pixels to be shifted is specified to perform a perception of movement. We then investigated the effects of changes in those gratings and scrambles parameters to subjects' roughness perception. In the first experiment, we investigated the effects of temporal frequency towards roughness perception by visual drifted grating stimuli. We could understand that gratings do have several limitations for roughness perception to human visual. In the second experiment, we changed our stimulation to scramble stimulation which originated from the grating stimuli. In order to examine the results of the second experiment, we carried out a magnitude estimation experiment on each of the difference temporal frequency of scramble stimuli. The results showed a more converged results during the perception of irregular spacing in scramble stimuli, suggesting the significance of spatial coding. However, we also found the evidence of how visual temporal factors influence the perception of roughness.

Chapter 2 Human Characteristics of Tactile-Visual Cross-modal on Roughness Perception

Abstract

Cognition of surface roughness at the same time by the two senses (tactile and visual) is still undeclared, and how both effects on each other could be intriguing. The main factor for roughness estimation of fine surface (spatial features below 200μm) is also unknown until present. In order to see the difference between cognition of both condition, we conducted two unimodal and two bimodal tasks involving both modalities using fine sandpapers. Tactile stimuli consisted of six types of different sandpapers that varied in their roughness, while visual stimuli are images of the correspondence tactile stimuli. In unimodal task, subjects need to compare which stimulus perceived were rougher, visually and tactually, while multiple sensory of visual and tactile were mixed in bimodal task. We also varied the type of roughness in bimodal task into two categories to discover whether there is any acceleration or suppression by different stimuli. We found that tactile sensory was dominant in the perception of roughness by fine surface. During cross modalities, visual information has almost no effects toward tactile sensory, but in the other hand tactile information had significance effects onto visual sensory. Furthermore, we found that stimuli with smaller particles bring more interference into subject's perception compared to bigger particles in fine surface. We suggest that particles sizes are as significant as the modalities in visual, tactile, or multisensory integration of both, in roughness perception of fine surface.

2.1 Introduction

Haptic and visual information contribute to our texture perception, lead human to recognize surface characteristics of objects by single glance or particular touch. In addition, we generally recognize object's texture by using multisensory inputs, combining both modalities to produce final judgement into understanding the texture. During the processes, how do those different modalities affects each other? Are they integrated or disconnect inside our brain?

Perception of textures can be divided into two; fine (spatial features smaller than 200μm) and coarse textures [1][2]. Texture depends on spatial and temporal cues and are mediated by different tactile receptors in the skin [3][4][5][6]. According to the duplex theory, the perception of a surface with element size lower than 100 μm is impaired in the absence of movement. In tactile texture perception, roughness is one of the most important characteristics of a textured surface and it is evident that, at least for fine surfaces, motion plays an important role in extracting roughness information from textured surfaces. Recent studies on the haptic perception of roughness have indicated that even temporal coding is involved in the haptic perception of a coarse surface (200 μm) and that encoded spatial properties are likely a key factor [7]. Information about the roughness of a surface can be encoded not only through active exploration of that surface but also by the surface rubbing passively against one's skin.

Plenty of psychological studies investigating tactile texture perception have been conducted using artificial stimuli such as dot surfaces, grating patterns or abrasive papers. In addition, a lot of research has been devoted to tactile rough-ness, in particular with respect to the role of vibration cues and to the neural mechanisms. Visual roughness is likely a factor that contributes to the perception of visual gloss [8][9]. To date, many studies investigated texture perception in separate visual and haptic paradigms and the effect of simultaneous visual and haptic exploration of textures has always been overlook. Overlap of visual and haptic texture may represents in some brain areas, but whether visual and haptic information interacts in these cortical regions is still subtle. Behavioural studies also indicate the existence of such cross modal interaction and matching effects in visuo-haptic tasks. It was shown that people consistently and absolutely match specific tactile vibration rates (simulating manual exploration of a textured surface) to visual spatial frequencies [10], indicating some kind of cross modal association effect in visual and haptic texture perception.

The main objective of the present chapter was to explore how the two modalities influence each other during rough-ness perception of fine surface. We designed two unimodal tasks and four bimodal tasks within both modalities using six different fine surfaces and six different grayscale photos. In unimodal visual task (V-V), subjects were asked to judge rougher visual stimuli between two stimuli that were presented in sequential order. In bimodal visual task, (V-Vt), subjects needed to do the same visual roughness judgement while perceiving an interference tactile stimulus at the second order of the presented stimuli. We expected to measure the influence of each modality by considering how subjects were interrupted by the emergence of the tactile interference stimulus. Furthermore, bimodal visual task is divided into two tasks, which applied rough tactile interference stimulus (V-Vt-rough) and smooth one (V-Vt-smooth). Unimodal and bimodal tactile task (T-T, T-Tv-rough, T-Tv-smooth) were the opposite, which subjects need to do tactile roughness judgement. We propose that the roughness of the interference stimulus may affects subjects judgment and different between the two types. In addition, small or big particles size of fine textures may also influence the perception of roughness in both modalities. Stimulus presentation was always bimodal, but the sensory information content differed as texture information was varied either in the haptic, visual or in both channels.

As discussed in previous chapter, cross modality between visual and tactile in human have been reviewed by many. The intention of this study is to demonstrate the theorem. Cross modality effects are different according to individual and the effects activated by it are also believed to be various. In this chapter, we expect to find the characteristics of those effects related to the cross modal of tactile and visual, during the perception of roughness.

2.2 Experimental stimuli

In this study, we outlined two types of stimuli throughout the experiment; tactile stimuli and visual stimuli. Along with these stimuli, we also arranged the indication stimuli which functioned as the instructor for the subjects. The indication stimuli make sure that a smooth and continuous experiment can be performed.

2.2.1 Tactile stimuli

Tactile stimuli consisted of six type of different sandpaper which varied in their roughness. Deliberately, the tactile roughness is exactly the same with the correspondence visual stimuli. The number of tactile stimuli presented is written under the stimulus count of file used in each stimulus is a (#). The numbers are: #400, #600, #1000, #2000, #3000, and #5000.

Table 1 Grades of sandpaper

Stimulus number (#)	400	600	1000	2000	3000	5000
Average particle diameter (μ m)	34	24	15.5	8.5	5.7	1.5

Index finger of the right hand of subjects contacted with the tactile stimuli. .Figure 2.1 is the samples of sandpapers that we used during examination. With 4.5cm width, 0.5mm thick, and 3.5cm of length, the six types variation are referring to the size of particles of abrading materials embedded in the sandpaper based on the Japanese Industrial Standards Committee (JIS).

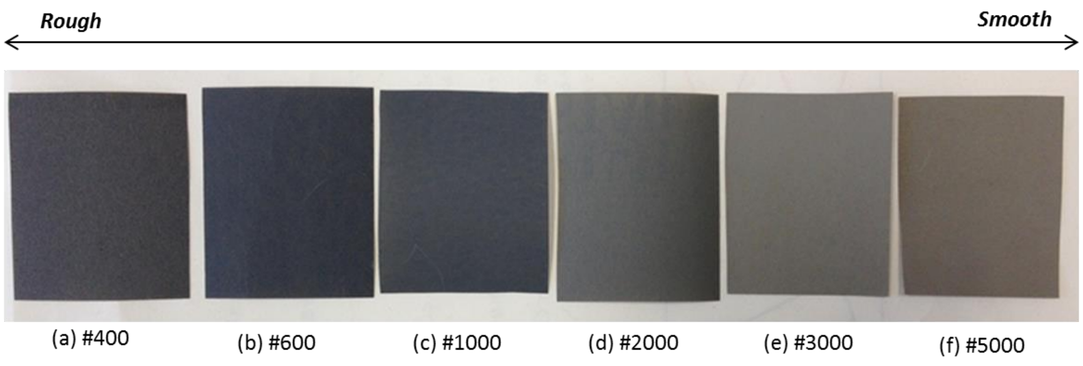
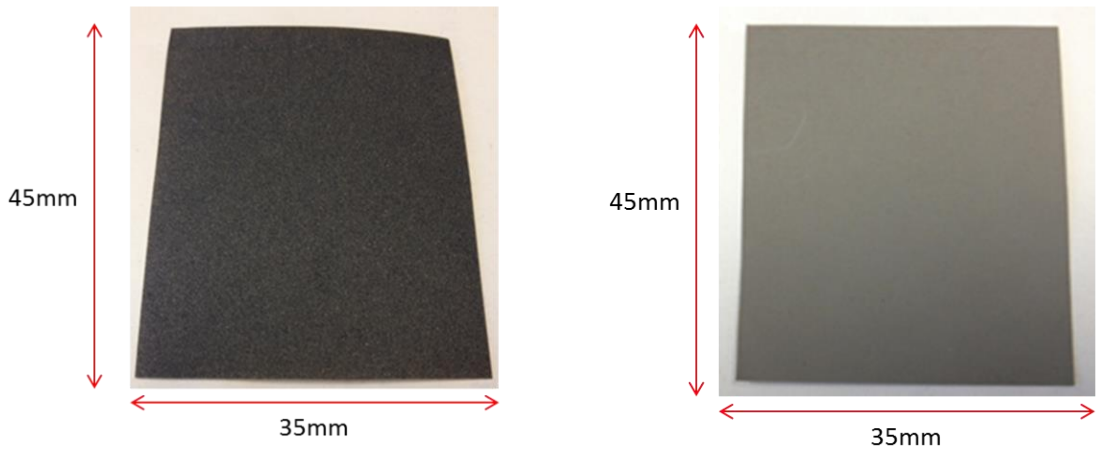


Fig 2.1 Samples of tactile stimuli

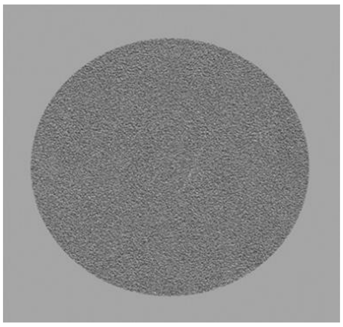


(a) Grit number #400, the roughest sandpaper (b) Grit number #5000, the smoothest sandpaper

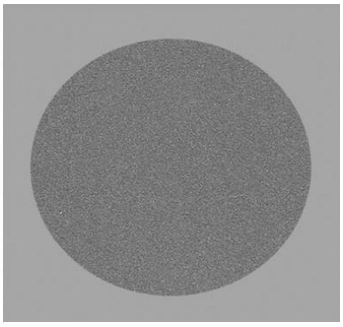
Fig 2.2 Close up of roughest stimuli (#400) and smoothest (#5000)

2.2.2 Visual stimuli

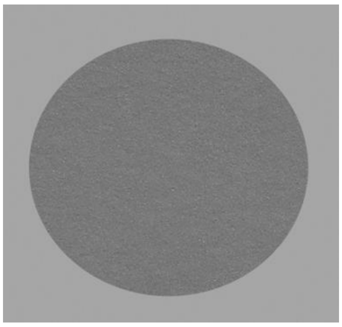
We used sandpaper with the same grade as tactile stimuli for all types of visual stimuli. Circle of those sandpapers with diameter of 22.2mm and central angle 25 ° was captured by scanner and their brightness of grey scale were fixed into one scale. Distance of presented visual stimuli from computer's display to subject's face is 500mm, and the visual roughness is exactly the same with the correspondence tactile stimuli. The circles were presented on a grey screen. The number of tactile stimuli presented in the display, is written in (#), while Reference Stimuli and Comparison Stimuli are randomized according to the task (refer 3.6)



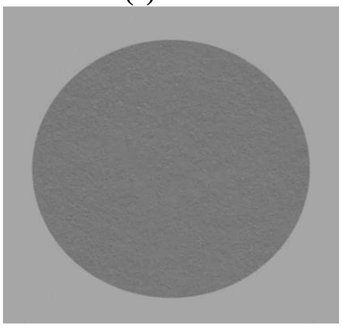
(a) #400



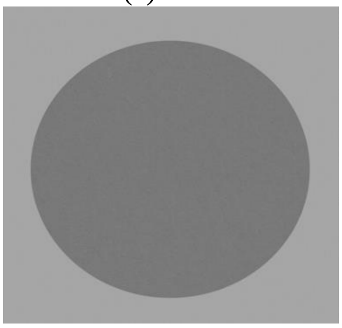
(b) #600



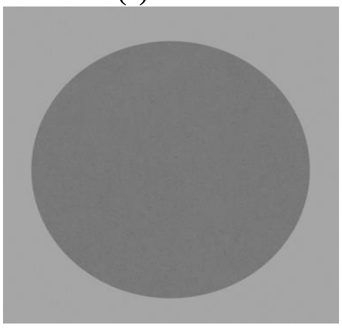
(c) #1000



(d) #2000



(e) # 3000



(f) #4000

Fig 2.3 Six samples of visual stimuli

2.2.3 Visual indication stimuli

Our future plans include exploring the neural substrates when subjects perceived roughness. To maximize the smoothness of presentation of tactile and visual stimuli, we designed an automated experimental system for maximum smoothness during fMRI experiments. For this reason, we arranged the visual indication stimuli. These stimuli can be divided into three colors. The three colors indicating three different instructions. For every task whether it is visual or tactile task, subjects will be presented two times. The initial stimulus is the Reference Stimulus while the secondary stimulus is the Comparison Stimulus.

As shown in (Figure 2.4), visual indication stimuli are three types of plus symbol (+), presented in the center of display, with 17.5mm size at 2 ° central angle. In what is shown in Figure 2.4 (a), white plus symbol indicates the initial stimulus will be presented in a little while. Black is a sign or reminder for comparison stimulus will be presented. Lastly, red visual indication stimulus is for subjects to touch the tactile stimuli presented to their right hand. Resultantly, red indicators will only be presented during presence of tactile stimuli. Figure 2.4 shown is the visual indication stimuli in an enlarged view which was used in the experiment.

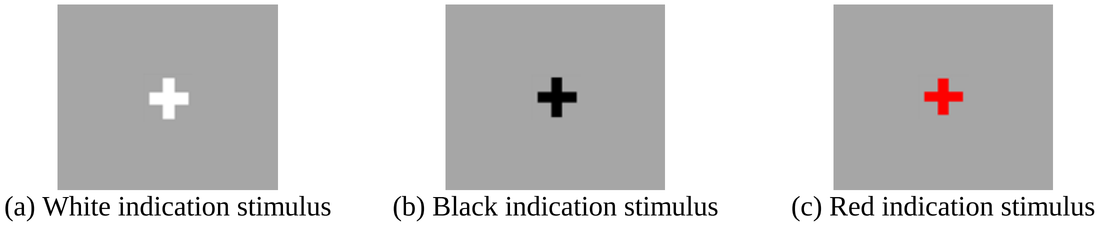


Fig 2.4 Visual indication Stimuli. From left: white (before Reference Stimulus presented), black (before Comparison Stimulus presented), and red (contact with tactile stimulation)

2.3 Experimental setup and device

2.3.1 Setup

General view is as in Figure 2.5. A display, an experimenter's computer, the experimental device, a jaw stand, and a partition plate all involved into the environment. Subjects needed to place their right hand on top of the cover-plate of the device, and we needed to place their jaw 50 cm from the display. The display was connected to the experimenter's computer and outputs of visual indication stimuli and visual stimuli were displayed and controlled by the experimenter through the computer.

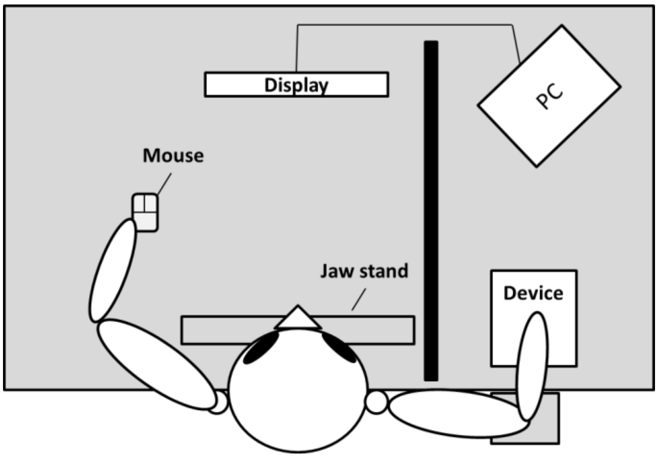


Fig 2.5 General view of experiment

The display and jaw stand were divided with experimenter's PC and the device by a partition plate. With the mouse on the left hand as the response key, the partition plate certainly prevents any visual information from the device and PC. The right hand, get placed on top of the cover-plate of the tactile presentation device and the arm was supported by elbow stand, located at certain location which can be moved according to the subject's hand's length (Figure 2.6).

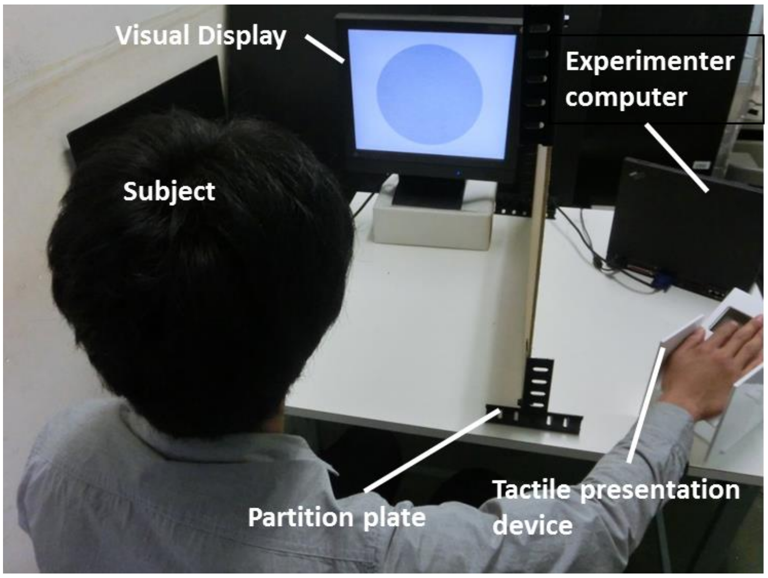
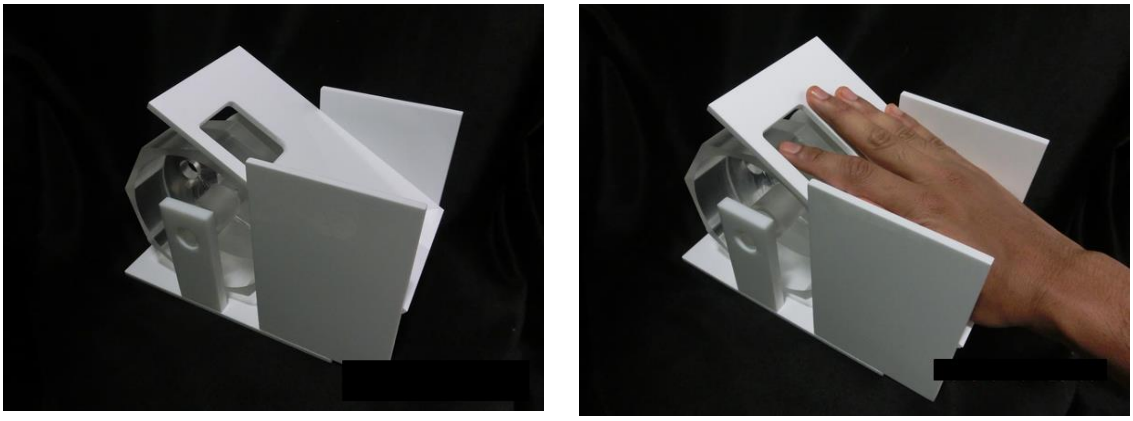


Fig 2.6 Experimental scene

2.3.2 Tactile presentation device

Figure 2.7 is the detailed elements of the tactile presentation device. Material of the device was all acrylic. The cover-plate allowed subjects to explore only one texture at a time and served as the resting position for the hand in between exploration trials. Beneath the cover-plate is an octagonal prism; fixed at the center as an axis and the presence of two stands with two bearings inside executed a rotation mechanism. The presentation of tactile stimulation was fully controlled by Presentation R software (Neurobehavioral Systems, Inc., Albany, CA, USA).

The octagonal prism is being supported by two stands with height of 90 mm each. Two bearings were inserted in each stands 75mm from the bottom. The axis of the octagonal prism was inserted into both ends of bearings, making it possible for rotation mechanism. One end of the axis was being connected to a gear; which is 90mm of diameters. The 90mm gears then were connected to another smaller gear (20mm diameters). The smaller gears connected to an ultrasonic motor (Canon precision Co., Ltd)



(a) Without exploration (b) With exploration

Fig 2.7 Tactile presentation device

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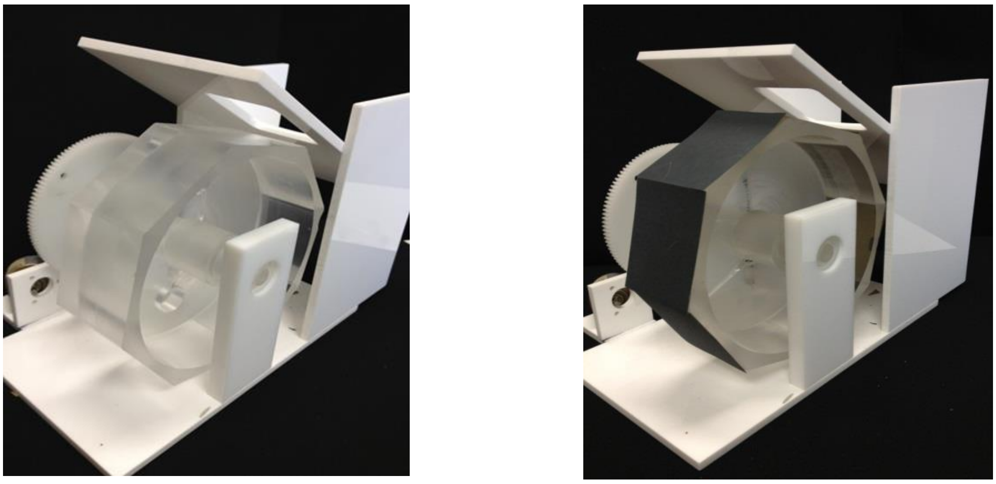
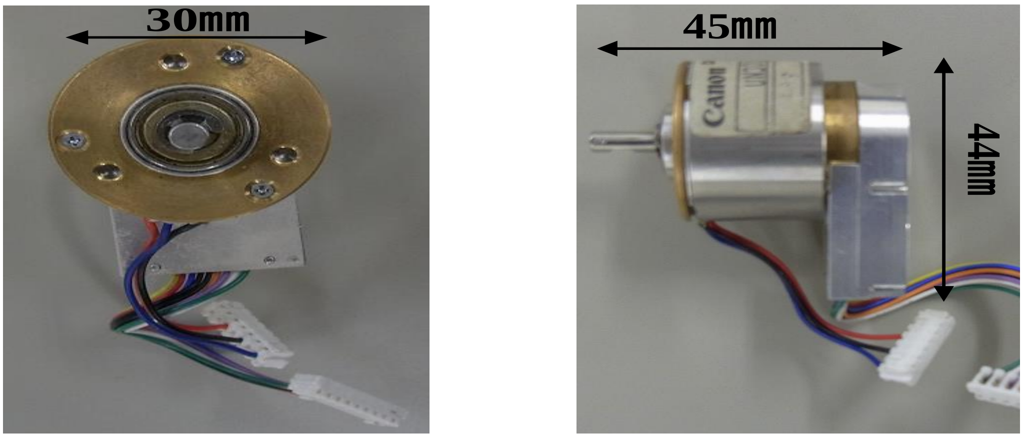
Eight surfaces were there in the prism. For this research, we only used six of them. The remaining two surfaced were unused but were built considering any possibilities in future fMRI studies. The surface is exactly the same size with the tactile stimuli (sandpapers) which is 35 mm long and 45 mm width.



(a) Without tactile stimuli (b) With tactile stimuli

Fig 2.8 The octagonal prism, without (left) and with tactile stimulation (Right)

The ultrasonic motor was used in this research as a preparation for fMRI study. Because the MRI contains strong magnets, metal objects are not allowed into the room with the MRI scanner. That is also why we used plastics as the main material of the device. The ultra-sonic motor was connected to the controller and experimenter's computer, and all of activity by the motor can be controlled by the experimenter, using the computer. Figure 2.9 is the top side view and lateral side view of the ultra sonic motor used.



(a) Lateral view (b) Top view

Fig 2.9 Ultrasonic motor used for the tactile presentation device

2.4 Materials and method

2.4.1 Subjects

Ten right-handed, healthy volunteers (all males, mean age of 22.2±1.8 years old) participated in this experiment. All subjects had no remarkable injuries to the hands or fingers, normal visions, and given written informed consent for participation. The local medical ethics committee of Okayama University approved the protocol.

2.4.2 Apparatus and stimuli

Tactile stimuli surfaces consisted of 0.5mm thick sandpapers with six different particle sizes, ranged from 1.5 to 34 μm (Figure 2.10). Each sandpaper was spray coated to prevent subject's finger from abrasive. Each sandpapers were fixed to side of prima to present to the subjects with 4.5cm width and 3.5cm of length. High-resolution scanned sandpapers were used as the visual stimuli. The average luminance of visual sandpapers stimuli used in this experiment were constant and they varied only along a single texture dimension, i.e. the average particles diameters, ensuring that changes in other surface properties like color do not influence the results. The six types variation of roughness in each stimulus referred to the size of particles of abrading materials embedded in the sandpaper based on the Japanese Industrial Standards Committee (JIS).

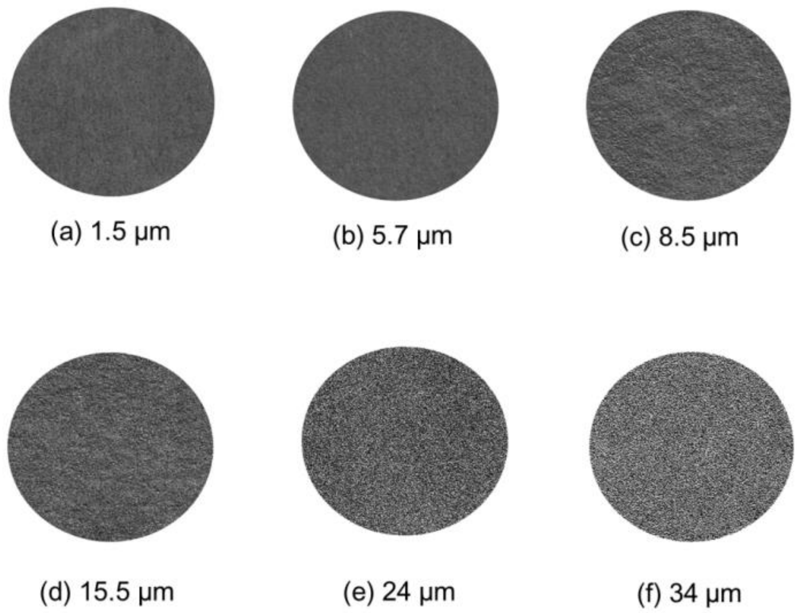


Fig 2.10. Six types of scanned sandpapers used in all task involving visually displayed stimuli. Numbers represented the average of particle sizes of each.

During tactile stimulus exploration, index finger of the right hand of subjects contacted with the tactile stimuli. The cover-plate allowed subjects to explore only one texture at a time and served as the resting position for the hand in be-tween exploration trials. Beneath the cover-plate is an octagonal prism; fixed at the center as an axis and the presence of two stands with two bearings inside executed a rotation mechanism. The octagonal prism was supported by two stands with height of 90 mm each. Two bearings were insert-ed in each stands 75mm from the bottom. The axis of the octagonal prism was inserted into both ends of bearings, making it possible for rotation mechanism. The presentation of tactile stimulation was fully controlled by Presentation R software (Neurobehavioral Systems, Inc., Albany, CA, USA). The surface is exactly the same size with the tactile stimuli (sandpapers) which is 35mm long and 45mm width. The display was connected to the experimenter's computer and outputs of visual indication stimuli and visual stimuli were displayed and controlled by the experimenter. The visual display and chin rest stand were divided with experimenter's computer and the tactile texture presentation device by a partition plate. With the mouse on the left hand as the response key, the partition plate certainly prevents any visual information from the device and PC. The right hand, get placed on top of the cover-plate of the tactile presentation device and the arm was supported by elbow stand, located at certain location which can be moved according to the subject's hand's length (Fig 2.11)

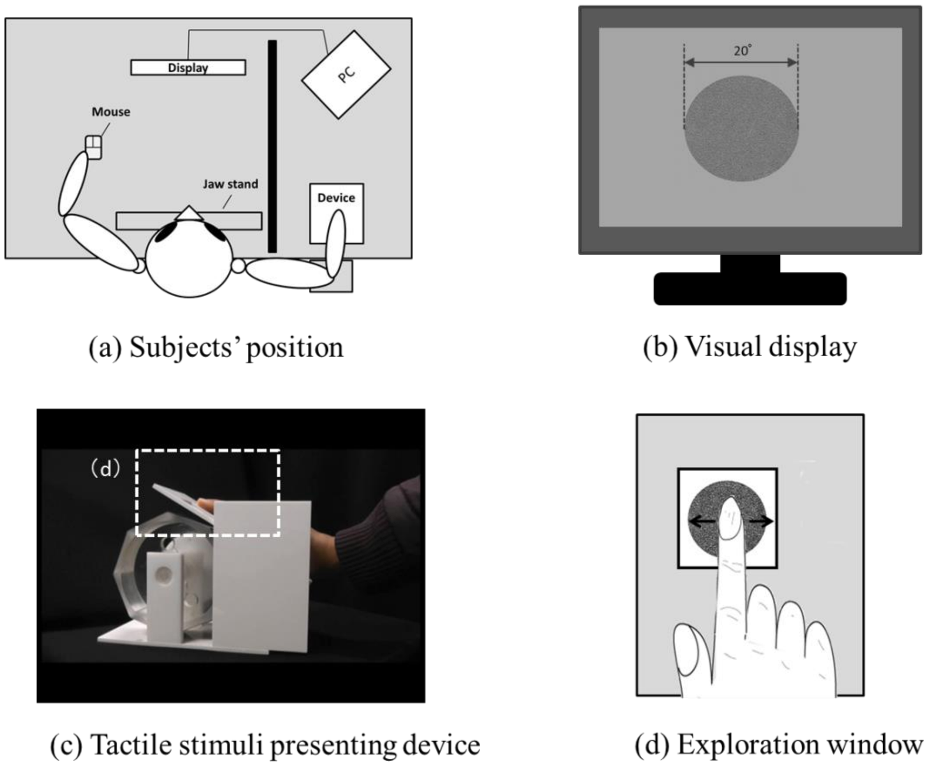


Fig 2.11 Subject's position, visual display, and tactile device (a) Illustration from the top view of the position of subject, display, mouse, and the tactile surface presenting device. Experimenter's computer and the device were distracted from subject's visual range by a partition plate. (b) Illustration of the visual display with 20 degree of angle view (c) Controlled tactile stimuli presenting device which positioned at subjects' right hand. Subject will explore the sandpapers at the exploration window by their index finger, such as in (d).

2.4.3 Procedures

Primarily, the experiment consisted of two unimodal tasks and two bimodal tasks. In unimodal task, subjects only need to perceive whether visually or tactually. Bimodal task is where subjects need to the same task as unimodal, but they were asked to perceive the interference stimulus. Bimodal task furthermore divided into two: one with rough interference stimulus (34μm) and smooth interference stimulus (1.5 μm). The all six tasks are:

1) Unimodal Tactile-only task (T-T)
2) Unimodal Visual-only task (V-V)
3) Bimodal Tactile Task with rough visual interference stimulus (T-Tv-rough)
4) Bimodal Tactile Task with smooth visual interference stimulus (T-Tv-smooth)
5) Bimodal Visual task with rough tactile interference stim-ulus (V-Vt-rough)
6) Bimodal Visual task with smooth tactile interference stimulus (V-Vt-smooth)

Subjects were presented sequentially two times in every trial; initial stimulation is called reference stimulus (RS) and the latter is comparison stimulus (CS). Subjects were instructed whether to look at the display or to explore the textures by sweeping their index finger in determined times with command by the indication stimuli.

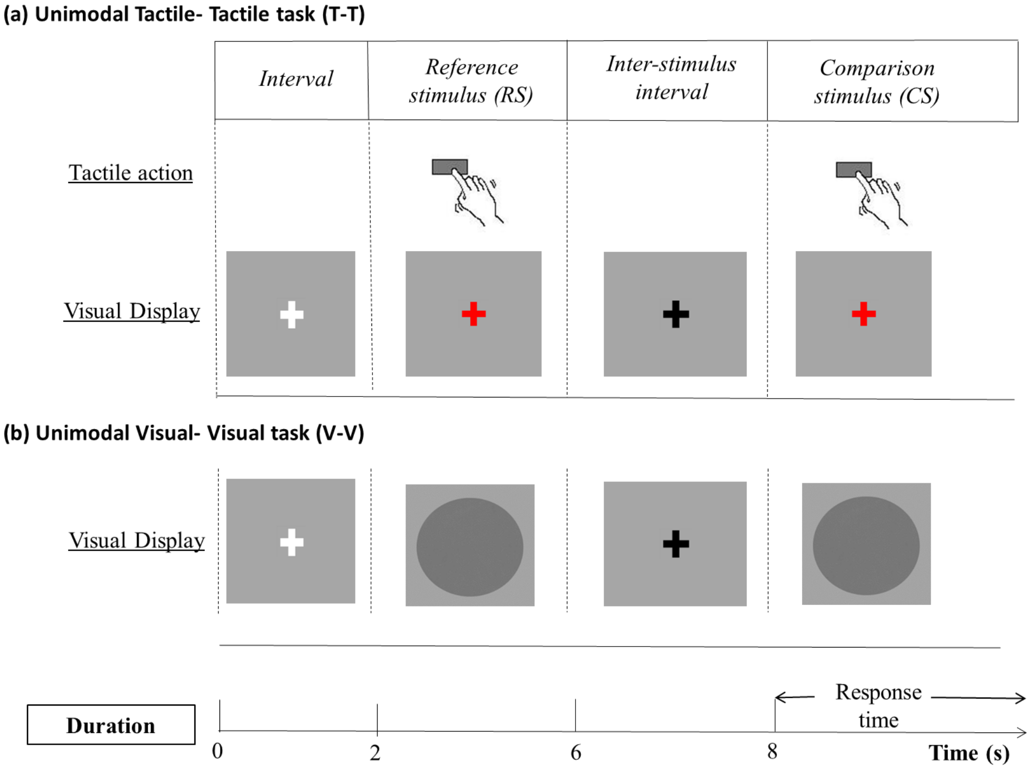


Fig 2.12 Time chart for one trial in the unimodal task of tactile T-T, visual V-V. Separated by two seconds of interval, subjects were presented with the stimuli twice in each task, which are the reference stimulus (RS) and the comparison stimulus (CS). In (a) T-T task, subjects need to explore the RS when the red signal presented before they may explore the CS. Once perceived the roughness of CS, the subjects will response by mouse click and the next trial will begin. In (b) V-V task, subjects performed the same procedures as in T-T task with the visual stimulation. In bimodal task, subjects need to do both task when perceiving CS. After the inter-stimulus interval, subjects need to response whether perceived CS was "rougher", "smoother", or "same" compared to RS, as soon as possible.

In T-T task, subjects need to identify the roughness of two different (or same) tactile stimuli. First, a white visual indication stimulus was presented on the screen for 2 seconds. Next, red visual indication stimulus was presented for 4 seconds. At the same time, tactile RS was presented to subject's right hand and subjects need to explore the stimulus with their index finger. Visual display then presented black inter-stimulus interval stimulus for 2 seconds to make sure the subjects ready for the CS. CS then presented to subjects, and simultaneously the response time was measured. After exploration, subjects needed to compare which explored stimulus were rougher between RS and CS and they needed to click the mouse with their left hand as soon as possible. Left click if CS was "rougher" than RS, right click if CS was "smoother" than RS, and middle click if they feel both roughness was at the "same" roughness. Once the subject response, it is counted as one trial. In V-V task, subject was asked to perform the same procedures as T-T, except they need to perceived roughness based on visual stimuli. In bi-modal T-Tv task, subjects need to identify the roughness of two different (or same) rough nesses of tactile stimuli with exploration of visual interference stimuli at CS. Procedures of V-Vt is vice versa of those in T-Tv. (Figure 2.13)

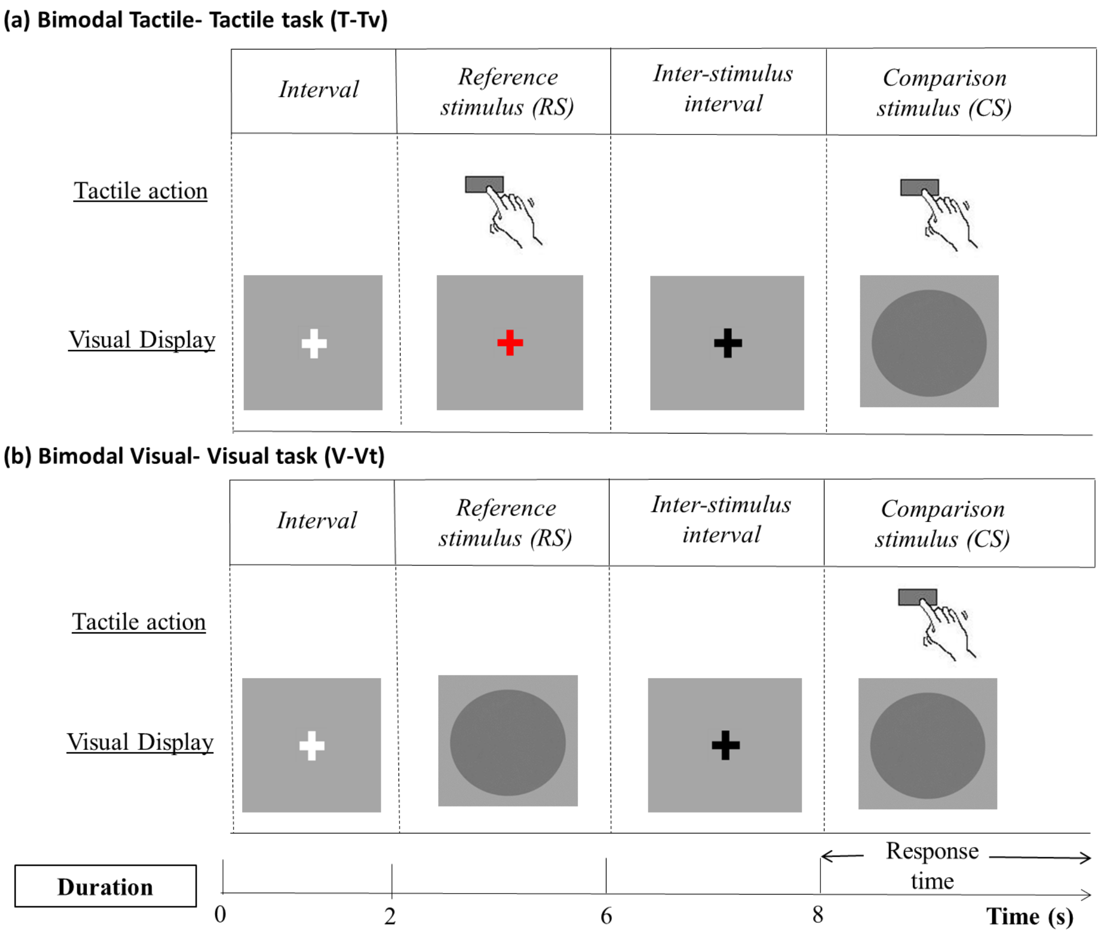


Fig 2.13 Time chart for one trial in the bimodal tactile T-Tv, and bimodal visual V-Vt. In (a) and (b), subjects need to perform the same task as the corresponding unimodal task, except they need to perceive different-modality interference stimulus with CS. The interference stimulus were two types which are the biggest particle 34 μm and smallest stimulus 1.5 μm.

Six types of stimuli were randomized between RS and CS, and all possible 36 combinations involved. Each combination was repeated 10 times in each session over the course of experiment. For unimodal task (V-V, T-T), there are 36 combinations in each task, which totaling 360 trials. For bi-modal task (V-Vt and T-Tv), the total amount of trial are doubled into 720 trials because of involvement of interference stimulus. Time estimated for each trial was about 10 to 15 seconds, depending on task. All tasks were randomized and divided into 6 sessions of 90 minutes to ensure all the subjects to avoid fatigue. Subjects at least had two times of intermission in the 90 minutes' session which was not compulsory. Only one session was carried out per day; subjects need at least 6 days to complete all trials. The experiment was carried out in a dark room to sharpen the perception of roughness visually and tactually.

2.4.4 Data processing and analysis

Each participant's response was analyzed to remove outliers and separate incorrect or double click responses. Reaction time and response distributions for each of the tasks were calculated for each subject. Data were then collapsed across participants and compared using two tasks (tactile and visual) × six CS conditions (six different particle sizes of CS) repeated measures analyses of variance (ANOVAs) in every RS condition (from 1.5, 5.7, until 34 μm; out coming six times of ANOVA per task) to determine if response distribution or reaction time differed by cross modal interaction. The level of significance was fixed at $P < 0.05$ and Bonferroni test ($\alpha = 5\%$) was performed. Post scanning roughness estimates and individual difference in accuracy and reaction time was analyzed in every RS condition that have main effects or significant interaction with CS conditions; in order to verify the validity of the experimental data obtained.

Subjects were forced to make a choice of what they perceived was the rougher of two stimuli, even if they could not detect a difference. The response rate of "same" by subjects were divided into half and were contributed to "rougher" and "smoother" response rate equivalently. As assumption, the guess rate (chance level) is 50% when subject perceive same size of RS and CS. The largest rate of the response "rougher" percentage is 100% and the smallest will be 0% when subject perceived CS is smoother than RS. Therefore, the sigmoid psychometric function changed from 0% to 100%. We also measured the CS threshold for each RS at 25% and 75%. The logistic curve is the most common sigmoid curve used extensively in cognitive psychological experiments for measuring thresholds [11][12][13]. The response rate data was applied to the following logistic function.

$$Threshold = d^{-1}Ln(\frac{1-X}{X})$$

In this equation, d is the unique degrees of freedom of the logistic curve. X is 0.25 or 0.75 when we calculated threshold for each RS at 25% and 75% respectively. All of the analyses were performed using RStudio Desktop version 1.0.136 (RStudio, Inc.) and SPSS version 17.0 (SPSS, Tokyo, Japan)

2.5 Results

The experiment demanded subjects to compare six different RS to six different CS in two unimodal tasks. A round robin of combinations demanded every subject to do 360 trials for each unimodal task. They also needed to do the same task while perceiving the interference stimulus, making it 720 trials for each bimodal task. In this study, we arranged subject's reaction time and response by each RS order, starting from RS 1.5, 5.7, until 34µm. We then performed a two modality (tactile and visual) × six CS conditions (six different particle sizes of CS) repeated-measures ANOVA on the data by each RS. We first checked whether there were any main effects of modality, main effects of CS conditions, or significant interaction between the modality and conditions (modality ×CS conditions) in every RS. In the present study, if there were no significant interaction, we will also consider the main effect of modality before doing the post hoc analysis.

2.5.1 Reaction time

Overall, subjects needed more time to response in tactile task compared to visual task (Figure 2.14). When we compared unimodal tactile and unimodal visual task, there was significance interaction between modality and CS conditions in almost all RS (e.g $F(5,95)=4.534$, $P<0.005$ in RS 1.5µm). This was expected since tactile task need the subjects to touch and perceived the tactile before clicking.

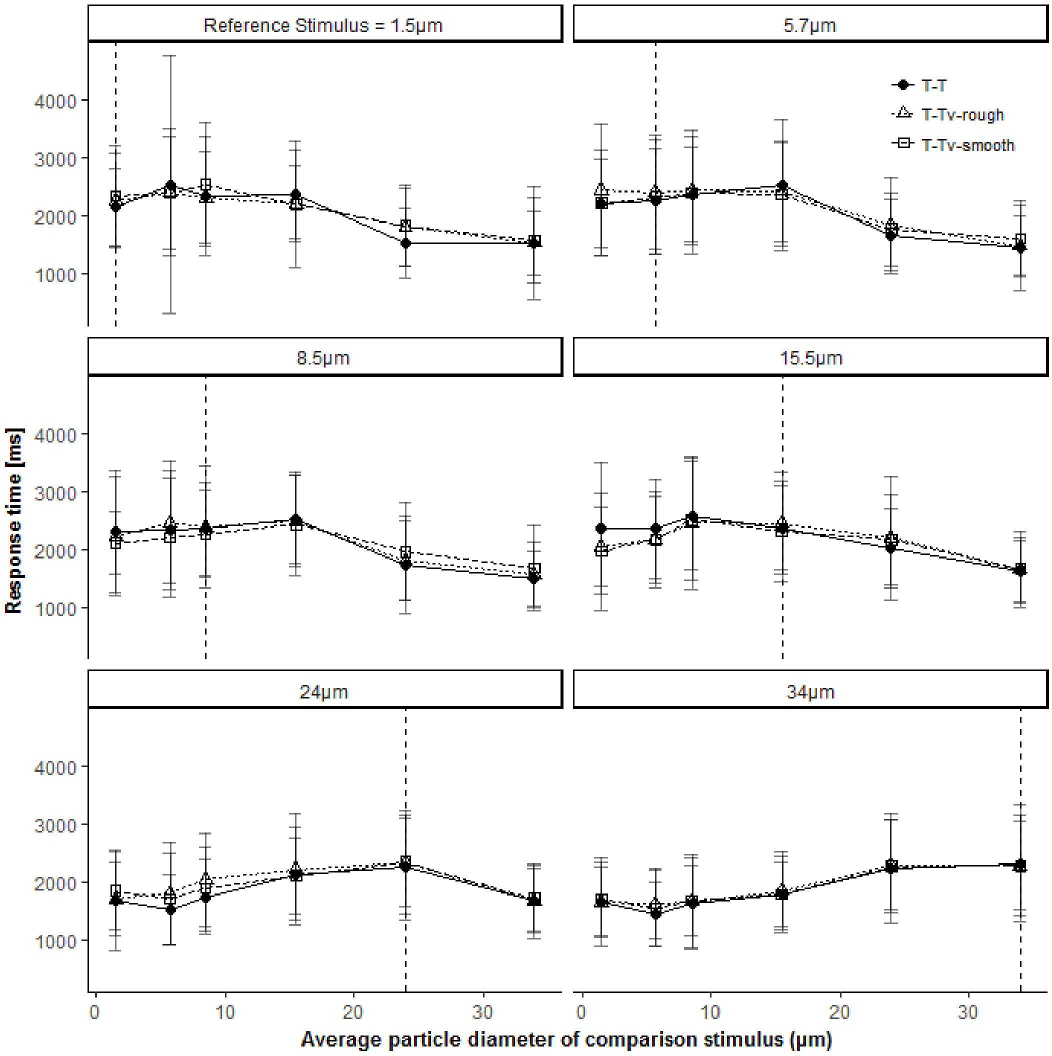


Fig 2.14 Response time and proportion of 'rougher' response between unimodal T-T

However, there were no significant differences of response time within each modality when we compared unimodal and bimodal task. This result showed that subjects can response in almost the same time during the bimodal task and the interference stimulus seems did not restraint the time for subjects to response; even in condition that demand them to perceive stimuli by both modalities. In the present study, we did not concentrate on reaction time for discussion

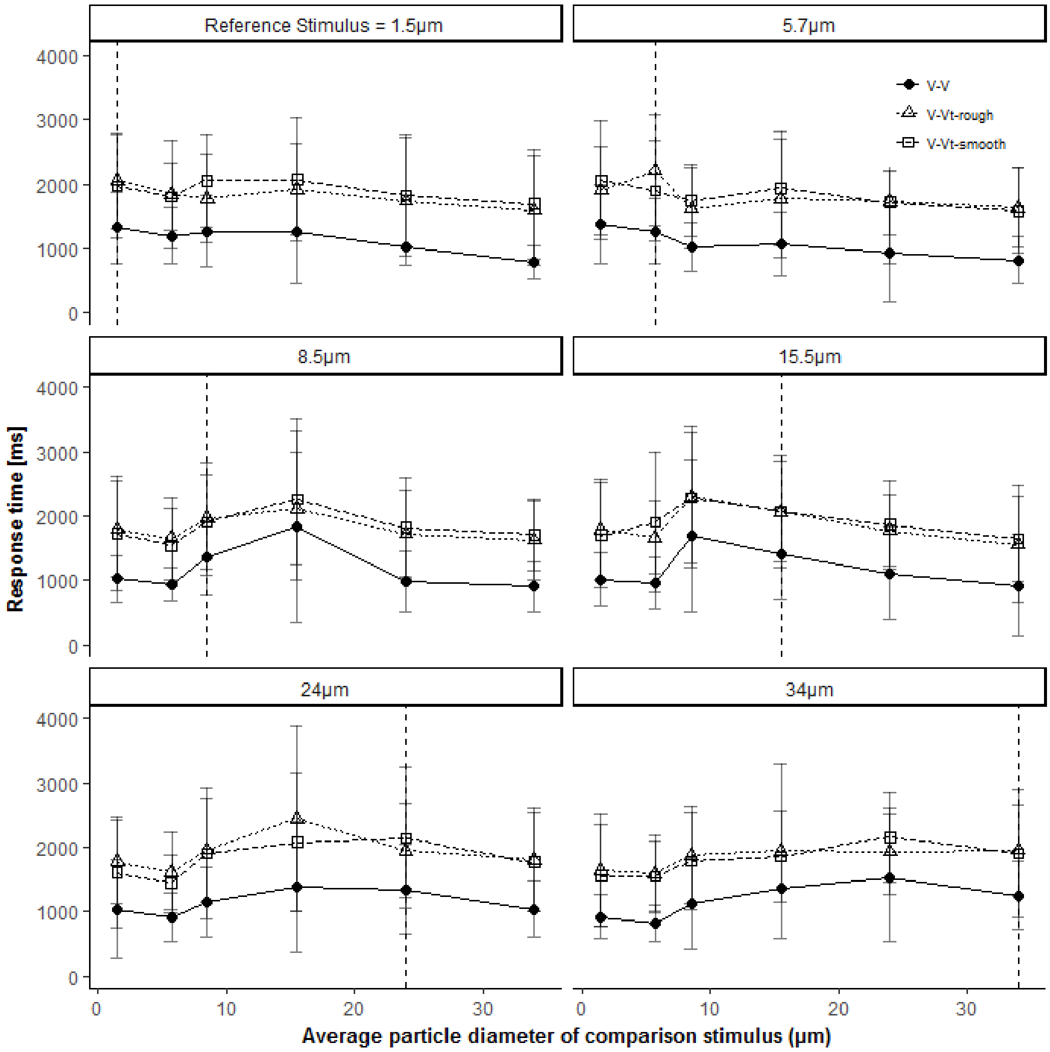


Fig 2.15 Response time between unimodal V-V and bimodal tasks

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2.5.2 Proportion of "rougher" response

Subjects needed to response whether left click, right click or middle click when they sensed CS was "rougher" than RS, "smoother" than RS, or the "same" roughness, respectively We analysed the response distributions of every subject in order to find any kind of effects that generated during bimodal task; visually or tactually. The proportions of "rougher" response by subjects in every task were analysed and we separated them according to RS and CS in order.

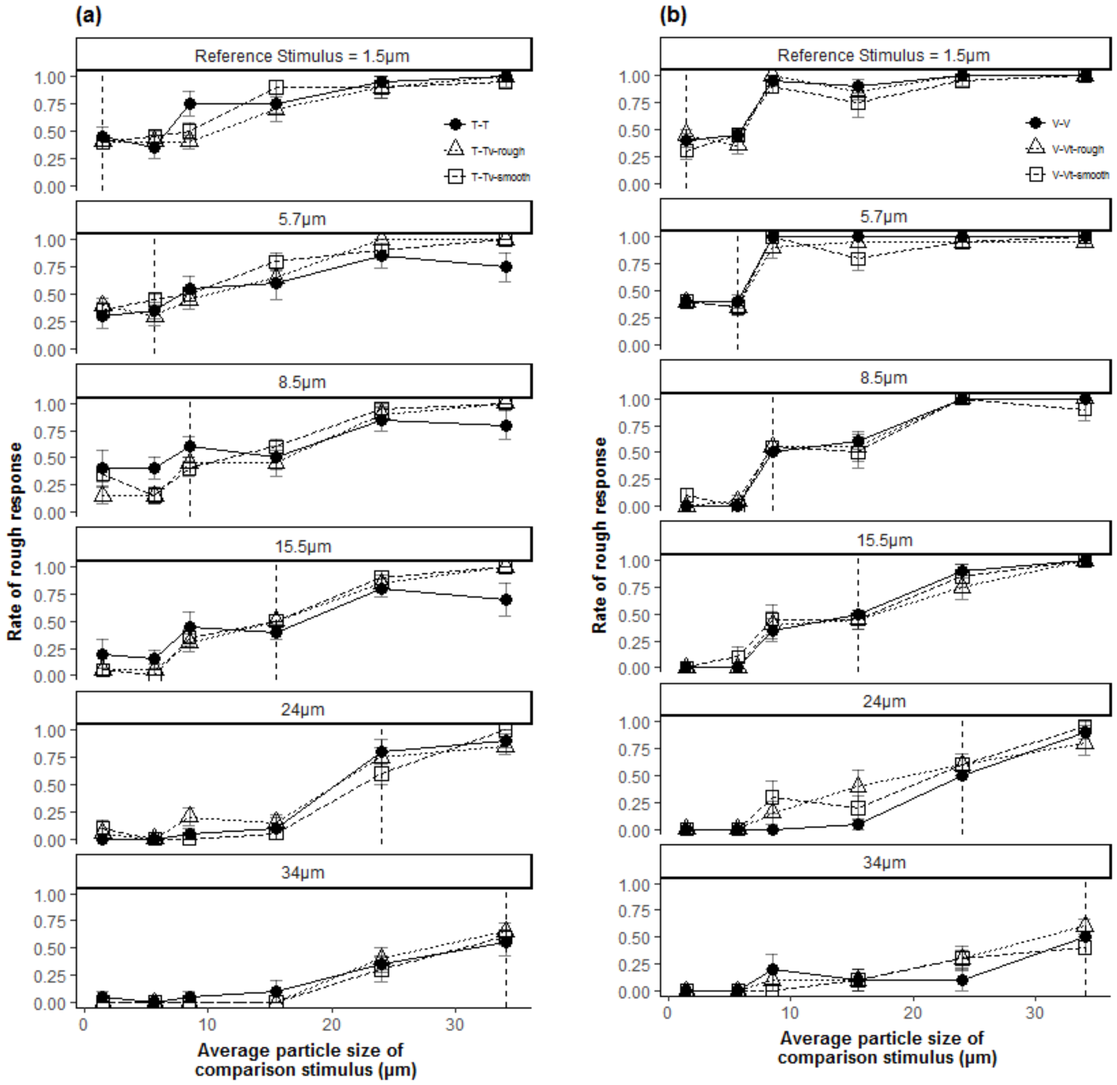


Fig 2.16. Individual results of (a) tactile task and (b) visual task.

The rates of the response "rougher" as a function of the particle size of the tactile CS are plotted in Figure 2.16 and Figure 2.17b. RS for each CS are arranged vertically in ascending order from 1.5 to 34μm.

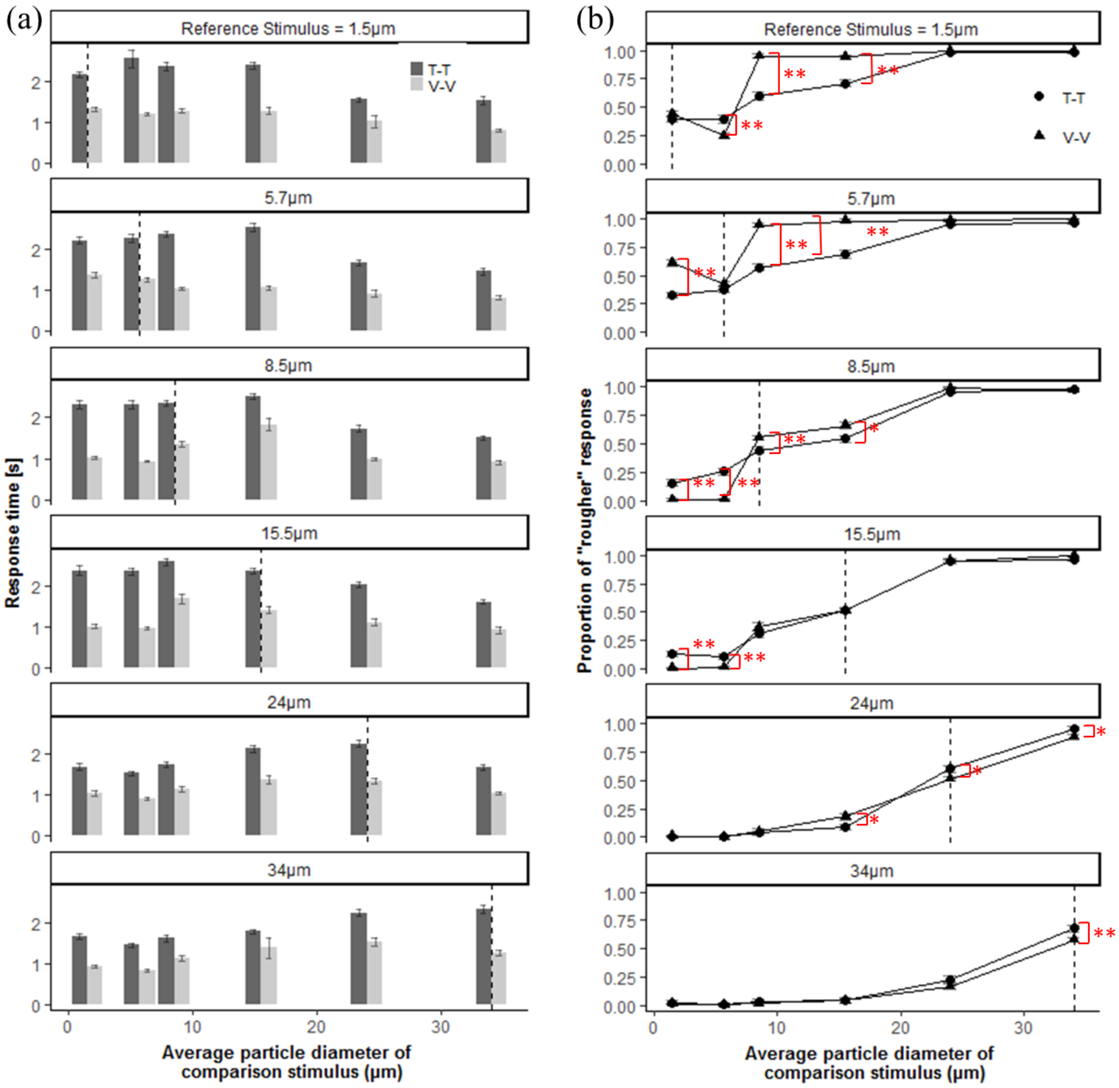


Fig 2.17 Response time and proportion of 'rougher' response between unimodal T-T and unimodal V-V. In (a), subjects needed more time to response in tactile tasks. In (b), roughness tendency were more to visual when the RS is below 8.5 μm, but more to tactile after RS of 15.5μm and above.

To show the difference between tactile and visual rough-ness perception, we compared the proportion of "rougher" response in the unimodal T-T to those in V-V task (Figure 2.17b). Overall, subjects tend to differentiate between smooth and rough excellently when RS and CS are not similar (e.g. 1.5 vs 34, 1.5 vs 24). We performed a two modality (tactile and visual) × six CS conditions (six different particle sizes of CS) repeated-measures ANOVA on the proportion of "rougher" response for each RS. We found significant main effect on modality [$F(1,99)=37.54$, $P < 0.001$ in RS 1.5μm] and significant main effect on CS conditions [F(5,95)=428.09, P < 0.001 in RS 1.5µm]. We also found a significant interaction between the modality and CS condition [F(5,95)=26.77, P < 0.001 in RS 1.5µm]. We made a post hoc comparison using Bonferroni correction and we focused on where there were significant difference between modalities on each comparison of RS and CS (asterisk in Fig 4). The post hoc comparison revealed that "rougher" response rate of V-V were significantly higher than those in T-T for RS of 1.5 until 8.5 µm. Interestingly, the opposite phenomenon can be seen from RS of 15.5µm as T-T were significantly higher than those in V-V, except for the comparison of 24µm and 15.5µm.

In order to understand the consequences of cross modalities between tactile and visual, we analyzed the difference between unimodal task and bimodal task, separately by respective modalities. Applying same method as previous paragraph, we highlighted the proportion of "rougher" response in unimodal and separately compared to the two corresponding bimodal task. In tactile, there were one condition with main effects when we compared T-T with T-Tv-rough (Figure 2.18a) and another three conditions when we compared T-T with T-Tv-smooth (Fig 2.18b). In Fig 2.18a, post-hoc analysis showed that rough visual interference stimulus made subjects tend to feel the same stimulus to be tactually rougher than origin (unimodal) perception. On the other hand, smooth visual interference stimulus affects subject's roughness perception with random pattern.

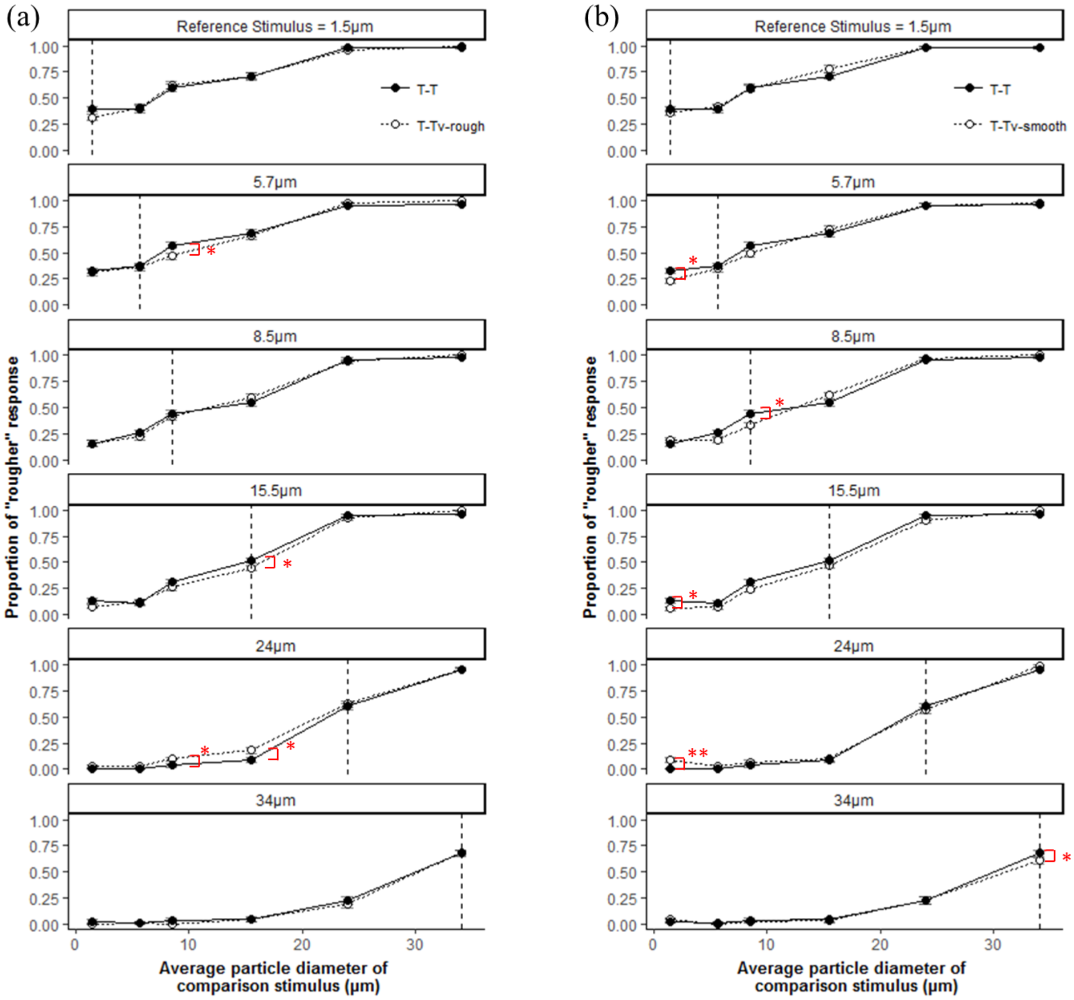


Fig 2.18 Proportion of 'rougher' response between unimodal T-T and bimodal T-Tv-rough and unimodal T-T and bimodal T-Tv-smooth. Bold areas (RS 24μm in (a), 8.5, 15.5, 24μm in (b)) are RS with main effects or interaction between the two tasks and CS conditions. Multiple comparisons showed that in (a), rough visual interference stimulus made subjects tend to feel the same stimulus to be tactually rougher than actual (unimodal) perception. In (b), smooth visual interference stimulus affects subject's roughness perception with random pattern.

Dissimilarly to tactile task, we detected even more conditions with main effects caused by tactile interference stimulus in visual task. As showed in Fig 2.18a, four conditions with main effects were spotted when we compared V-V with V-Vt-rough. Multiple comparisons in each RS and CS combinations showed that subjects tend to perceive rougher in bimodal rough task. Furthermore, we so identified all conditions with main effects with most of post hoc analysis recorded p-value less than 0.005 between V-V and V-Vt-smooth (Fig 2.18b). Overall, rough and smooth tactile interference stimulus affects subject's roughness perception randomly in visual tasks.

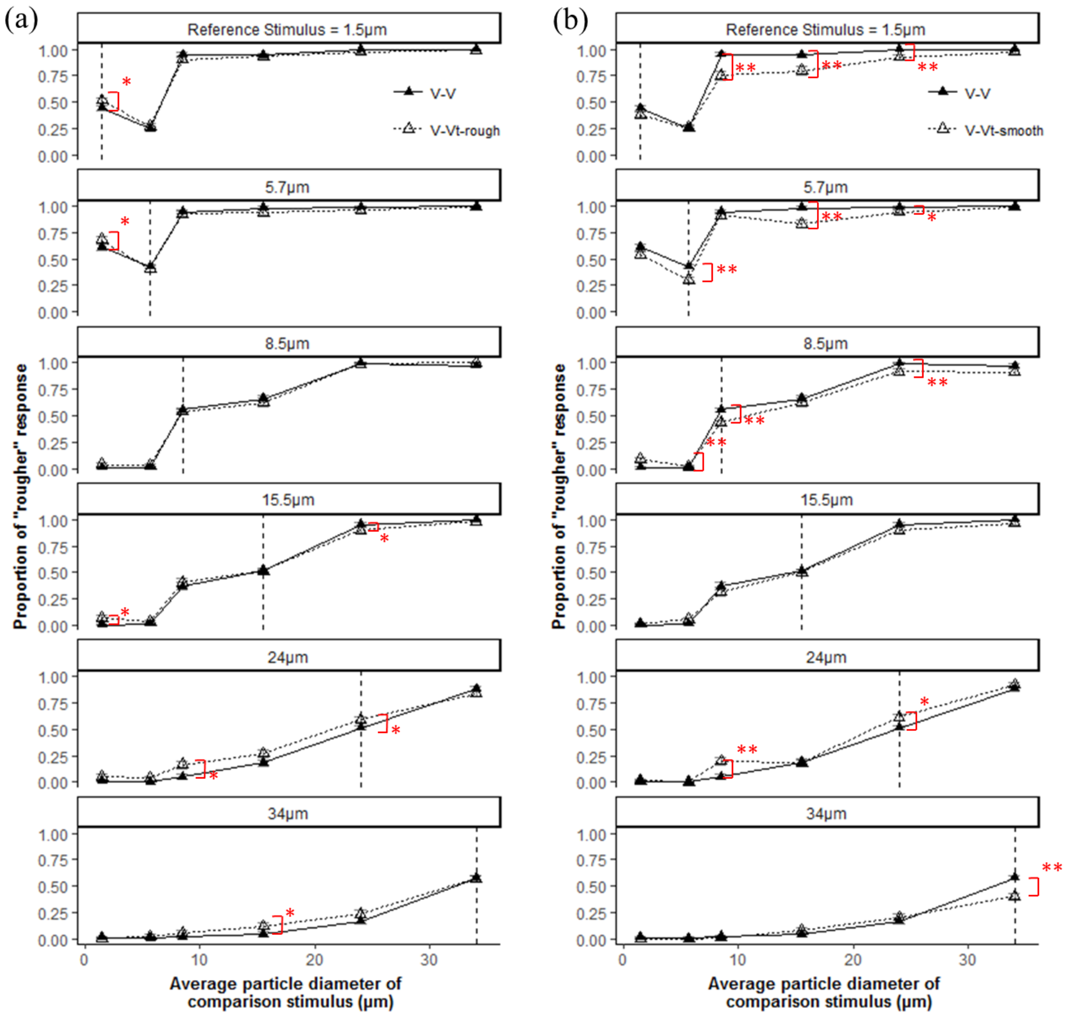


Fig 2.19 Proportion of 'rougher' response between unimodal V-V and bimodal V-Vt-rough and unimodal V-V and bimodal V-Vt-smooth. Post-hoc multiple comparison showed significant difference was detected in more pairs of RS (bold area) compared to those in unimodal and bimodal tactile task. Moreover, far notable amount of significant difference was found in (b) rather than (a). Overall, rough and smooth tactile interference stimulus affects subject's roughness perception randomly.

To understand the reason of significant differences be-tween modalities, we analyzed and evaluated six stimuli that we used in this study. According to Weber's Law, the ratio of the increment threshold to the background intensity is a constant. Applying this law, we calculated the 25% and 75% threshold of CS for each RS in every task, find the middle point, and divide by corresponding RS.

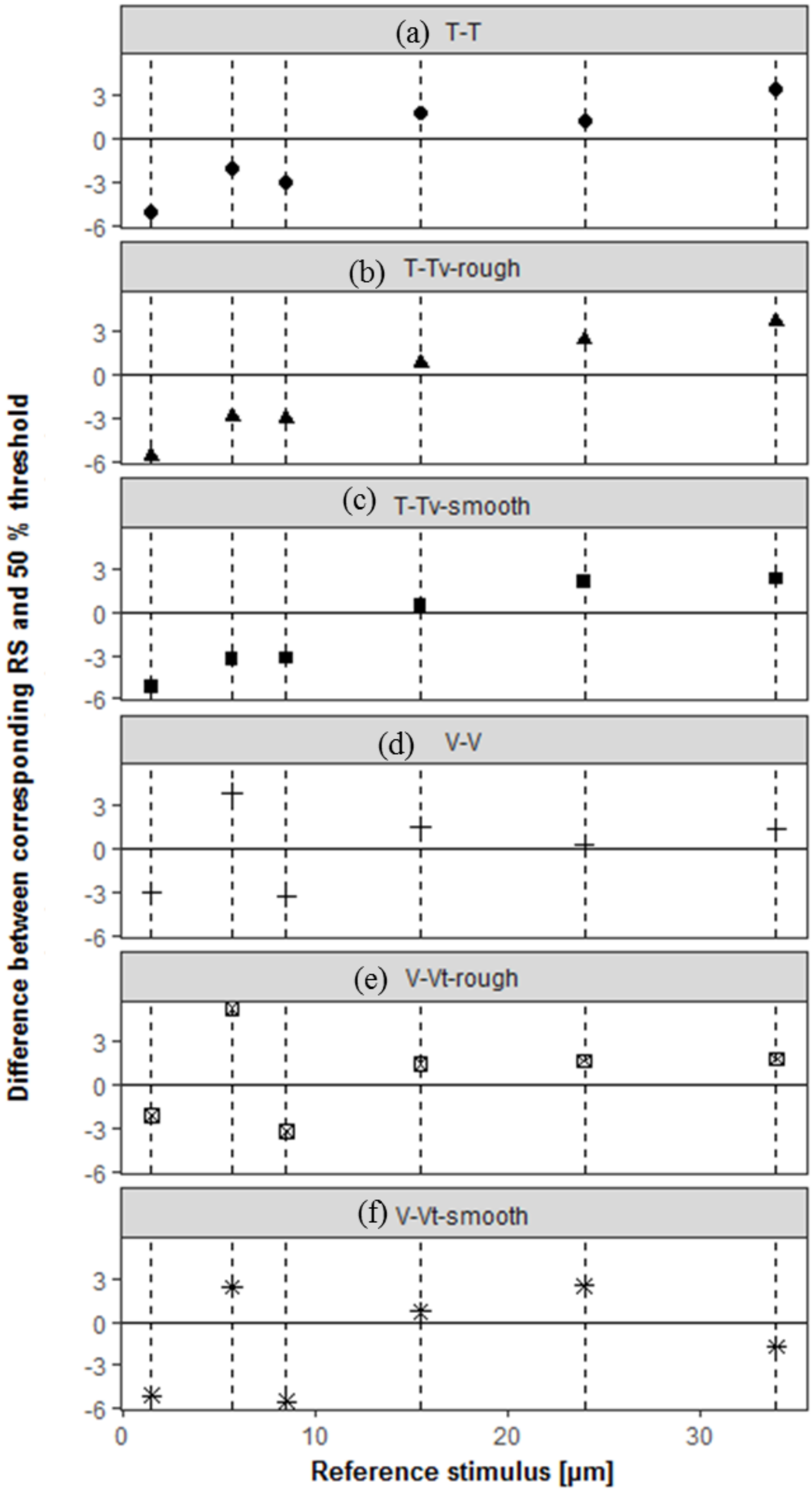


Fig 2.20 For example, in T-T task, with a reference of 1.5μm, subjects need CS of approximately 5μm to eventually perceive it as the same roughness. In this figure, small particle (1.5, 5.7 μm) showed greater value compared to others in each task

The outcome constant number showed the Weber's constant which is the increment threshold of each RS to perceive the same size of CS (e.g. RS 8.5 and CS 8.5). As showed in Fig 7, all six tasks showed the same pattern; high constant of small particles and very low constant in big particles (from 15.5µm). As an example, in T-T task, to compare with reference stimulus of 1.5 µm, the increment threshold that subjects needed were 5.1 to perceive CS of 1,5µm.

2.6 Discussion

We were interested to explore the mechanism inside tactile, visual and the interaction between them in the perception of roughness using fine textures. By designing two unimodal tasks and four bimodal tasks accompanying both modalities, we expected to understand more about how humans perceive roughness in behavioral level of tactile and visual

2.6.1 Tactile dominant roughness perception of fine surface

The comparison of unimodal tasks (T-T and V-V) in our study suggested that roughness comparison was related to the spatial properties of the surfaces. We focused on combinations where subjects need to compare CS that was larger than the RS, where subjects were presented CS that were rougher than comparison (right side of reference line in Fig 2.17b, 2.18, 2.19). We detected that subjects perceived a surface rougher visually when the RS is small, but perceived rougher tactually when the RS is bigger (Fig 2.17). This phenomenon can be clarified as the RA (rapidly adapting) and PC (Pacinian corpuscle) afferents in the skin were considered to encode temporal variations related to different surfaces, and the subjects could use the temporal features to reach their final decision regarding their perception. Two factors that can be considered to determine the human perception of haptic roughness are the spatial properties and the temporal properties by touch [5][14][15]. Surfaces with small particles may generate high temporal frequencies, which led the subject to perceive a smoother surface tactually. Bensmaia et al [7] also stated that the perception of surface larger than 200µm was encoded by the spatial and temporal properties that were dominant in the haptic perception of fine surface roughness. In the present study, subjects' roughness estimation almost showed particle size dependence, therefore led the subject to perceive a smoother surface.

While in visual, the perception of visual roughness is a complex process that may generate more complex neural activations, which much depends on the direction of illumination, viewpoint, and the shadow [9][16][17]. Even we con-trolled the average luminance of all visual stimuli, small particles might give little information to subjects compared to other factors as the visual texture perception mainly focuses on the ability to different distributions of properties such as brightness, size, color, or slope[18].

2.6.2 Influence of interference stimulus in each other modality during cross modalities

How multisensory information is integrated from different modalities and accommodate in brain is still unclear. The bimodal tasks that we composed into present study were carried out in order to find if there is any type of acceleration or suppression in either accuracy rate or reaction time during the appearance of another sensory in a single sensory task. These experiments demanded participants' ability to make quick and accurate discriminations between multisensory stimuli.

Our results suggested that in bimodal sensory tasks, both visual and tactile tasks roughness perception were influenced, although in different volume. Visual sensory receive a big impact when cross modality occurred from tactile information, more than tactile sensory received. This can be explained by behavioral evidence by Klatzky et al [19] that indicated surface roughness is particularly salient to the tactile sense. On the contrary, we suggest that tactile sensory receiving little effects from visual information when two sensory are working. This may suggest that information encoded across vision and touch may not transfer efficiently across modalities, but we proposed tactile to do the "job" better than vision does.

Moreover, subjects needed more time to response in tac-tile task compared to visual task, but we found no significant differences of response time within each modality when we compared unimodal and bimodal task. This result showed that subjects can response in almost the same time during the bimodal task and the interference stimulus seems did not restraint the time for subjects to response; even in condition that demand them to perceive stimuli by both modalities. In the present study, we did not concentrate on reaction time for discussion but we did observe a trend for reductions in the magnitude of the performance decrements under bimodal tasks, but such changes were quite small in tactile. However, things were different in visual task. As roughness is recognizes as an important perceptual dimension of texture, this result supports the study by Guest et al [20] which stated the dominance of tactile in texture perception. Moreover, these may suggest that both modalities information processing may not be excellently integrated and dependently different across them.

2.6.3 "Smooth" and "rough" in fine textures

Katz in his review [3] noted that spatial features under 100 μm have different mechanism for perceiving haptic roughness. In the present study, we can divide fine textures into two types, the smoother group (1.5, 5.7, 8.5 μm) and coarser group (15.5, 24, 34 μm). Comparing unimodal tasks directly showed us that subjects perceive the smoother and coarser group differently. This difference showed the importance of spatial features for tactile roughness perception but also challenged on how subjects perceive visually. We suggest that even in spatial features under 100μm, the perception of haptic roughness might diverse in small particle recognition where visual is dominant.

In addition, by looking for type of acceleration or suppression in direct comparison with rough and smooth bimodal tasks, we found that smooth interference stimulus (1.5μm) played a big role to interfere with subject's perception. In Figure 2.21, small particle has big Weber's constant in every tactile and visual task. Subjects need more "roughness" to match two visual or tactile stimuli with small particles textures (1.5, 5.7 μm) rather than big particles (8.5, 15.5, 24, 34 μm). By touch or by visual, small particle such as 1.5μm have big "noise" during recognition caused the subjects to confuse during perceiving interference stimulus. The lack of evidence of better performance in bimodal relative to unimodal conditions may be due to different information encoded in each modality and the "noise" might affect the relative dominance of each modality to the percept.

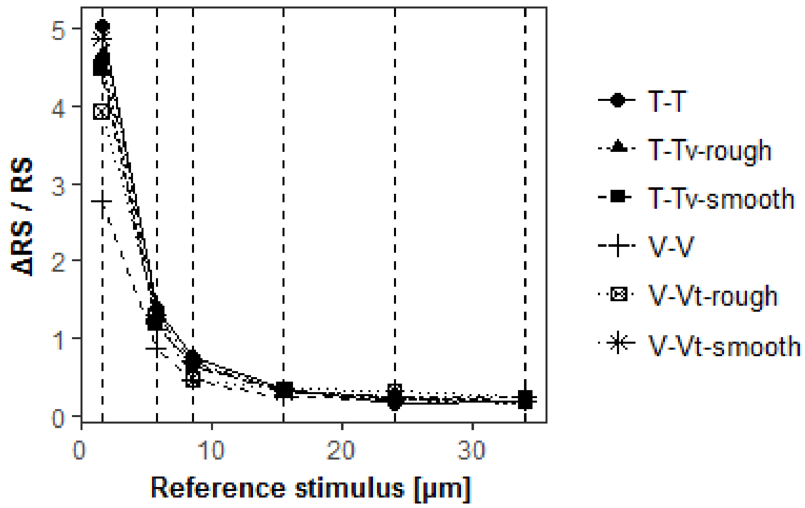


Fig 2. 21 Weber's constant (refer: Weber's law) of each RS within every task. We define the outcome Weber's constant here as the increment threshold of each RS to perceive the same size of CS (e.g RS 8.5 and CS 8.5). For example, in T-T task, with a reference of 1.5µm, subjects need CS of approximately 5µm to eventually perceive it as the same roughness. In this graph, small particle (1.5, 5.7 µm) showed greater value compared to others in each task

Vibrotaction of small particles may be the best explanation for the "noise" in tactile tasks. In tactile, fine textures are well acknowledged to be perceived by vibrations evoked on the skin during exploration [2][21], but relied on the amplitude Sandpapers with small particles that we used in the present study might yields a great amplitude across the fingertip compared to the coarser group. Moreover, despite most of previous studies give less attention to the role of vision in roughness perception and most claimed that these modalities encode in separate manner, we found visual stimuli in present study have the same tendency as those in tactile stimuli. However, the fact bimodal tasks were not accelerated nor suppressed the "noise" compared to unimodal tasks suggest that the roughness information encoded differently in each modality.

2.7 Conclusion

In many situations, stimuli from different sensory modalities will likely convey non-matching information, potentially impairing the ability to process one or more of the stimuli. One common example of this situation occurs during a telephone conversation, when it is highly not probable that the visual stimuli in your environment counterpart the auditory stimuli of the telephone conversation.

These experiments demonstrate the two modalities influence each other during roughness perception of fine surface. We were interested to explore the mechanism inside tactile, visual and the interaction between them in the perception of roughness using fine textures. By designing two unimodal tasks and four bimodal tasks accompanying both modalities, we expected to understand more about how humans perceive roughness in behavioral level of tactile and visual. The experimental results are summarized as follows;

1) Tactile dominant roughness perception of fine surface
2) In bimodal sensory tasks, both visual and tactile tasks roughness perception were influenced, although in different volume.
3) Smaller particles give more influences to accelerate or suppress roughness judgement in each other modality

Chapter 3 Neural mechanisms of Roughness Perception by Tactile Visual Cross-modal dot pattern

Abstract

Human sensations always involve in interaction, but a lot of brain's response during the interaction is still unknown. This study was designed to discover the unresolved part of the brain during performing visual and tactile interaction roughness recognition experiments. We intended to measure the peak value of roughness recognition during the behavioural experiments, but it was not possible to obtain the peak value. For this study, we measured brain activity using fMRI. We designed four types of tasks: visual task (VV), tactile task (TT), visual - tactile task (VT), tactile - visual task (TV). The common area of each of the brain activation during each task was analysed; and the results showed that activations located in the frontal and parietal, suggesting these regions were actively involved in the cross-modal processing. Specific activation for the information from the tactile and visual modality was seen in the frontal and parietal lobe, respectively, suggesting the particular activation in each at this region.

3.1 Introduction

Humans need to be able to differentiate surface qualities of objects not only by touch but also visually. This is important for object recognition and for the interaction with objects in our environment[22]. Behavioural studies showed that both haptic and visual information add to texture perception [23] and that a cross modal transfer of texture information between both sensory modalities occurs[24].

Several neuroimaging studies focused on texture matching and discrimination [25][26][27][28] [29][26] as well as on different dimensions of texture perception within the tactile and visual modality; examples include spatial density [30] [31], spatial orientation [32][31];) and roughness [33][30] [34] [35][36] . Most of the tactile studies states the importance of the parietal operculum and the posterior insula [27][34] [35][36] [37] for processing surface textures, while studies focusing on visual texture perception often report regions near the collateral sulcus, the lingual gyrus and areas in early visual cortex[25][38] [39][40] [28][37] [29]

A recent approach by Hiramatsu et al [41] investigated how visual material properties are coded in the cortex along the ventral visual pathway. A similar distributed network was described by Sathian et al [29] for the processing of haptic texture information. In connectivity analyses Sathian and colleagues showed a flow of texture information from task-non-selective regions of the postcentral gyrus to texture-selective areas in the parietal operculum and further to regions of the middle occipital cortex. Despite the pure tactile stimulation in many paradigms, consistent visual cortex activation was reported in several of these studies[42] [36][37].

All of the studies that have been mentioned discussed texture perception in separate visual and haptic paradigms. The effect of simultaneous visual and haptic exploration of textures perception has been mostly ignored. An overlap of visual and haptic texture representations in some brain areas can be expected, but interaction between visual and haptic information in the regions were not anticipated. The imaging study by Sathian et al [29] might give the first idea. Behavioral studies also indicate the existence of such crossmodal interaction and matching effects in visuo-haptic tasks. It was shown that people consistently and absolutely match specific tactile vibration rates to visual spatial frequencies [10] indicating some kind of crossmodal association effect in visual and haptic texture perception. Additionally, simultaneous tactile stimulation can disambiguate binocular rivalry, a process in which two equally salient but dissimilar monocular stimuli are presented to corresponding retinal locations [43].

The main objective of the present chapter was to investigate texture perception in a paradigm that combines visual and haptic input in a single condition in order to explore crossmodal interactions at the cortical level. Cross modality effects are different according to individual and the effects activated by it are also believed to be various. In this study, we expect to find the characteristics of those effects related to the cross modal of tactile and visual, during the perception of roughness. We would expect these crossmodal effects already in early sensory cortices, e.g. postcentral gyrus and posterior occipital cortex[44] [41] [42] [29] [37], but perception-related differences rather in higher-order cortical regions, the parietal operculum and the insula [40][41][34]. Occupying on earlier studies we assumed roughness perception by haptic to be correlated with the dot spacing [45][46].

3.2 Experimental stimuli

In this study, we outlined two types of stimuli throughout the experiment; tactile stimuli and visual stimuli. Along with these stimuli, we also arranged the indication stimuli which functioned as the instructor for the subjects. The indication stimuli make sure that a smooth and continuous experiment can be performed.

3.2.1 Tactile stimuli

Tactile stimuli consisted of five types of different acrylic plates which embossed with different dot patterns. Deliberately, the tactile roughness is exactly the same with the correspondence visual stimuli. Each plate is 50.0mm length and 40mm width, which sums the surface area of the stimuli to 20 cm^2. The dots were arranged periodically. The dots are 0.6mm high and diameter of 0.8mm.

Index finger of the right hand of subjects contacted with the tactile stimuli. Figure 3.1 is the samples of tactile dot patterns that we used during examination. The inter dot spacing ranged from 1mm to 9mm, in steps of 2mm. The stimuli were manufactured by machining equipment of Okayama University.

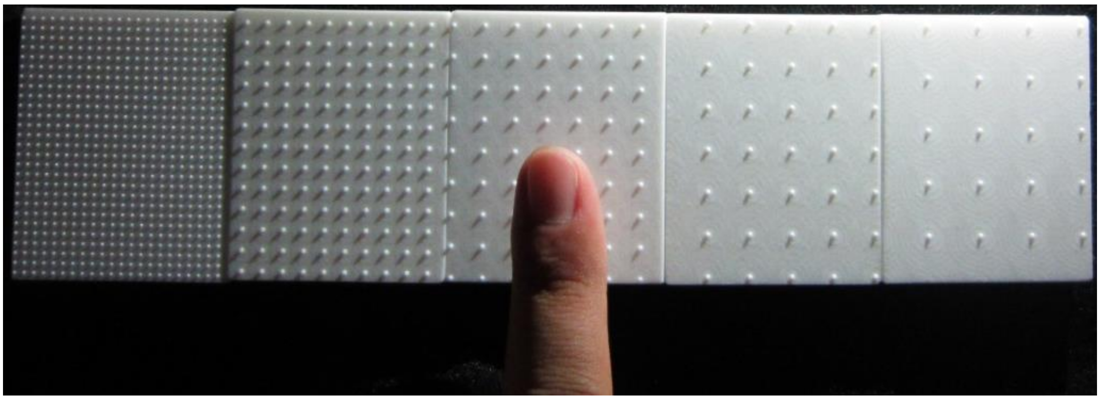


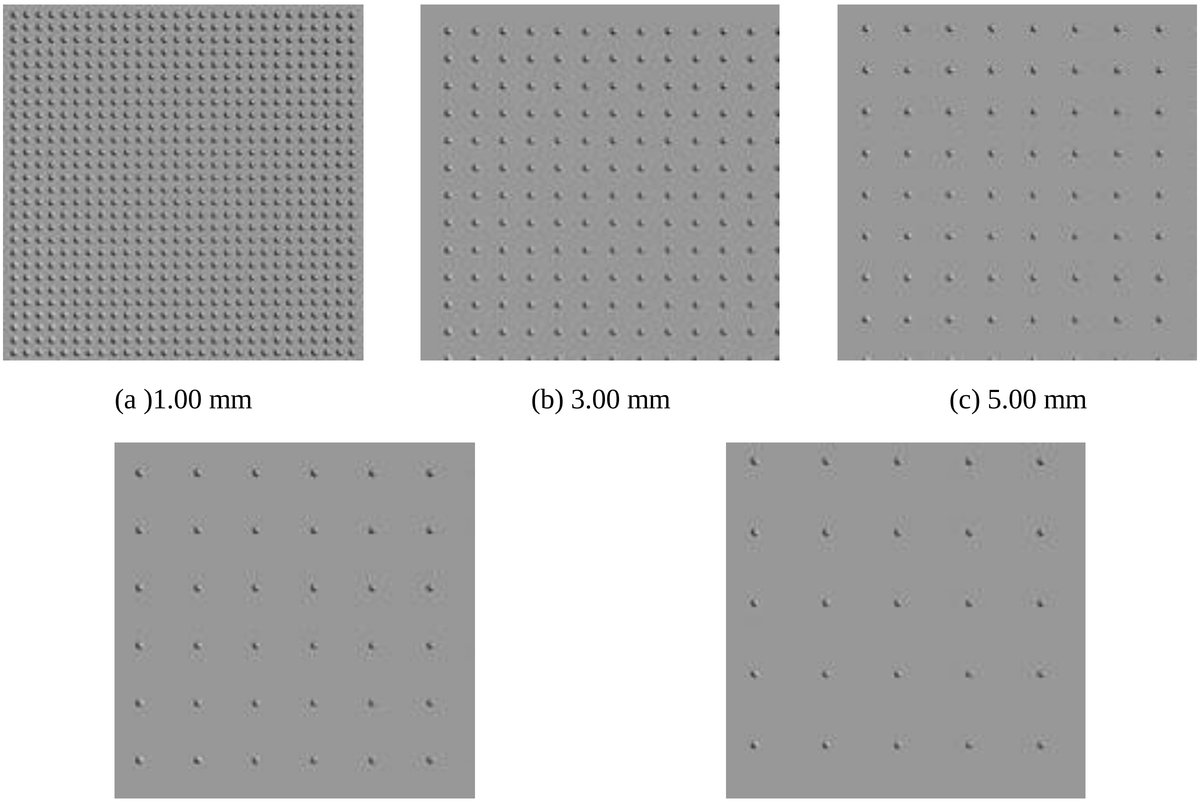
Fig 3.1 Samples of tactile stimuli

Table 3.1 Samples of tactile stimuli

Stimulus	1	2	3	4	5
Inter-dot spacing mm()	1.00	3.00	5.00	7.00	9.00

3.2.2 Visual stimuli

We used dot patterns with the same inter-dot spacing as tactile stimuli for all types of visual stimuli. The brightness of grey scale was fixed into one scale. Distance of presented visual stimuli from computer's display to subject's face is 500mm, and the visual scale is exactly the same with the correspondence tactile stimuli. The circles were presented on a grey screen.



(a)1.00 mm (b) 3.00 mm (c) 5.00 mm

(d) 7.00 mm (e) 9.0 mm

Fig 3.2 Five samples of visual stimuli

3.2.3 Visual indication stimuli

To maximize the smoothness of presentation of tactile and visual stimuli, we designed an automated experimental system for maximum smoothness during fMRI experiments. For this reason, we designed the visual indication stimuli. In this chapter, these stimuli can be divided into four types with four colors. The four colors indicating four different types of instructions. For every task whether it is visual or tactile task, subjects will be presented three times. The initial stimulus is the Reference Stimulus while the secondary stimulus is the Target Stimulus.

As shown in Figure 3.3, visual indication stimuli are four types of cross symbol (+), presented in the center of display, with 17.5mm size at 2 ° central angle. In what is shown, white cross symbol indicates the initial stimulus will be presented in a little while and the subjects need to prepare. Blue and green cross symbols are signs or reminder for subjects to explore the tactile stimulation (dot stimuli). Lastly, red cross symbol is a sign or reminder for subjects to response their answer with the response button. Blue and green indicators will only be presented during presence of tactile stimuli. Figure3.3 shown is the visual indication stimuli in an enlarged view which was used.

(a) White indicator (b) Red indicator (c) Blue indicator (d) Green indicator

Fig 3.3 Visual indication stimuli. From left: white (before Reference Stimulus presented), black (before Comparison Stimulus presented), and red (contact with tactile stimulation)

Besides, to avoid subject confusion during experiment, we designed another two types of visual indication stimuli. The experiment was carried out randomly within four tasks. Thus, subjects need to be aware of the type of forthcoming stimuli, whether it is visual or tactile stimulation. Before the presentation of visual/ tactile stimuli, two Japanese characters which defined "visual" and "tactile" were presented to subjects for two seconds.

(a)Indication stimuli before visual stimuli presentation

(b) Indication stimuli before tactile stimuli presentation

Fig 3.4 Pre-visual and pre-tactile indication stimuli.

3.3 Experimental setup

3.3.1 Pre experiment

Before the main experiment, we held a pre experiment to verify each stimulation. A roughness measure was used in the experiment. Subjects needed to place their right hand at the tactile stimulation, and their left hand need to estimate the roughness by using the measure.

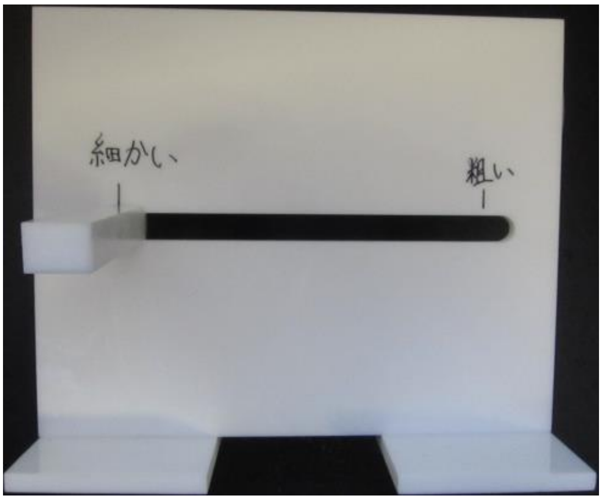


Fig 3.5 Six types of scanned sandpapers used in all task involving visually displayed stimuli. Numbers represented the average of particle sizes of each.

3.3.2 Functional MRI experiment

Since MRI uses strong magnetic fields around the head of the subject within a narrow tunnel, any device used concurrently with MRI must be free of ferromagnetic elements and not interactive with the magnetic field. Therefore, we used plastic to build the tactile stimuli and experimenters who deliver the tactile patterns. Figure 3.7 illustrates the tactile presentation system. In case of an emergency, we will stop all activation. During functional MRI experiments, the experimenter will guide the subjects in the MRI room once the scans have started. Subjects can be easily modified to move their finger along the tactile dot stimuli.

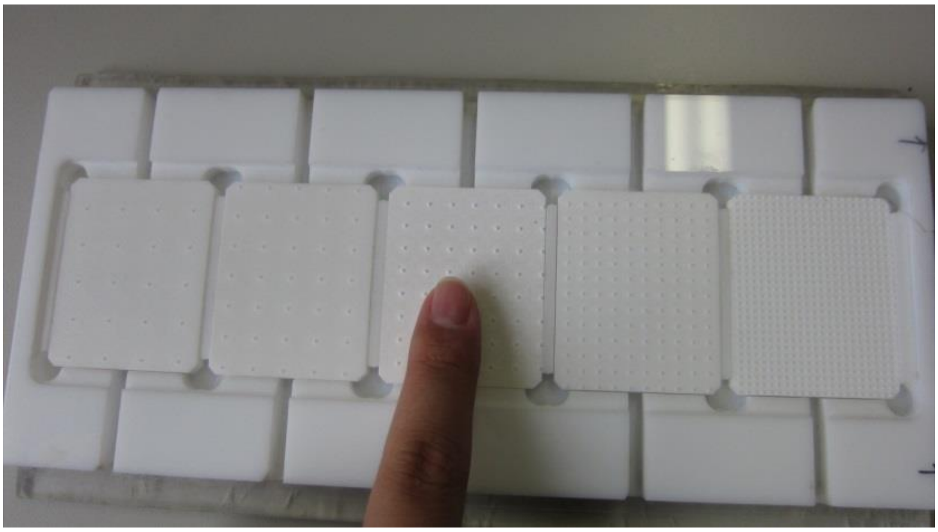
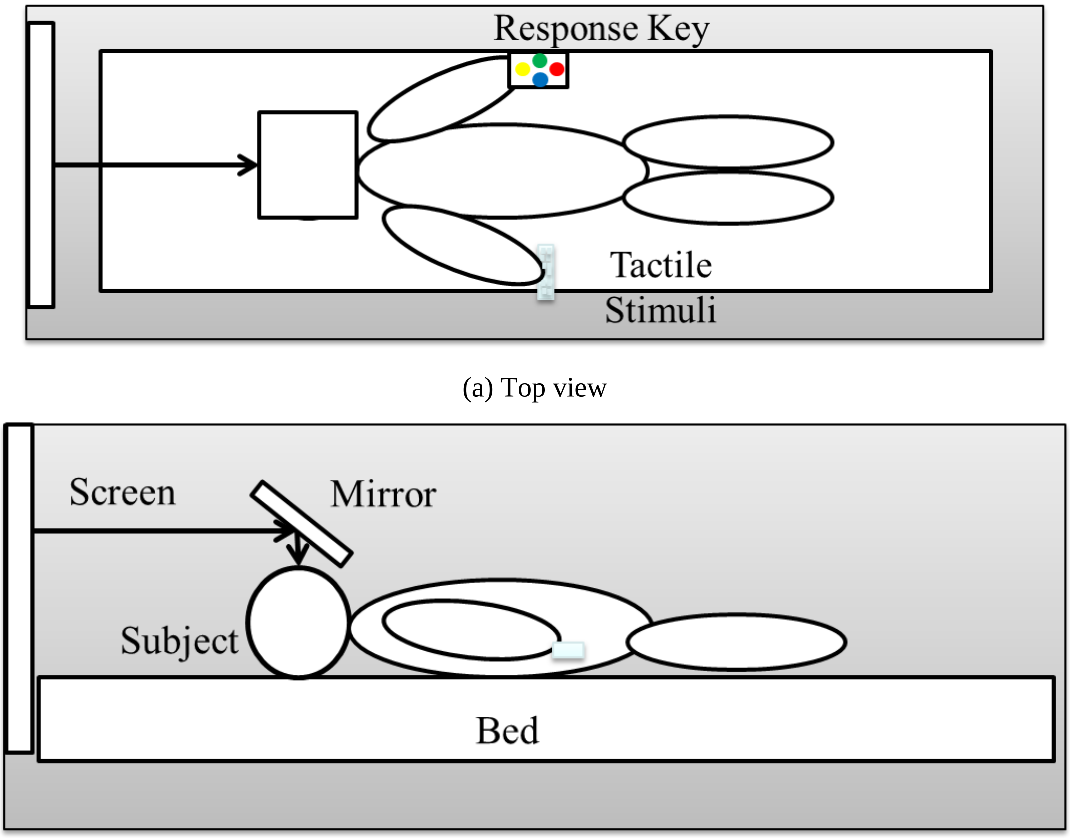


Fig 3.6 General view of tactile stimulation in the fMRI room

Fig 3.7 General view of subjects lied down inside the fMRI tunnel

A device operating in an MRI environment is required to be free of ferromagnetic elements. The device cannot create any radio frequency interference that could potentially degrade the MRI image. We verified that the response button was working properly and that stable waveforms were recorded during the MRI scans. The wires for the motors and optical sensors were shielded cables (copper type) to reduce any radio frequency interference.



(a) Top view

(b) Lateral view

Fig 3.8 Illustration of subject's position inside the tunnel

The insulation of the electrical components and the possible radio frequency heating of the wires were important factors considered in the design. The system has all control and signal cables contained within a plastic frame, eliminating possible contact with the subject. The device and its setup must allow the safe exit of the subject in an emergency. If the subject experiences an emergency condition, the primary device will stop all motors through the safety switch.

3.4 Materials and method

3.4.1 Subjects

Seven right-handed healthy male volunteers aged 23–28years (mean age 24.6 $\pm$ 0.71 years) participated in the fMRI study. Before the start of the experiment, all subjects participated in a training session outside of the MR scanner in which they were instructed to perform all the procedures in the protocol. All subjects gave their informed written consent, and this study was approved by the Ethics Committee of Human and Animal Experiments, Okayama University, Japan.

3.4.1 Apparatus and stimuli

Haptic stimuli consisted of seven 5 × 5 cm2 plastic plates, six embossed with different dot patterns and one control stimulus without any dots. The dots were arranged non-periodically and were 0.8 mm in diameter and 0.6 mm in elevation. The only characteristic that varied between the textures was the mean center-to-center dot spacing of each stimulus and hence the number of texture elements (dots). The average inter-dot spacing ranged from 1.50 mm to 2.75 mm and increased in steps of 0.25 mm (see Table 1 for detailed information on the stimulus characteristics)..

3.4.2 Procedures

Primarily, the experiment consisted of two unimodal tasks and two bimodal tasks. In unimodal task, subjects only need to perceive whether visually or tactually. Bimodal task is where subjects need to the same task as unimodal, but they were asked to perceive the interference stimulus. The all four tasks are:

1) Unimodal Visual-only task (V-V)
2) Bimodal Visual-tactile task (V-T)
3) Unimodal Tactile-only task (T-T)
4) Bimodal Tactile-visual task (T-V)

Subjects were presented sequentially two times in every trial; initial stimulation is called reference stimulus (RS) and the latter is target stimulus (TS). Subjects were instructed whether to look at the display or to explore the textures by sweeping their index finger in determined times with command by the indication stimuli.

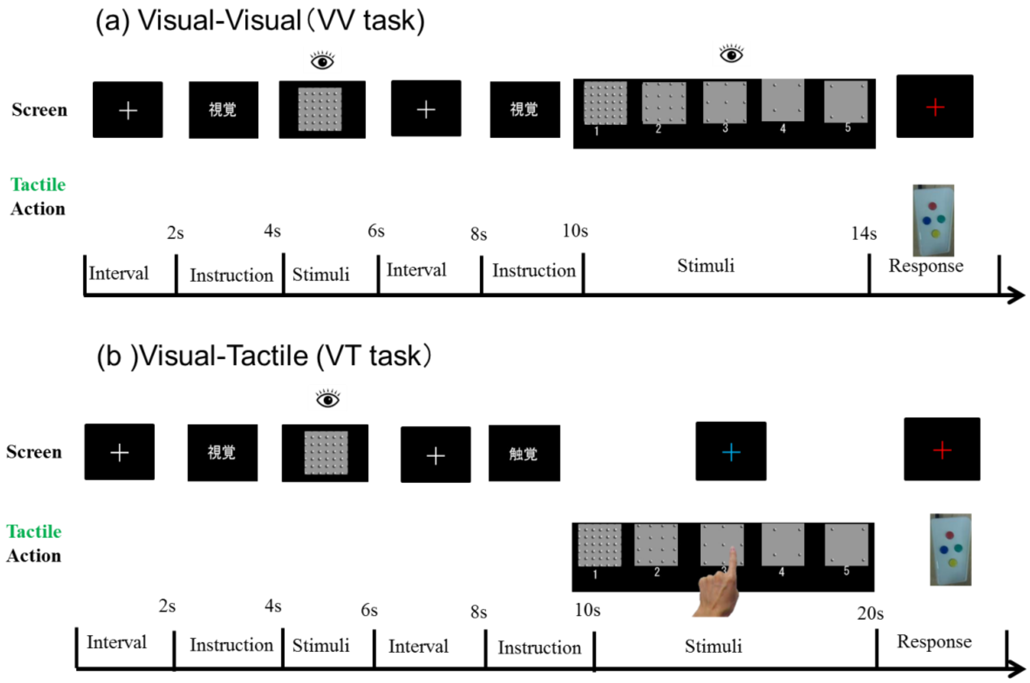


Fig 3. 9 Time chart for one trial in the unimodal task of V-V and bimodal V-T. Separated by four seconds of interval and instruction, subjects were presented with the stimuli twice in each task, which are the reference stimulus (RS) and the target stimulus (TS)

In V-V task, subjects need to compare the roughness of visual stimuli twice. First, a white visual indication stimulus was presented on the screen for 2 seconds. Next, pre-visual indication stimulus was presented for 2 seconds, demanding subjects to prepare for visual stimulation. Next, subjects presented the first visual stimulation for two seconds. Visual display then presented white inter-stimulus interval stimulus for 2 seconds to make sure the subjects ready for the TS. Pre-tactile indication stimulus then presented to subjects for two seconds. Next, subjects will be presented TS for four seconds. In TS, five types of dot pattern were presented with each were numbered from 1 to 5, and subjects needed to compare which stimulus had the same roughness with the first stimulation at RS. After four seconds, red interval stimulus will be presented and simultaneously the response time was measured. Subjects needed to pick which stimulus had the same roughness from TS compared with RS and they needed to push the response button with their left hand as soon as possible. The button response were four colours and subjects needed to press red for “1”, green if “2”, yellow if “3”, and blue if “4”. Subjects were asked to press yellow and blue (no sequential order required) for the response “5”. Once the subject response, it is counted as one trial.

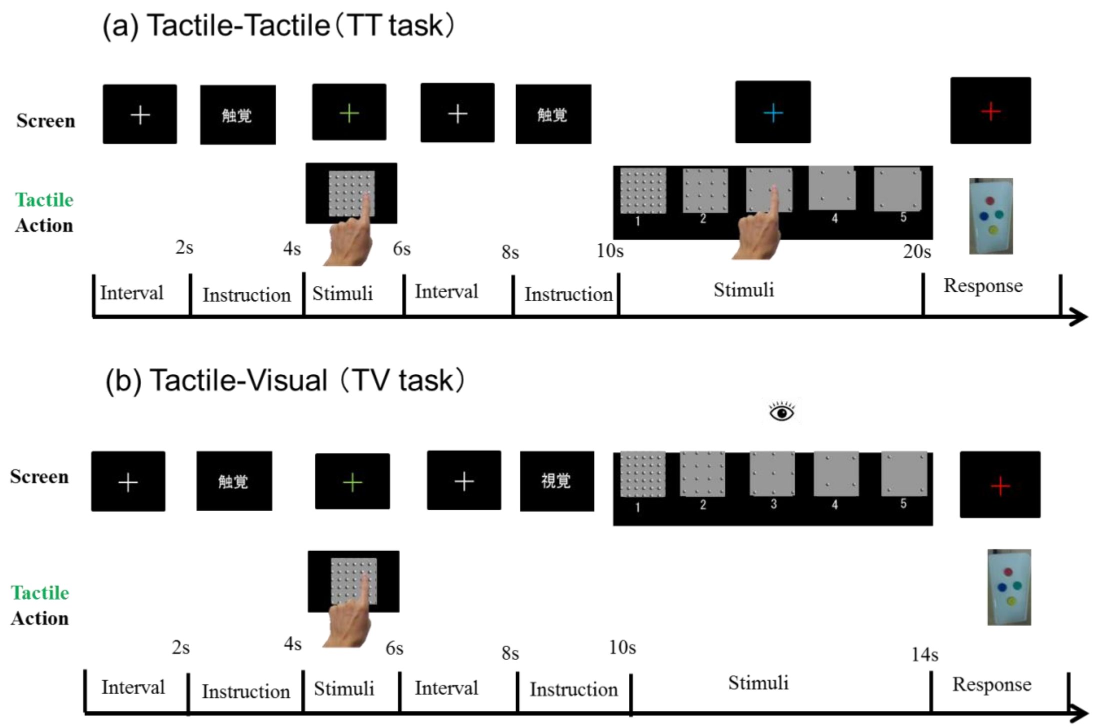


Fig 3.10 Time chart for one trial in the unimodal task of tactile T-T and bimodal T-V. Separated by four seconds of interval and instruction, subjects were presented with the stimuli twice in each task, which are the reference stimulus (RS) and the target stimulus (TS)

In T-T task, subject was asked to perform the same procedures as V-V except they need to perceived roughness based on tactile stimulation. In bimodal V-T task, subjects need to select the roughness of tactile stimuli in TS which have the same roughness with the first visual stimulation at RS. Procedures of T-V is vice versa of those in V-T (Fig 3.10)

Stimulus timing and presentation was controlled by Presentation® software (Neurobehavioral Systems, Inc., Albany, CA, USA). Subjects were informed that they would be presented with two visual, two haptic, or one of each task at each trial. Participants were instructed to explore the textures by sweeping twice with their right index across the surface while simultaneously focusing on the visual image presented on the screen. The importance of the simultaneous start and termination of the visual and haptic exploration was specifically stressed by the experimenter in order to control the temporal synchrony of the sensory input. Trial intervals were intermixed with intervals of rest. Auditory cues delivered via headphones instructed the experimenter to turn to the correct tactile stimulation during the inter-stimulus-intervals. Right before scanning started; subjects practiced the exploration movement in the scanner with two dot pattern textures that were not used in the experiment. The practice session lasted until the movement was experienced by the subject as effortless, it was synchronized with the duration of the exploration interval and all other motion was reduced to a minimum. This took on average five minutes but never longer than ten minutes. The practice session ensured that the attention of the subject was not focused on the motion sequence but on the tactile and visual sensations.

There was a visual, haptic, and visual–haptic condition in which the availability of texture information for the tactile and visual sense was varied but the input modalities and motor task demands were kept constant. Each dot pattern was repeated 10 times in each condition over the course of the experiment. The condition and stimulus presentation was semi-randomized and the events of interest were randomly presented. The experiment was split into 3 functional runs. The event-related fMRI design was based on an approach described by Eck et al [16].

3.4.3 Data processing and analysis

Functional magnetic resonance imaging was acquired on a 3-T Siemens Trio whole-body MRI system. Standard sequence parameters were used to obtain the functional images as follows: repetition time = 2000 ms; echo time = 25 ms; flip angle=77° ; field of view =260×260. A T1-weighted high-resolution anatomical image volume was obtained from each participant (voxel size=$1\times1\times1$ mm^3) before the acquisition of the functional data.

Statistical Parametric Mapping 5 (SPM5, Wellcome Department of Imaging Neuroscience, University College London, London, UK) software was used for the images and statistical analyses. Statistical analysis was conducted with a fixed effects analysis using the general linear model framework. Significantly activated voxels were identified if they reached the height threshold of $p < 0.001$ uncorrected.

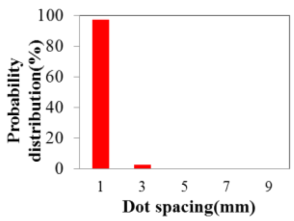
3.5 Results

We divided the results into two parts; behavioral and fMRI results. In behavioral, we looked on how accurate were the subjects responded the same dot pattern between the first reference stimulation (RS) and target stimulation (TS).

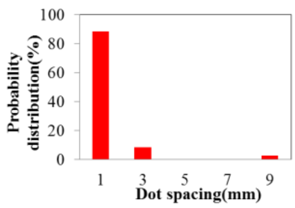
3.5.1 Behavioral results

The chance level to response the same spatial dot pacing between RS and TS was 20% (5 types of target stimulus). In general, probability distribution of TS increased when the same reference and target were presented, visually and haptically.

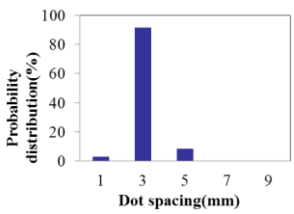
In V-V task, subjects responded 80% to 100% the same dot spacing as reference when the RS was 1mm and 3mm. The lowest distribution was during RS of 9mm. This result showed that subjects can almost accurately judge the spatial spacing of each of five types of visual stimulation, with the lowest distribution was above 50%.



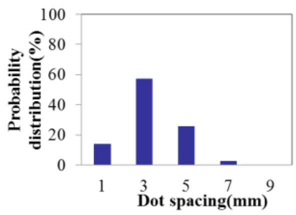
(a) Reference stimulus = 1 mm



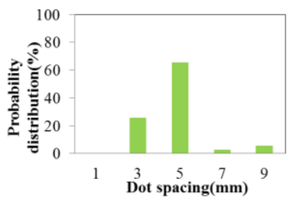
(a) Reference stimulus = 1 mm



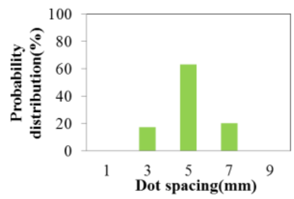
(b) Reference stimulus = 3 mm



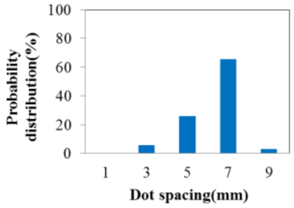
(b) Reference stimulus = 3 mm



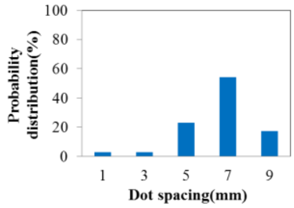
(c) Reference stimulus = 5 mm



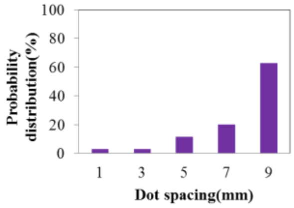
(c) Reference stimulus = 5 mm



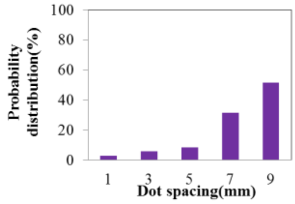
(d) Reference stimulus = 7 mm



(d) Reference stimulus = 7 mm



(e) Reference stimulus = 9 mm



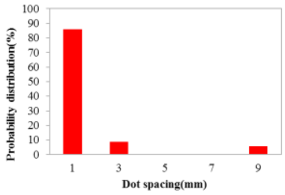
(e) Reference stimulus = 9 mm

Fig 3.11 Behavioral results of VV task

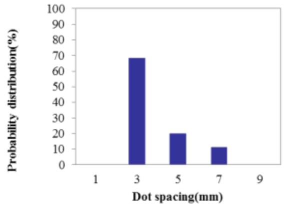
Fig 3.12 Behavioral results of VT task

In V-T, subjects responded more than 80% the same dot spacing of target stimulus as reference when the RS was 1mm. The lowest distribution was during RS of 9mm. This result showed that subjects were also managed to almost accurately judge the spatial spacing even when the main modality during reference and target was different. These results may suggest the efficient connection between visual and tactile during roughness perception.

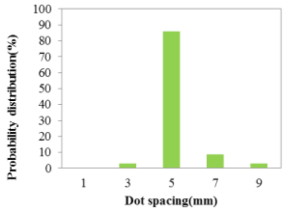
In T-T task, subjects responded more than 80% the same dot spacing of target stimulus as reference when the RS was 1mm and 5mm. The lowest distribution was during RS of 3mm. This result showed that subjects were also managed to almost accurately judge the spatial spacing of each of five types of tactile stimulation, with the lowest distribution was above 50%.



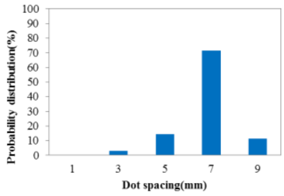
(a) Reference stimulus = 1 mm



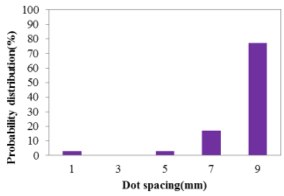
(b) Reference stimulus = 3 mm



(c) Reference stimulus = 5 mm

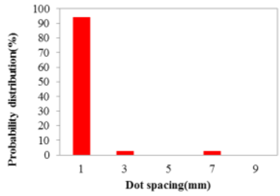


(d) Reference stimulus = 7 mm

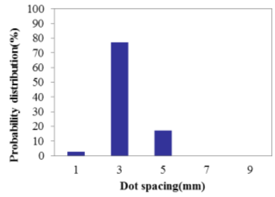


(e) Reference stimulus = 9 mm

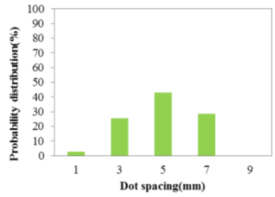
Fig 3.13 Behavioral results of TT task



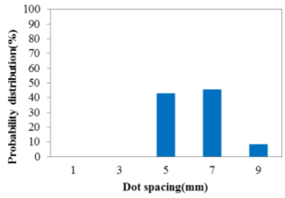
(a) Reference stimulus = 1 mm



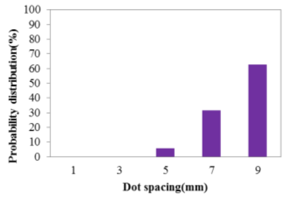
(b) Reference stimulus = 3 mm



(c) Reference stimulus = 5 mm



(d) Reference stimulus = 7 mm



(e) Reference stimulus = 9 mm

Fig 3.14 Behavioral results of TV task

Similar with V-T task; in T-V task, subjects responded more than 80% the same dot spacing of target stimulus as reference when the RS was 1mm. However, low distribution can be seen from RS of 5mm and above. The lowest distribution was during RS of 7mm, which almost had same distribution with another size of spacing (in Figure

3.13, the case was 5mm). This result showed that even subjects managed to almost accurately judge the spatial spacing even when the main modality during reference and target was different, there were different tendency between visual-tactile sequence and tactile-visual sequence within experiment task These results may suggest the difference between visual and tactile dominance during roughness perception.

3.5.2 Neural activation in specific stimuli cognition

We analyzed the neural activation and examine the brain activation during all situations in each task to compare the activations between cognition of reference and target stimuli.

Main activation during recognition of reference stimulus in V-V task: was seen in left and right side of Middle Occipital Gyrus, Fusiform Gyrus, and left Inferior frontal Gyrus. The left inferior frontal gyrus (IFG) is remarkably important for language comprehension and production due to the fact that most language processing takes place in the left hemisphere. Commonly known as "Broca's area", persons with damage in this region often have a type of non-fluent aphasia known as Broca's aphasia.

Table 3.2 Main foci during recognition of RS in V-V task

				MNI coordinates		
Cluster [voxel]	Anatomical region	side	T value	X	Y	Z
221	Middle Occipital Gyrus	left	5.12	−21	−90	6
	N/A	left	5.11	−24	−81	−6
190	Middle Occipital Gyrus	right	5.65	27	−87	3
	Fusiform Gyrus	right	5.03	30	−81	−6
32	IFG (p.Opercularis)	left	4.21	−42	9	24

Main activation during recognition of Target Stimulus: in V-V task was seen in right Fusiform Gyrus, left and right Linual Gyrus, Middle Occipital Gyrus, and Cuneus, left Precentral Gyrus, Inferior Frontal Gyrus, and right Precentral Gyrus. The precentral gyrus is a prominent structure on the surface of the posterior frontal lobe. It is the site of the primary motor cortex (Brodmann area 4). The precentral gyrus lies in front of the postcentral gyrus, mostly on the lateral (convex) side of the cerebral hemispheres from which it is separated by the central sulcus. Medially, it is contiguous with the paracentral lobule.

Table 3.3 Main foci during recognition of TS in V-V task

				MNI coordinates		
Cluster [voxel]	Anatomical region	side	T value	X	Y	Z
4753	Fusiform Gyrus	right	10.54	27	−69	−15
	Linual Gyrus	right	10.19	18	−81	−3
	Linual Gyrus	left	0.68	−6	−81	−3
	Middle Occipital Gyrus	right	8.89	30	−81	15
	Cuneus	right	7.42	18	−93	15
	Middle Occipital Gyrus	left	7.26	−18	−90	15
	Linual Gyrus	left	6.65	−24	−60	−12
161	Precentral Gyrus	left	4.78	−54	9	33
	IFG (p. Opercularis)	left	4.29	−42	6	24
111	Precentral Gyrus	right	5.84	45	6	30
	IFG (p. Opercularis)	right	4.41	48	9	21
54	Precentral Gyrus	right	4.58	30	−9	51

Main activation during recognition of reference stimulus in T-T task was seen in Supramarginal Gyrus, left Precentral Gyrus, the Insula lobe, Postcentral gyrus, rolandic Operculum, Thalamus, Putamen, and right pallidum. The somatosensory cortex activated by the tactile experiment is a site that reacts when recognizing tactile stimuli, which is consistent with previous studies. The thalamus is the large mass of gray matter in the dorsal part of the diencephalon of the brain with several functions such as relaying of sensory and motor signals to the cerebral cortex and the regulation of consciousness, sleep, and alertness.

Table 3.4 Main foci during recognition of RS in T-T task

Cluster [voxel]	Anatomical region	side	T value	MNI coordinates X	Y	Z
3534	SupraMarginal Gyrus	left	11.05	−51	−24	42
	Precentral Gyrus	left	10.52	−30	−21	63
	Precentral Gyrus	left	9.59	−54	6	27
	Insula Lobe	left	9.28	−36	−6	9
	Postcentral Gyrus	left	9.26	−39	−24	54
	Inferior Parietal Lobule	left	9.13	−39	−30	42
	Postcentral Gyrus	left	8.05	−54	−21	27
	Rolandic Operculum	left	8.05	−48	−24	18
	Thalamus	left	7.82	−12	−21	3
412	MCC	left	5.55	−6	−27	48
	posterior-medial frontal	left	5.33	−6	−3	51
	ACC	left	4.19	−3	3	30
370	Cerebelum (IV-V)	right	10.44	9	−54	−21
	Cerebelum (VI)	right	8.72	24	−45	−30
352	Insula Lobe	right	6.61	36	−6	12
	Precentral Gyrus	right	6.25	45	6	30
	IFG (p. Opercularis)	right	5.44	51	9	18
341	Postcentral Gyrus	right	8.46	54	−15	33
65	IFG (p. Triangularis)	left	5.47	−39	33	12
65	Putamen	right	4.69	30	18	3
21	N/A	right	3.71	18	3	12
	Pallidum	right	3.67	18	3	6
20	IFG (p. Triangularis)	right	4.42	45	33	9

Main activation during recognition of target stimulus in T-T task was seen in SupraMarginal Gyrus, Precentral Gyrus, Inferior Parietal Lobule, Postcentral Gyrus, Precentral Gyrus, IFG (p. Opercularis), Superior Parietal Lobule, Postcentral Gyrus, Inferior Parietal Lobule, Cerebelum (IV-V), Superior Parietal Lobule, Superior Occipital Gyrus, Precentral Gyrus, IFG (p. Opercularis), Cerebelum (VI), IFG (p. Triangularis), Middle Frontal Gyrus, IFG (p. Triangularis), and left and right Middle Frontal Gyrus. The main foci of these activations are shown in Table 3.5. In addition to its direct role in motor control, the cerebellum is necessary for several types of motor learning, most notably learning to adjust to changes in sensorimotor relationships.

Table 3.5 Main foci during recognition of TS in T-T task

Cluster [voxel]	Anatomical region	side	T value	MNI coordinates X	Y	Z
6034	SupraMarginal Gyrus	left	11.82	−51	−24	42
	Precentral Gyrus	left	11.21	−27	−24	69
	Inferior Parietal Lobule	left	9.95	−39	−30	42
	Postcentral Gyrus	left	9.27	−30	−33	60
	Precentral Gyrus	left	9.23	−54	6	27
	IFG (p. Opercularis)	left	8.56	−57	9	21
	Superior Parietal Lobule	left	8.4	−30	−48	60
604	Postcentral Gyrus	right	8.61	54	−15	33
	Inferior Parietal Lobule	right	5.21	33	−48	48
430	Cerebelum (IV−V)	right	10.56	9	−54	−21
312	Superior Parietal Lobule	right	5.41	18	−63	57
	Superior Occipital Gyrus	right	3.86	27	−66	42
231	Precentral Gyrus	right	5.98	48	3	30
	IFG (p. Opercularis)	right	5.58	54	9	21
100	N/A	left	5.14	−18	−57	−30
	Cerebelum (VI)	left	4.29	−30	−48	−36
86	IFG (p. Triangularis)	left	3.81	−48	42	6
	Middle Frontal Gyrus	left	3.76	−27	39	24
	IFG (p. Triangularis)	left	3.54	−42	39	9
	Middle Frontal Gyrus	left	3.54	−45	54	0
31	Middle Frontal Gyrus	right	4.4	36	57	18

Main activation during cognition of reference stimulus in V-T task was seen in Middle Occipital Gyrus and Superior Occipital Gyrus. The main foci of these activations are shown in Table 3.6.

Table 3.6 Main foci during recognition of RS in V-T task

Cluster [voxel]	Anatomical region	side	T value	MNI coordinates X	Y	Z
46	Middle Occipital Gyrus	right	4.35	27	−93	9
32	Middle Occipital Gyrus	left	4.31	−27	−93	15
	Superior Occipital Gyrus	left	3.85	−18	−96	18

Activation during recognition of Target stimulus in V-T task was seen in Precentral Gyrus, SupraMarginal Gyrus, Inferior Parietal Lobule, Precentral Gyrus, IFG (p. Opercularis), Superior Parietal Lobule, Rolandic Operculum, posterior-medial frontal, Insula Lobe, Cerebelum (IV-V), Middle Frontal Gyrus, IFG (p. Triangularis), Middle Orbital Gyrus, Thalamus, Pallidum, Superior Frontal Gyrus, Middle Frontal Gyrus, Postcentral Gyrus, Superior Parietal Lobule, Precentral Gyrus, IFG (p. Opercularis), Superior Parietal Lobule, and the Insula Lobe. In each hemisphere of the brain the insular cortex is a portion of the cerebral cortex folded deep within the lateral sulcus.

Table 3.7 Main foci during recognition of TS in V-T task

				MNI coordinates		
Cluster [voxel]	Anatomical region	side	T value	X	Y	Z
3523	Precentral Gyrus	left	9.93	−30	−21	63
	SupraMarginal Gyrus	left	9.79	−51	−24	42
	Inferior Parietal Lobule	left	8.48	−39	−30	42
	Precentral Gyrus	left	7.44	−54	6	24
	IFG (p. Opercularis)	left	7.05	−54	9	15
	Superior Parietal Lobule	left	6.5	−30	−48	60
	Rolandic Operculum	left	5.65	−42	−24	18
	posterior-medial frontal	left	5.49	−6	3	51
	Insula Lobe	left	5.32	−39	−6	9
291	Cerebelum (IV-V)	right	8.38	9	−54	−21
176	Middle Frontal Gyrus	left	4.13	−27	39	24
	N/A	left	3.77	−33	63	21
	IFG (p. Triangularis)	left	3.63	−36	36	15
	Middle Orbital Gyrus	left	3.42	−42	57	−3
159	Thalamus	left	5.69	−15	−21	6
	Pallidum	left	3.95	−18	3	6
155	Superior Frontal Gyrus	right	5.14	27	−9	57
	Middle Frontal Gyrus	right	4.54	27	3	51
147	Postcentral Gyrus	right	7.21	54	−15	33
130	Superior Parietal Lobule	left	4.7	−18	−66	51
109	Precentral Gyrus	right	4.73	48	3	30
	IFG (p. Opercularis)	right	4.37	51	6	21
76	Superior Parietal Lobule	right	3.95	18	−66	57
23	N/A	left	4.37	−27	15	6
	Insula Lobe	left	4.31	−30	18	3

Main activation during recognition of Reference stimulus in T-V task was seen in SupraMarginal Gyrus, Insula Lobe, Precentral Gyrus, IFG (p. Opercularis), Precentral Gyrus, Inferior Parietal Lobule, Postcentral Gyrus, Thalamus, Rolandic Operculum, Insula Lobe, Precentral Gyrus, IFG (p. Opercularis), Cerebelum (IV-V), posterior-medial frontal, Postcentral Gyrus, Insula Lobe and Putamen.

Table 3.8 Main foci during recognition of RS in T-V task

				MNI coordinates		
Cluster [voxel]	Anatomical region	side	T value	X	Y	Z
2855	SupraMarginal Gyrus	left	10.43	−51	−24	42
	Insula Lobe	left	9.53	−36	−6	9
	Precentral Gyrus	left	9.14	−33	−21	63
	IFG (p. Opercularis)	left	8.88	−57	9	24
	Precentral Gyrus	left	8.84	−54	6	27
	Inferior Parietal Lobule	left	8.21	−39	−30	42
	Postcentral Gyrus	left	7.78	−39	−24	54
	Thalamus	left	7.58	−12	−21	6
	Rolandic Operculum	left	7.12	−51	−18	15
399	Insula Lobe	right	6.44	36	−3	9
	Precentral Gyrus	right	5.76	48	6	30
	IFG (p. Opercularis)	right	5.17	48	9	15
360	Cerebelum (IV−V)	right	9.72	9	−54	−21
347	posterior−medial frontal	left	5.56	−6	−3	54
	MCC	right	4.98	9	15	42
	MCC	left	4.18	−6	−24	45
	MCC	left	3.73	−3	3	33
289	Postcentral Gyrus	right	8.24	54	−15	33
46	Insula Lobe	left	5.53	−30	18	6
23	Putamen	right	3.95	30	15	3

Main activation during recognition of Target stimulus in T-V task was seen in Fusiform Gyrus, Linual Gyrus, Linual Gyrus, Middle Occipital Gyrus, Middle Occipital Gyrus, Fusiform Gyrus, Superior Occipital Gyrus, Middle Occipital Gyrus, Linual Gyrus, Precentral Gyrus, IFG (p. Triangularis), IFG (p. Opercularis), Precentral Gyrus, Postcentral Gyrus, Precentral Gyrus, posterior-medial frontal, Precentral Gyrus, Insula Lobe, and Hippocampus.

Table 3.9 Main foci during recognition of TS in T-V task

				MNI coordinates		
Cluster [voxel]	Anatomical region	side	T value	X	Y	Z
5871	Fusiform Gyrus	right	11.81	30	−66	−15
	Linual Gyrus	right	11.11	15	−81	−3
	Linual Gyrus	left	10.67	−6	−81	−3
	Middle Occipital Gyrus	right	10.01	30	−81	15
	Middle Occipital Gyrus	left	7.47	−18	−87	12
	Fusiform Gyrus	left	6.91	−30	−63	−18
	Superior Occipital Gyrus	right	6.51	27	−66	39
	Middle Occipital Gyrus	left	5.92	−24	−63	39
	Linual Gyrus	left	5.87	−21	−48	−9
260	Precentral Gyrus	left	5.18	−57	12	33
	IFG (p. Triangularis)	left	5.17	−54	21	27
	IFG (p. Opercularis)	left	4.85	−48	9	15
233	Precentral Gyrus	right	5.3	30	−12	54
	Postcentral Gyrus	right	3.97	51	−18	39
113	Precentral Gyrus	right	4.97	45	6	30
	IFG (p. Opercularis)	right	4.39	51	9	18
71	posterior-medial frontal	left	4.19	−6	9	51
	MCC	right	3.85	9	15	45
54	Precentral Gyrus	left	3.94	−36	−3	57
46	IFG (p. Triangularis)	left	4.65	−48	42	9
36	Insula Lobe	left	5.26	−30	18	3
28	Hippocampus	right	4.39	21	−30	−6

In rodents as model organisms, the hippocampus has been studied extensively as part of a brain system responsible for spatial memory and navigation. Many neurons in the rat and mouse hippocampus respond as place cells: that is, they fire bursts of action potentials when the animal passes through a specific part of its environment. Hippocampal place cells interact extensively with head direction cells, whose activity acts as an inertial compass, and conjecturally with grid cells in the neighboring entorhinal cortex. In Alzheimer's disease (and other forms of dementia), the hippocampus is one of the first regions of the brain to suffer damage; short-term memory loss and disorientation are included among the early symptoms [47][48][49].

Table 3.10 Main foci during recognition of TS in T-V and V-V task

				MNI coordinates		
Cluster [voxel]	Anatomical region	side	T value	X	Y	Z
202	N/A	left	5.18	−24	−27	27
	N/A	left	4.82	−21	−24	24
	N/A	left	4.34	−36	−9	27
	N/A	left	4.32	−30	−12	27
	N/A	left	4.11	−21	−3	30
	N/A	left	3.9	−30	−6	27
	N/A	left	3.73	−15	−42	21
79	N/A	right	4.2	27	−21	27
	N/A	right	4.15	21	−12	27
	N/A	right	4.14	27	−27	30
	N/A	right	4.14	21	−6	33
	N/A	right	3.74	21	3	36
	N/A	right	3.73	24	−15	33
	N/A	right	3.55	30	−18	33

Main activation during recognition of V-T task target stimulus versus T-T task target stimulus was seen in Superior Medial Gyrus (Table 3.11). Main activation during V-V task target stimulus vs T-V task target stimulus was also seen in the Superior Medial Gyrus (Table 3.12)

Table 3.11 Main foci during recognition of TS in V-T and T-T task

				MNI coordinates		
Cluster [voxel]	Anatomical region	side	T value	X	Y	Z
42	Superior Medial Gyrus	left	3.98	−12	57	21

Table 3.12 Main foci during recognition of TS in V-V and T-V task

				MNI coordinates		
Cluster [voxel]	Anatomical region	side	T value	X	Y	Z
7	Superior Medial Gyrus	left	3.6	−3	60	0

Main activation during T-T task target stimulus vs V-T task target stimulus was seen in Precentral Gyrus, Postcentral Gyrus, Inferior Parietal Lobule, Paracentral Lobule, Precentral Gyrus, Cerebellar Vermis (4/5), Linual Gyrus, and Inferior Occipital Gyrus.

Table 3.13 Main foci during recognition of TS in T-T and V-T task

				MNI coordinates		
Cluster [voxel]	Anatomical region	side	T value	X	Y	Z
78	N/A	right	3.96	54	−21	60
	N/A	right	3.95	39	−27	72
	Precentral Gyrus	right	3.85	45	−18	60
72	Postcentral Gyrus	right	3.76	42	−39	66
	Inferior Parietal Lobule	right	3.59	27	−45	51
44	Paracentral Lobule	left	4.17	−6	−15	78
	N/A	left	4.13	0	−6	78
42	Precentral Gyrus	left	4	−24	−15	75
31	Cerebellar Vermis (4/5)	right	3.79	6	−54	−21
	N/A	right	3.72	3	−48	−24
27	Linual Gyrus	left	3.93	−21	−90	−18
23	Inferior Occipital Gyrus	right	3.82	30	−87	−9
	N/A	right	3.77	27	−84	0

Common area during the recognition of target stimulus was seen in left Precentral Gyrus, left IFG (p. Opercularis), right Precentral Gyrus, IFG (p. Opercularis), Inferior Parietal Lobule, Superior Parietal Lobule, and right Precentral Gyrus.

Table 3.14 Main foci during the recognition of target stimulus

				MNI coordinates		
Cluster [voxel]	Anatomical region	side	T value	X	Y	Z
86	Precentral Gyrus	left	4.72	−54	9	30
	IFG (p. Opercularis)	left	4.16	−45	6	18
59	Precentral Gyrus	right	4.5	48	6	30
	IFG (p. Opercularis)	right	4.18	51	9	21
53	Inferior Parietal Lobule	left	4.27	−30	−45	42
49	Superior Parietal Lobule	left	4.24	−21	−69	48
21	Precentral Gyrus	right	4.31	30	−9	54

3.5.3 Neural activation during visual and tactile input

In order to understand the consequences of cross modalities between tactile and visual, we analyzed the neural activation separately by respective modalities.

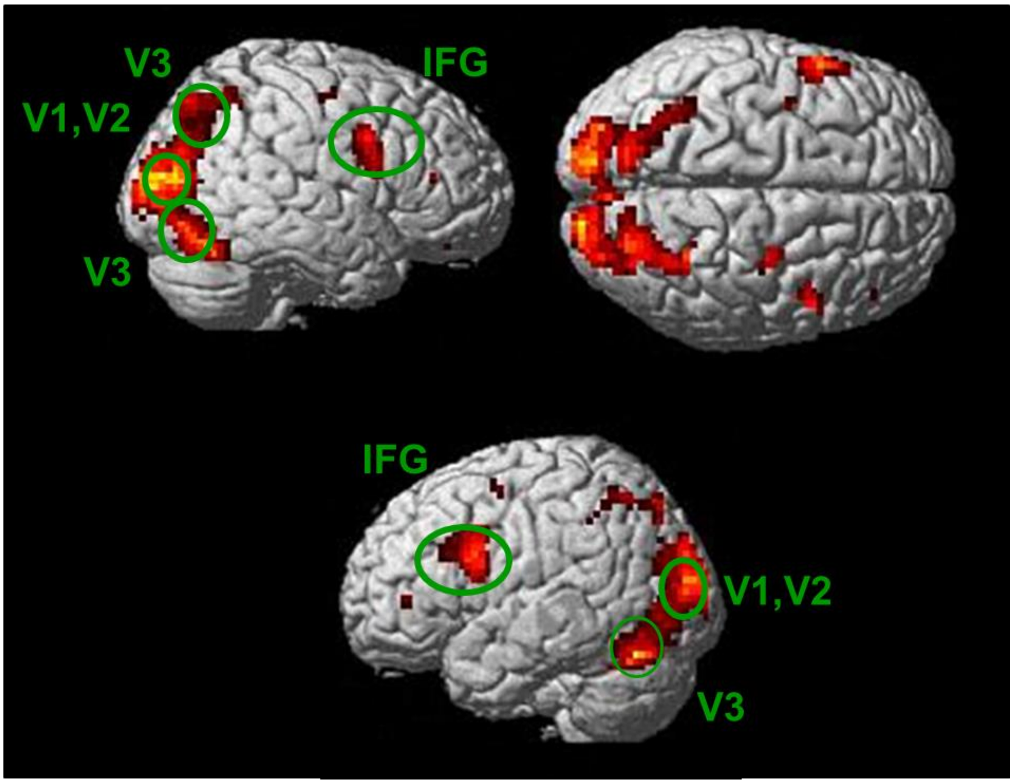


Fig 3.15 Activation during visual stimulation

Main activation during visual stimulation was seen in Primary visual Cortex (V1), Secondary visual cortex (V2), visual area V3, and the inferior frontal gyrus (IFG). In the roughness recognition of dot pattern, the temporal lobe activated in the visual experiment activates because it recognizes the visual stimulus at the site called the visual cortex, coincides with the previous studies [16][6].

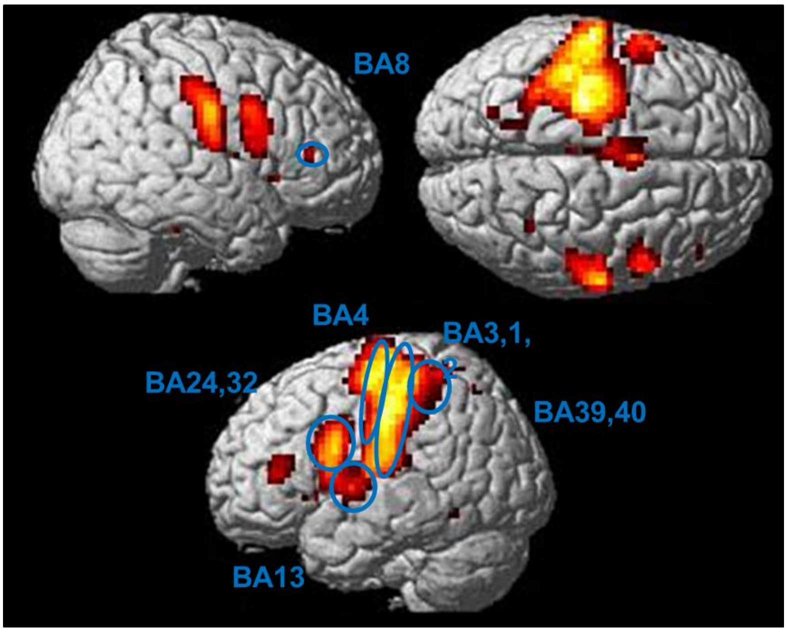


Fig 3.16 Activation during tactile stimulation

Main activation during tactile stimulation was seen in Brodmann Area areas 3,1 and 2 (Primary somatosensory cortex), Area 4 (Primary motor cortex), Area 8 , Area 13 (Insular cortex) , area 39 (Angular gyrus), area 40 (Supramarginal gyrus), area 24 (ventral anterior cingulate cortex) and area 32 (Dorsal anterior cingulate cortex). The somatosensory cortex activated by the tactile experiment is a site that reacts when recognizing tactile stimuli, which is consistent with previous studies. [16][32].

3.5.3 Common neural activation during target stimulus cognition

Common area of activation during the second stimulation (target stimulus) was seen in Precentral Gyrus (PrG), Inferior frontal gyrus (IFG), Inferior parietal lobule (IPL), and the Superior parietal lobule (SPL). The areas commonly activated through the second stimulation are areas that reacted irrespective of the type of sensory organ and it is considered that these areas are related to cross modalities.

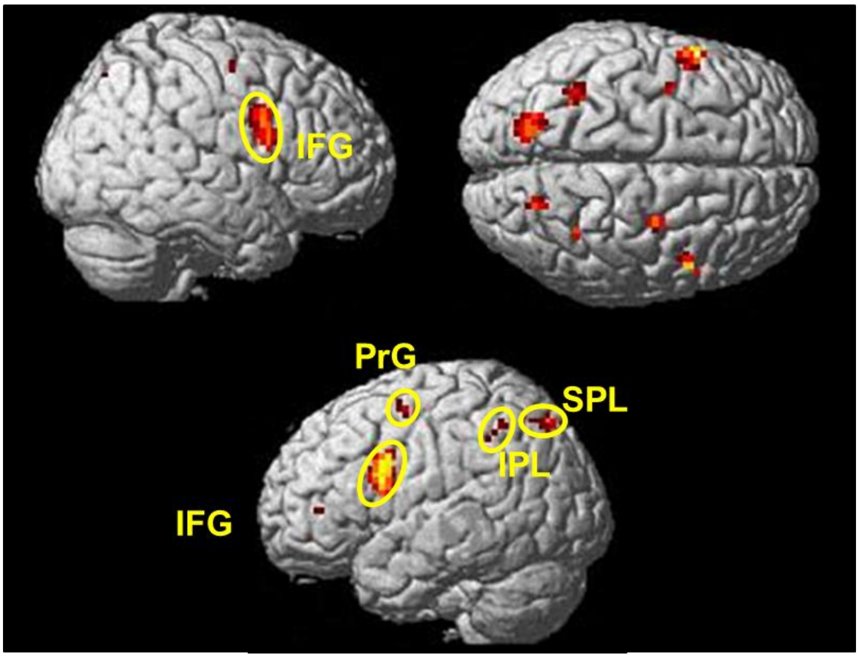


Fig 3.17 Common area during the recognition of target stimuli (target stimulation)

3.6 Discussion

We were interested to explore the mechanism inside tactile, visual and the interaction between them in the perception of roughness using dot pattern stimuli by designing two unimodal tasks and two bimodal tasks accompanying both modalities.

3.6.1 Effects of input by each modality

In the second chapter, we have discussed that surfaces with small particles may generate high temporal frequencies, which led the subject to perceive a smoother surface tactually. Bensmaia et al [7] also stated that the perception of surface larger than 200μm was encoded by the spatial and temporal properties that were dominant in the haptic perception of fine surface roughness. While in visual, the perception of visual roughness is a complex process that may generate more complex neural activations, which much depends on the direction of illumination, viewpoint, and the shadow.

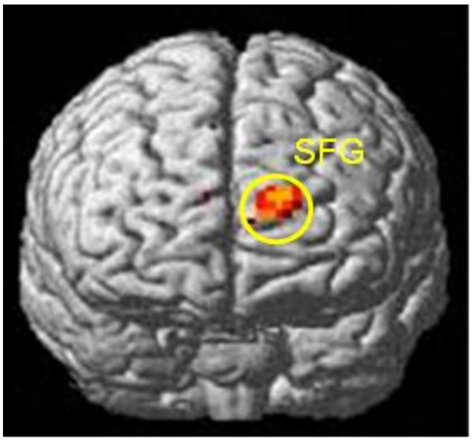


Fig 3.18 Superior frontal gyrus: main area during task with visual stimulus

The perception of textures developed activations corresponded with brain domains that were previously suggested to function in haptic and visual texture perception, (the parietal operculum and insula) regions in the early visual cortex as well as the middle occipital gyrus, the collateral sulcus and the posterior fusiform and lingual gyrus [38] [39][29]. In contrast, we did not find the activation of prefrontal areas. One potential explanation for this difference is the involvement of active cognitive task in present paradigms.

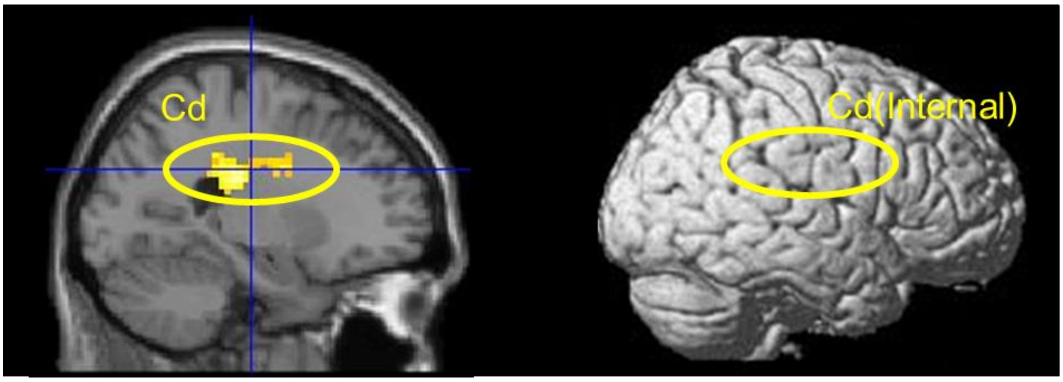


Fig 3.19 Caudate nucleus: main area during task with tactile stimulus

3.6.2 Cross modal integration process

From the results, common area of activation during the second stimulation was seen in PrG, IFG, IPL, and SPL. The areas commonly activated through the second stimulation are areas that reacted irrespective of the type of sensory organ and it is considered that these areas are related to cross modalities.

In this study, we asked the subjects to judge the roughness of their stimulation, even if they were not able to. Following the results, we can claim that the activity in the visual cortex exists during tactile perception of roughness. However, although visual imagery has been implicated in the tactile perception of some macro-geometric properties of objects, its engagement in the perception of surface is thought to be in small volume. This suggests that two properties, orientation and roughness are unconnected and are further based by specific regions in our brain.

3.7 Conclusion

In this chapter, we measured the brain activity during pattern perception using functional magnetic resonance imaging (fMRI). Human sensations always involve in interaction, but a lot of brain's response during the interaction is still unknown.. This study was designed to discover the unresolved part of the brain during performing visual and tactile interaction roughness recognition experiments. We designed four types of tasks: visual task (VV), tactile task (TT), visual - tactile task (VT), tactile - visual task (TV). The common area of each of the brain activation during each task was analyzed; and the results showed that activations located in the frontal and parietal, suggesting these regions were actively involved in the cross-modal processing. Specific activation for the information from the tactile and visual modality was seen in the frontal and parietal lobe, respectively, suggesting the particular activation in each at this region.

Chapter 4 Effects of Temporal Frequency toward Roughness Perception by Visual Stimuli

Abstract

Previous studies proved that a spatial mechanism can only account for the processing of coarse textures. In the present study, we proposed temporal coding mechanism involves converting the fine spatial structure of grating and scramble surface into a temporal drifting and flicking pattern. This temporal mechanism complements the spatial one and greatly extends the range of tangible textures. We proposed that gratings with regular spatial structure but different temporal mechanism have different influence toward roughness perception. However, great individual differences of roughness perception by grating stimuli take us to create scramble stimuli to do the same experiment. Results showed that a combination of spatial and temporal mechanisms accounts for perceptual judgments of roughness, however with some limitation from the stimulus pattern.

4.1 Introduction

Texture information is widely believed to be conveyed in spatial patterns of activation evoked across one of three populations of cutaneous mechanoreceptive afferents that innervate the fingertips. To understand the perceptual processes involved in perceiving texture by touch, typical approach relies on determining the relationship between a physical factor in the environment and a quantifiable measure of the perception of that factor as texture. Mainly, the studies were centered in roughness domain [50][51][52][53][54][55][56][57].

A carefully controlled analysis of the relationship between physical stimuli and roughness was conducted by Lederman [54]. Perceived roughness was directly related to the spatial deformation of the fingertip's skin by the textured grooves [58][59]. Temporal coding is also disconfirmed by the finding that selective adaptation of receptors to vibration results in little change in perceived roughness.

Roughness is a surface property that can be used to describe materials or to discriminate them, and it can be critical in the classification of materials. One can readily discriminate the different grits both visually and haptically. For our purposes, roughness is an aggregate or statistical measure of the shape, size, and distribution of elements on a surface. It may be classified haptically or visually [60][61]. Parameters that affect haptic roughness include inter element spacing and grating groove width [54].

Haptic perception of roughness textures is evidently affected by changes by spatial mechanism conditions [16][46] and , if visual perception of the roughness of 3D textures were well calibrated to haptic perception of the same textures, we might expect roughness dependability across changes in the temporal mechanisms of visual textures. The main objective of the present study was to explore how temporal mechanism influences the roughness perception of subjects. In the present study, we used computer-assembled gratings and scrambles images to define temporal characteristics of visual roughness. Here, we investigate the effects of changes in those gratings and scrambles parameters to subjects' roughness perception.

In the first experiment, we investigated the effects of time frequency towards roughness perception by visual drifted grating stimuli. We could understand that gratings do have several limitations for roughness perception to human visual. In the second experiment, we changed our stimulation to scramble that originated from the gratings.

4.2 Effects of temporal frequency towards roughness perception by visual drifted grating stimuli

4.2.1 Subjects

Ten subjects (9 males, 1 female; ages 20–28 years old) provided informed consent and participated in this study. Subjects sat with the left and right arm resting on a support on the desk. Stimuli were presented in a dark room.. All procedures were approved by Okayama University.

4.2.2 Stimuli

The experimental stimuli was written in the numerical computing programming language MATLAB R2015b (The Mathworks, Inc.) with interfaces of Psychophysics Toolbox Version 3 (PTB-3).

The parameters of the grating including pixels per cycle, spatial frequency, and visible size were calculated and one single static grating image was generated. The actual sine grating and drift speed (in cycles per second) were then computed and the amount of pixels to be shifted is specified to perform a perception of movement.

In this study, we used 7 types of drift speed as target stimuli; which has been tested in pilot experiment, which are 0.1, 0.5, 2, 4, 6, 10, and 20 cycles per second. Three of them (2, 4, 6 cycles/second) were used as standard stimuli for the subjects' reference during each trial. All seven speeds were used as target stimuli, pairing with those three speeds of reference. Thus, reference stimuli and target stimuli with same speed were also involved. Subjects assessed the same pair of reference and target ten times, totaling of 210 trials per subject.

4.2.3 Procedures

Experiment 1 was divided into two tasks; “speed cognition task” and “roughness cognition task”. In the speed cognition, subjects performed a two-alternative forced choice (2-AFC) task which they need to response which grating stimuli is “faster” between two presented on the left and right at the screen. In the roughness cognition, subjects performed a two-alternative forced choice (2-AFC) task which they need to response which grating stimuli is “rougher” between two presented on the left and right at the screen. Direction of comparison (left) and target stimulus (right) were always 90 degrees different to prevent adaptation by subjects. Reaction time was calculated between the start of gratings presentation and subject response and no time limit was appointed. Between trial stimulation, subjects viewed two crosses fixation to prevent any kind of afterimage.

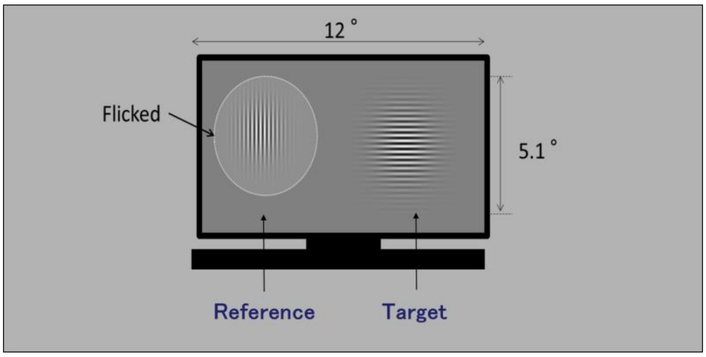


Fig 4.1.: Design of grating stimulation set that was presented to subjects in Experiment 1.

Experiments were carried out in a room with no light and sound. Before the experiment, subjects needed to sit inside the room and were asked to rest without any special instruction. The process is called “eye adaptation”, a significant procedure in visual physiology. It is well accepted as the ability of the eye to adjust to various levels of darkness and light [62][63]. Since all subjects were younger than 30 years old and the dark adaptation is performed better by young people [64], subjects needed to accomplish only ten minutes of dark adaptation first.

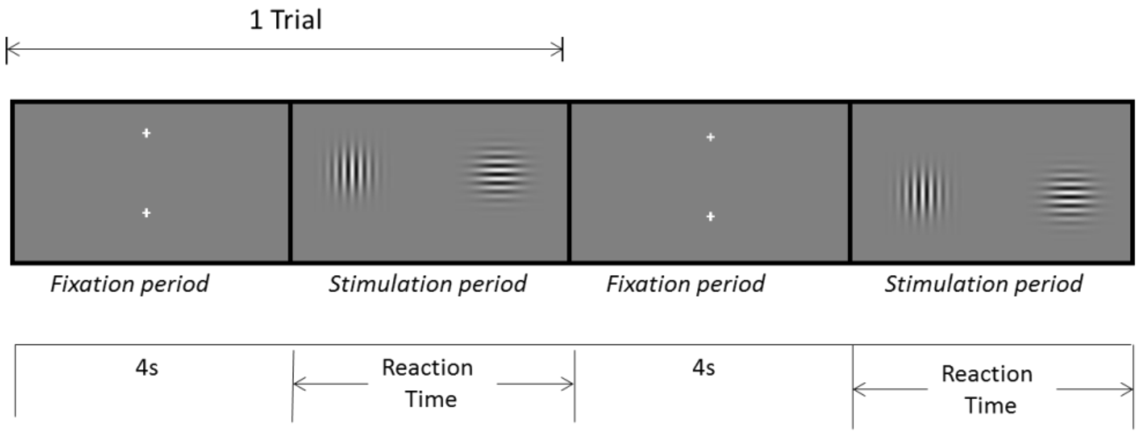


Fig 4.2.: Trial sequence of Experiment 1.

Subjects then practiced three minutes of light adaptation. During this process, subjects were presented a blank screen with the color of gray background and they were asked to look at the screen and get used to the color. In the light adaptation, the eye has to immediately adapt to the background color of screen [65]. The experiment will start thirteen minutes after the subjects entered the room (10 minutes of dark adaptation + 3 minutes of light adaptation). Dark adaptation, light adaptation, and the actual experiment were all controlled by computing programming MATLAB to avoid difference between subjects.

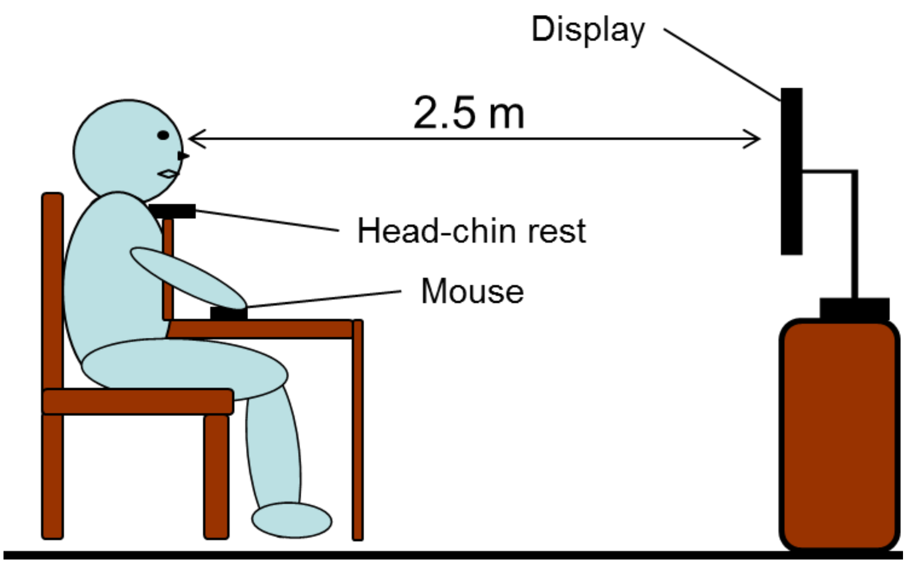


Fig 4.3.: Subjects condition during Experiment 1 and 2

Inside the experiment room, subject will sit on a chair with their right hand placed on computer numeric keyboard for task`s response. The keyboard size was 15mm long and 8mm width; fitting subject's finger. A chin rest was provided fixed to the table for two main reasons. First, to prevent subject`s fatigue during the experiment and secondly for limiting subject`s eye distance to be approximately 2.5 meters from the computer display. Experimenter was always outside the room to control the computing programming and to be on guard for subjects from sleeping during adaptation or experiment. Experimenter`s voice can always be heard from inside the room.

Subjects will feedback all their response by the computer numeric keyboard with only three buttons horizontally arranged. In the speed cognition, subjects need to judge whether target stimulus on the right was "faster" than reference stimulus on the left side. During task description before the experiment start, subjects were asked to press right button if stimulus on the right side was faster or left button for the opposite. In case subjects could not decide which stimulus was faster between those two, they were asked to press the third button which was placed at the middle. In the roughness cognition, subjects needed to select stimulus which was "rougher" between two presented on the left and right at the screen. Similar with speed cognition task, subjects were asked to press left button if stimulus on the left side was rougher, right button if stimulus on the right side was rougher and middle button if they could not conclude any of them.

4.3 Effects of temporal frequency towards roughness perception by visual flicked scramble stimuli

4.3.1 Subjects

Ten right-handed, healthy volunteers (6 males, 1 female; ages 20–28 years old) participated in this experiment. All subjects had no remarkable injuries to the hands or fingers, normal visions, and given written informed consent for participation. The local medical ethics committee of Okayama University approved the protocol.

4.3.2 Scramble stimuli

Originated from the grating stimuli in experiment 1, we specified a division pitch width p and randomly arranged the particles divided using exclusive program of MATLAB and Psychophysics Toolbox. The parameters of the grating including pixels per cycle, spatial frequency, and visible size were calculated and one single static grating image was generated. The actual sine grating and drift speed (in cycles per second) were then computed and the amount of pixels to be shifted is specified to perform a perception of movement.

For the second experiment, we controlled the flick frequency of the scramble stimuli to demonstrate roughness perception to the subjects. After several pilot tests, six type of frequencies were used in this experiments which is 1, 2, 4, 8, 16, and 32 (Hz, per second)

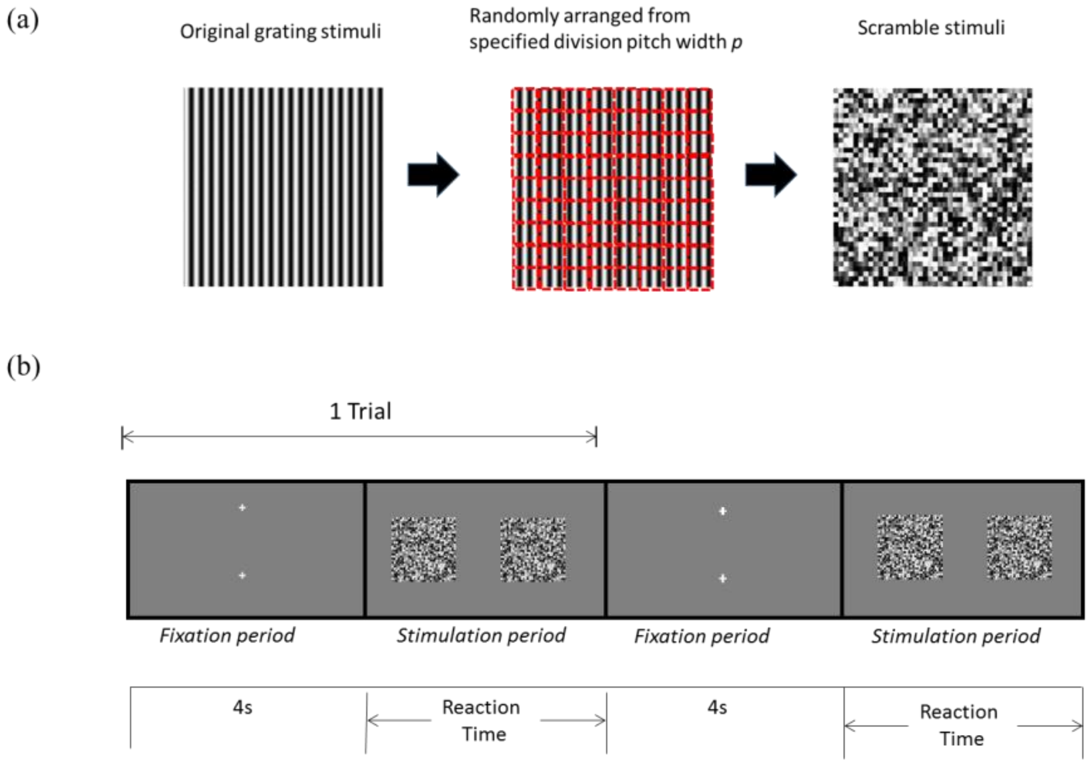


Fig 4.4. (a) Design of the scramble stimuli. We randomly arranged the divided particles of grating stimuli from Experiment 1 by specified pitch width *p* and recombined to original size to construct the new scramble stimuli (b) Trial sequence of Experiment 2

4.3.3 Procedures

Identically to those in experiment 1, we used a two-alternative forced choice (2AFC) procedure in which the subjects were presented two scramble textures simultaneously. In a pre-experiment, we carried out a speed cognition task (identical to Experiment 1) by controlling the frequencies of scramble stimuli. The results were identical to those in Experiment 1 for all subjects and we extend Experiment 2 for only roughness condition task. Comparisons between each of three standard stimuli and each of six target stimuli were carried out for 10 times in one set. Subjects completed two sets of experiment in two different days, with at least 5 days between each set to exclude subject's perception of gratings and reset subjects' dedication toward the experiment. Stimuli's contrast, spatial frequency, specified division pitch width p, and brightness of backgrounds were held constant throughout the experiment.

4.4 Results

The results and discussions were divided into three parts. The first part is the result of the first experiment using the grating stimuli. Second part is the result of the second experiment which used scramble stimuli. To discuss the applicability of the second part, we carried out a magnitude estimation experiment (ME). The result of ME is in the third part.

4.4.1 Grating

We collected subject's response and only examined the "rougher" response by subjects. The third response (if the subjects could not decide which stimulus was faster/ rougher) were divided and inserted equally into another two responses. Results were plotted as the distribution of "faster" or "rougher" response when subjects perceived the target stimuli and compared with the reference. Figure 4.5 is the individual result of 10 subjects during speed cognition of Experiment 1.

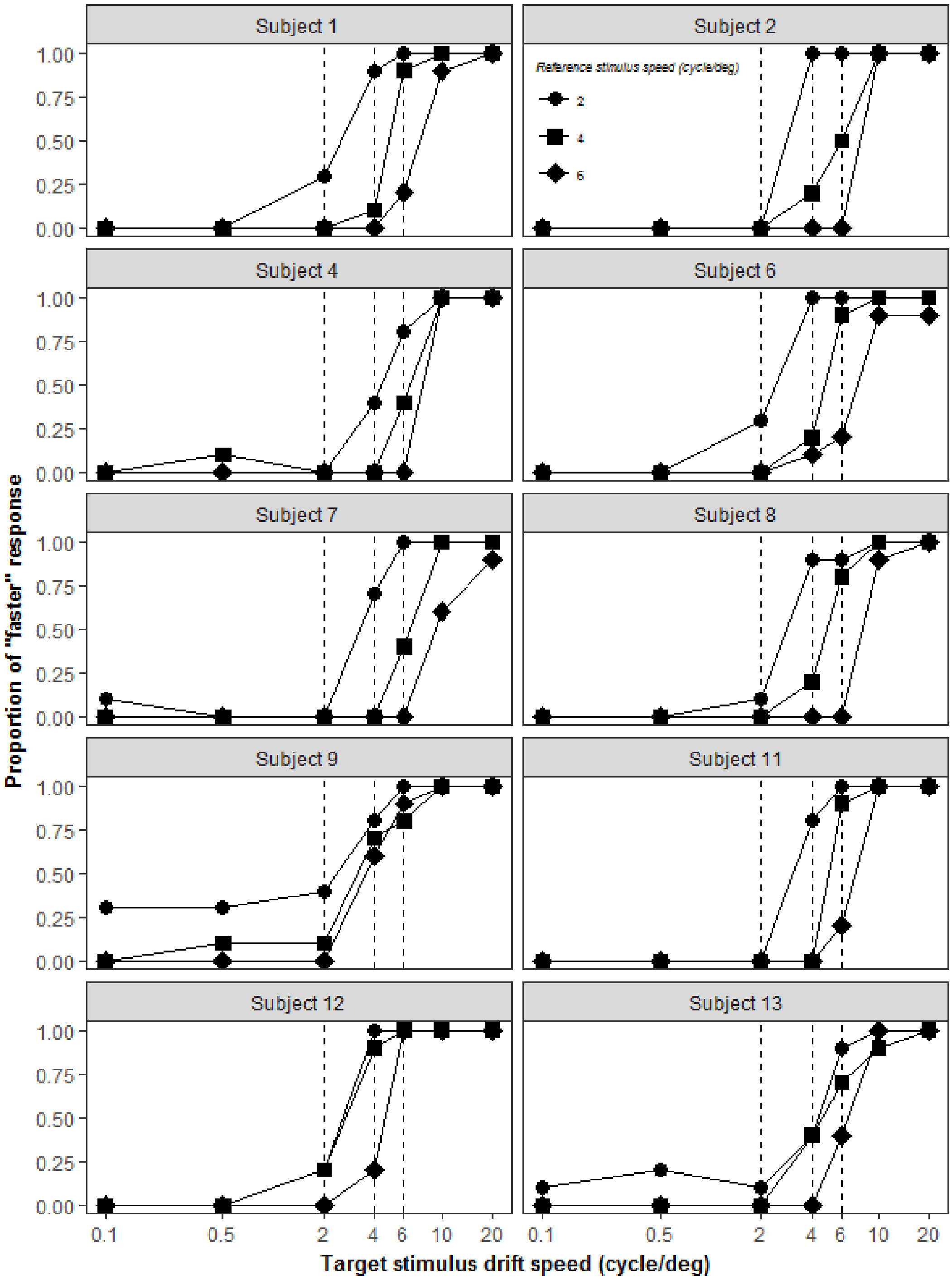


Fig 4.5 Results of 10 subjects for speed response.

In Fig 4.5 afterwards, three vertical lines are the three reference stimulus speed (2, 4, and 6 cycle/s). In speed cognition task, all subjects have the same trend. They accurately perceived the speed of target stimulus; “faster” responses increased when the drifted speed of target stimulus increased. This result was expected and showed that subjects did not having any difficulties to percept and recognize each of grating stimuli.

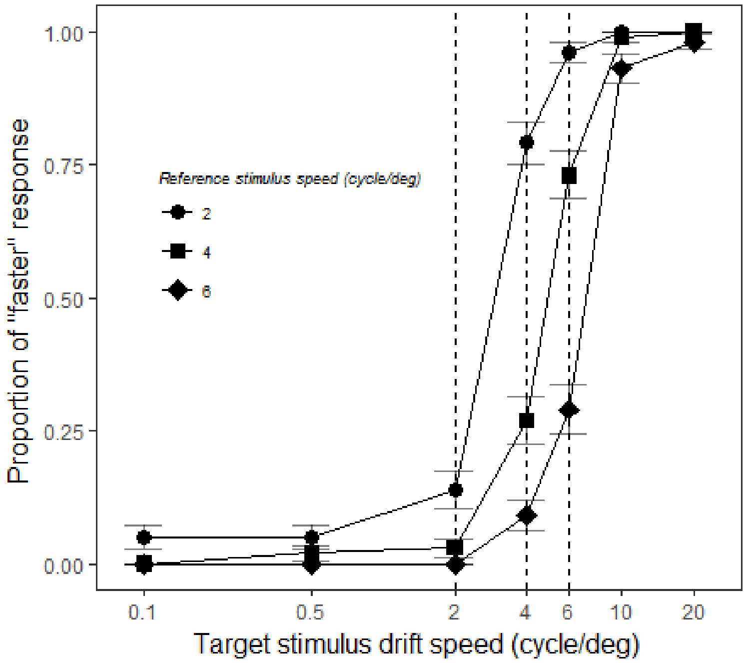


Fig 4.6 Mean of 10 subjects for speed response.

Mean of 10 subjects for "faster" response in speed cognition task are shown in Figure 4.6. Error bar represents the standard deviation. The chance level for "faster" response was 33.33%, since there were three types of response. Proportion during the same drift speed between reference and target showed that subjects were around the chance level in 4 and 6 cycle/deg, but less in 2 cycle/deg. The proportion of "faster" response of target stimulus 20 cycle/deg was almost 100% for each comparison to reference stimuli and proportion of "faster" response of target stimulus 0.1 cycle/deg was almost 0.

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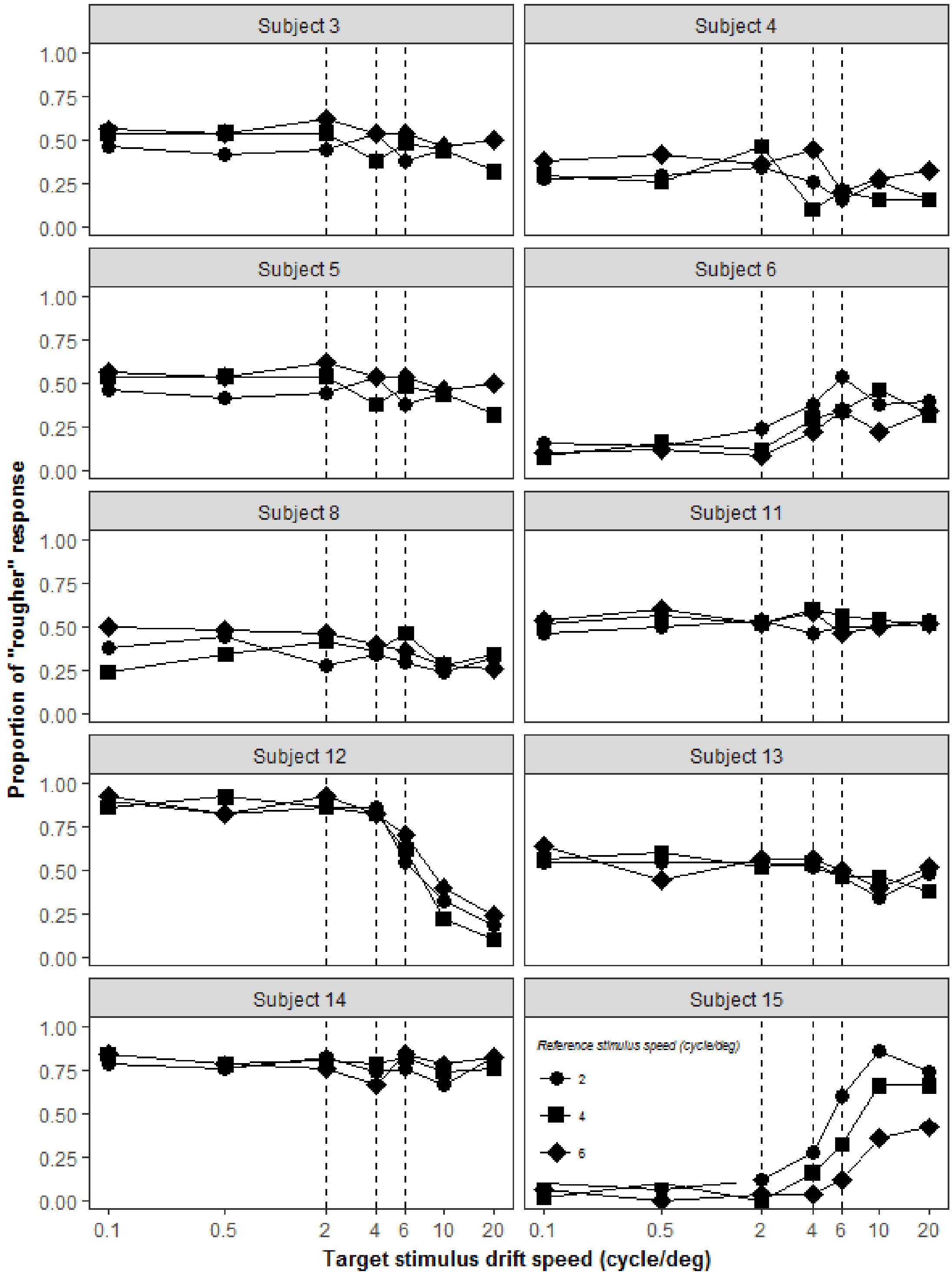


Fig 4. 7 Results of roughness response. Roughness percentage of target stimulus was plotted for each reference stimulus speed.

In roughness cognition task, inconsistent results between ten subjects were earned. Individual results of 10 subjects for "rougher" response in roughness cognition task are shown in Figure 4.7. Error bar represents the standard deviation. The chance level for “rougher” response was 33.33%. From the figure, numerous possibilities can be seen for roughness perception of grating stimuli. Therefore, we divided the result into three types, according to their cognitive characteristics.

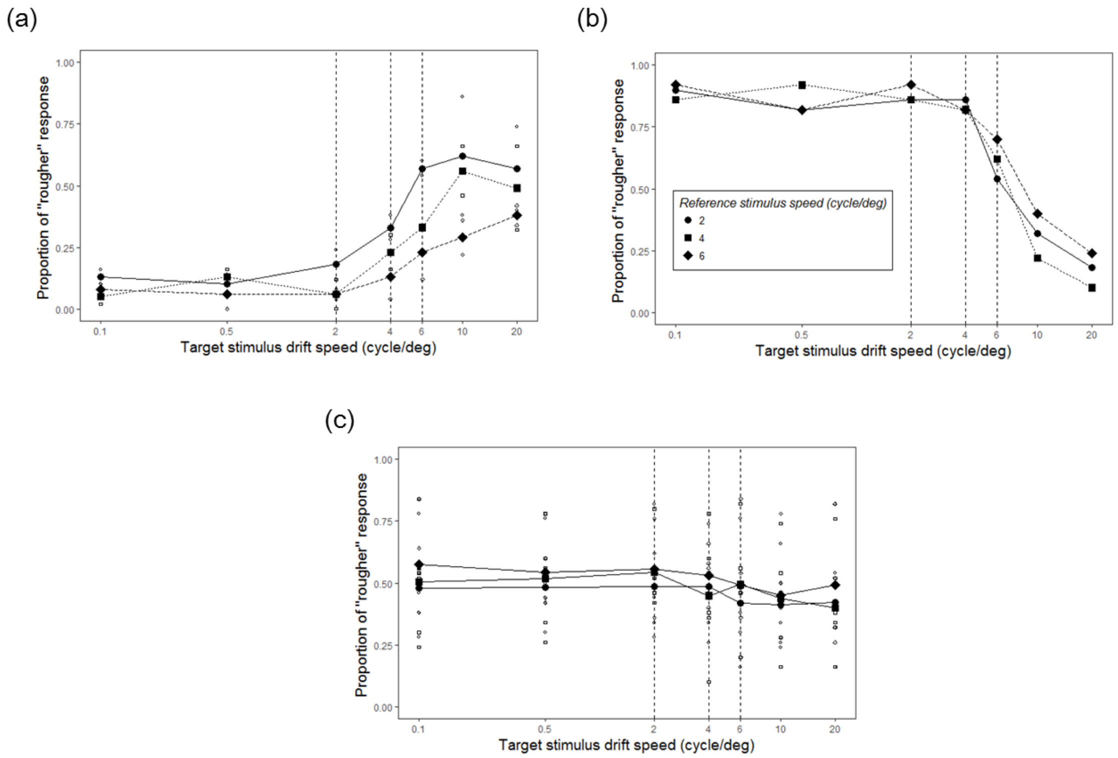


Fig 4. 8 Results of roughness response. Roughness percentage of target stimulus was plotted for each reference stimulus speed. Generally, results can be divided in three types of roughness responses. In (a), subject tends to feel rougher when target stimulus was faster, but dropped slightly after 10 cycle/s. In (b), subjects primarily felt smoother when target stimulus is faster. In (c), constant roughness were detected as the drift speed of target stimulus increased

Individual results were divided and “rougher” response in roughness cognition task is shown in Figure 4.8. The results of roughness cognition task can be divided into three groups. In group (a), subject tends to feel rougher when target stimulus was faster, but dropped slightly after 10 cycle/s. Proportion during the same drift speed between reference and target showed that subjects were around the chance level in 4 and 6 cycle/deg, but less in 2 cycle/deg. The proportion of “rougher” response of target stimulus 20 cycle/deg was slightly dropped for each comparison to reference stimuli and proportion of “rougher” response of target stimulus 0.1 cycle/degree was near to 0.

The fact that subject`s maximum roughness proportion was during target stimulus 10 cycle/degree was rather interesting, suggesting drift speed around 20 cycle/degree contribute to weaken roughness properties of visual textures.

In group (b), subjects primarily felt smoother when target stimulus is faster. Proportion during the same drift speed between reference and target showed that subjects were high above the chance level in 4 and 6 cycle/deg. The proportion of “rougher” response of target stimulus 20 cycle/degree was almost 10% for each comparison to reference stimuli and proportion of “faster” response of target stimulus 0.1 cycle/deg was almost 100%. The results were relative with group (a), logically proposing same tendency of fast speed of drift stimuli. However, no slight increase of “rougher” proportion between 10 and 20 cycle/degree. In group (c), constant “rougher” proporton was detected as the drift speed of target stimulus increased. The proportion was around 40 to 60 % which was above the chance level. Accordingly, subjects can sense the “roughness” inside the grating stimulation, but could not discriminate the difference of roughness in different speed.

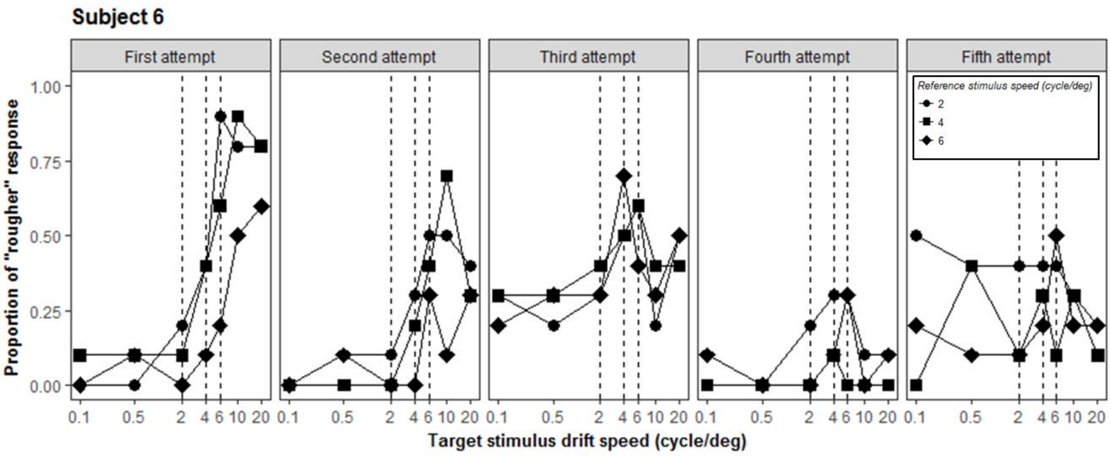


Fig 4.9 Proportion of ‘rougher’ response of a subject through five attempts of roughness cognition task

Interestingly, certain subjects were also not consistent for the duration of five attempts of roughness cognition task. As an example Figure 4.9 showed the results of subject 6 through each attempt from first to fifth week. Subject 6 participated the experiment from the first week and performed the experiment in every week for 5 weeks. At the first attempt, subject’s proportion of “rougher” response increased when the drift speed of target stimulus increased. However, the range of minimum and maximum value of the proportion was decreased since the third attempt. From the fourth attempt, the increase pattern of the graph cannot be seen any longer.

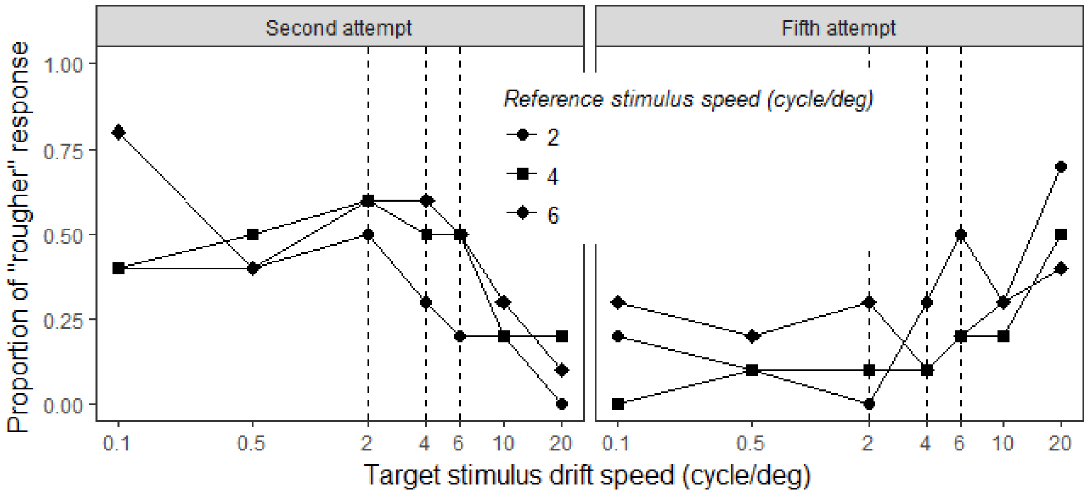


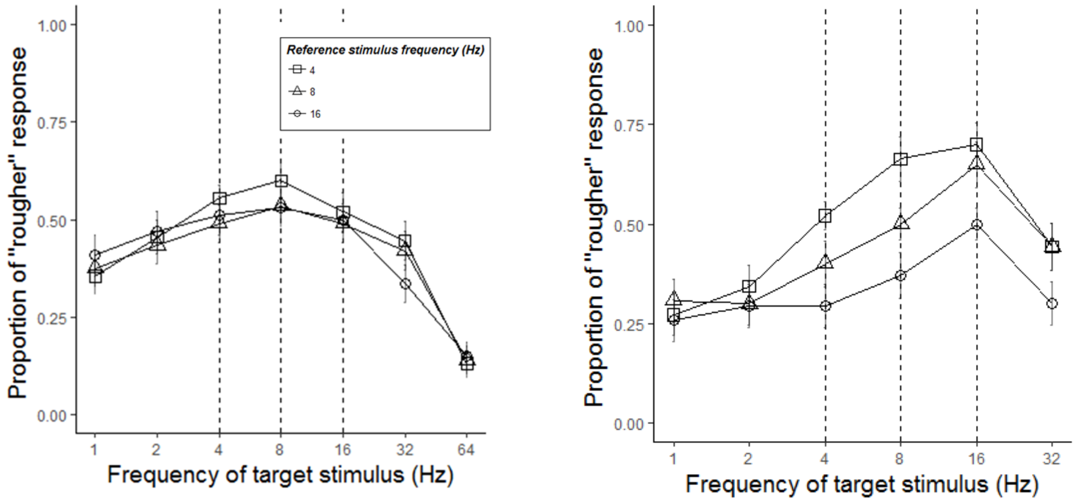
Fig 4.10 Proportion of 'rougher' response of a subject (Subject 8) for experiment 1. During the second set of the experiment (solid line), subject conformed type (b) of the roughness result in Fig 4. Three weeks later, the opposite results take place.

Subject 6 were also participated the experiment from the first week and performed the experiment in every week for 5 weeks. During the second attempt of the experiment), subject 6 conformed type (b) of the result in Figure 4.8. Three weeks later on the fifth attempt, the opposite result appeared.

In the roughness cognition task, we carefully controlled the experimental parameter and environment to be consistent in every task and every subject over the five attempts. It is unreasonable to conclude that the parameters influence the inconsistency among subjects. The fact that subject did not response consistently throughout five weeks may suggest that spatial mechanism in grating stimuli carried less consequence for roughness perception in visual task.

4.4.2 Scramble stimuli

Similar with Experiment 1, in Experiment 2, we collected subject's response and only examined the "rougher" response by subjects. The third response (if the subjects could not decide which stimulus was rougher) were divided and inserted equally into another two responses. Results were plotted as the distribution of “rougher” response when subjects perceived the target stimuli and compared with the reference. Figure 4.11 is the average of 10 subjects during roughness cognition task of Experiment 2.



(a) (b)

Fig 4.11 An average result of 10 subjects for roughness percentage of target stimulus was plotted for each reference stimulus flick frequency (Hz) for (a) first attempt and (b) second attempt.

An average result of 10 subjects for roughness percentage of target stimulus was plotted for each reference stimulus flick frequency (Hz). Comparing to Experiment 1, all subjects were more consistent in perceiving roughness of scramble stimuli. Subjects tend to feel rough when the flick frequency is higher, topping at 8 to 16 Hz. Afterwards, inclination of the graph start to drop during target stimulus was 32 Hz. In a pre-experiment (a), we executed the 64 Hz of target stimuli into the experiment. However, the percentage of “rougher” response was completely 0% in all subjects. This can be understood because of several physical factors limit the highest spatial frequencies that can be perceived by the human eye [66]. Therefore, the results for 64Hz were excluded in this study.

In Figure 4.11 (a), subject’s maximum rough proportion was during 8 Hz but 16 Hz in (b) but the difference was not significant. The chance level for “rougher” response was same as Experiment 1 which is 33.33%, since there were three types of response. Proportion during the same frequency between reference and target which were presented to subjects showed that subjects were around 30 to 50%. No target stimulus had the proportion reaching 100% or 0% for each comparison to reference stimuli. This clearly suggest that subjects properly perceived the scramble stimulation and looking for the undisclosed roughness components under the irregular spatial pattern.

We were interested on the minor difference between maximum proportions of two attempts in Figure 4.11. Even though there were no significant difference between the two maximum value, the transition may suggesting the optimum temporal frequency of irregular scramble stimuli that human can perceive to feel it "rough" sufficiently.

Therefore, we designed a magnitude estimation task for the same subjects in Experiment 2. Six types of target stimulus frequency in Experiment 2 were used and presented randomly to subjects. Only one reference stimulus was presented in each trial, placed at the same visual degree in Experiment 2. Size of the stimulus was also the same as those in Experiment 2. Subjects were asked to see each target stimulus and mention any number that represents the roughness of the stimuli. They were unrestrained to say any number but they were instructed to demonstrate small number for "smooth" stimuli and bigger number for "rougher" stimuli, with the roughness of reference stimuli were given as a "10". Apart from that, the experimental procedure and environment was carried out as similar as Experiment 2.

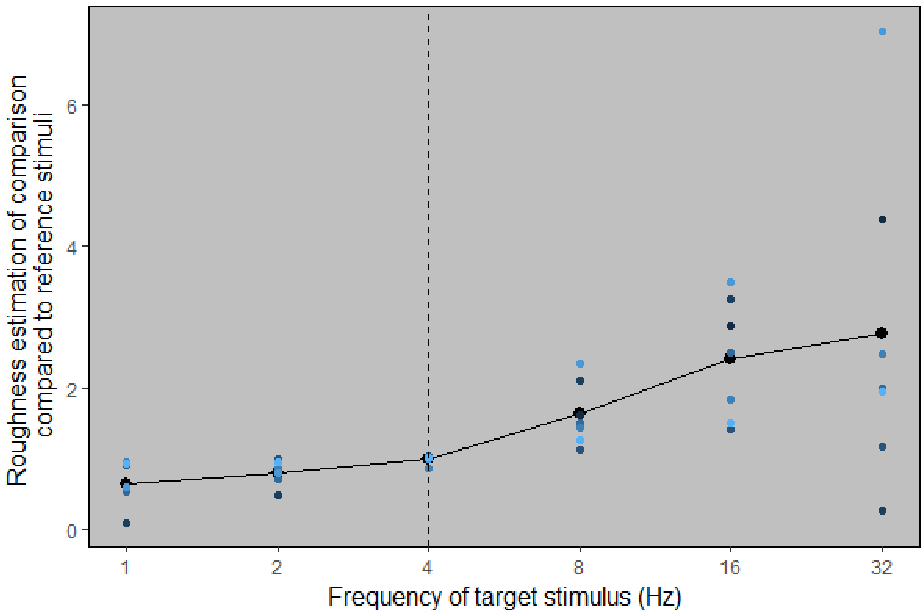


Fig 4.12 Results of roughness perception by magnitude estimation.

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The magnitude estimation result is summarized in Figure 4.12. No subjects responded more than 100 or less than 0 during the estimation task. Y axis is how rough the subjects perceive compared to the reference stimuli (4 Hz). The result is obviously shown the ability of subjects to declare the roughness of each target scramble stimuli when comparing with the reference. Generally, the roughness estimation was increased as the frequency of the scramble was increasing. Except for Subject 7, each subject showed similar tendencies of roughness perception to target flick frequency. However, bigger frequency such as 16 or 32 Hz had a bigger deviation compared to smaller frequencies. More subjects for the estimation task may be needed to confirm this account.

Contrast were also one of the main factors of roughness perception [67][68][69][70]. We also controlled the contrast of scramble stimulation as one of the parameter in a new task. Visual texture provides valuable information and events in the environment, and can be described along different perceptual dimensions such as roughness, contrast and glossiness [68][71].If there any turnaround of roughness response in subjects when we change the stimulus contrast, previous results might be invalid and the irregularity of spatial factors in scramble might not be the case in visual roughness perception.

Three different contrasts of each stimulus were created. We defined stimuli's contrast in this study as the different between the highest and lowest point in numeric presentations of RGB color model (black and white). In Experiment 1 and 2, only contrast 1.0 were used, which means RGB triplet of (0.0, 0.0, 0.0) and (255, 255, 255) were applied to grating and scramble stimuli. The contrast of the background was always remaining the same. In the next contrast-control task, we added another two contrasts which was 0.5 and 0.125, half and quarter value of original stimuli.

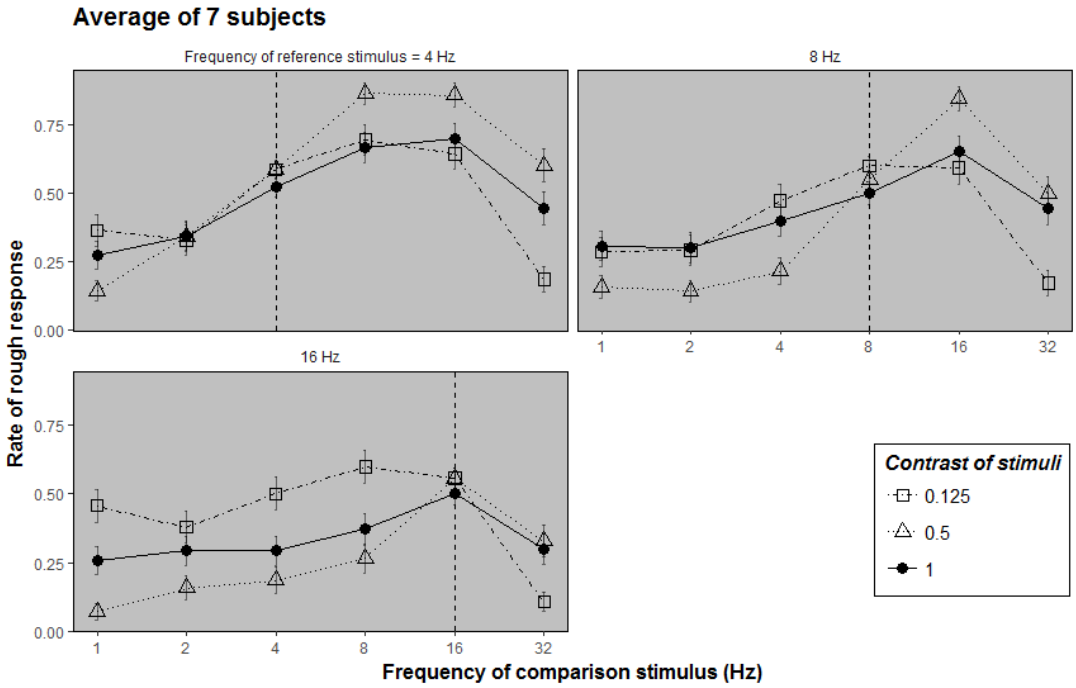

Fig 4.13. An average result of 7 subjects for roughness percentage of target stimulus was plotted for each reference stimulus flick frequency (Hz) in three different contrasts.

Similar task with Experiment 1 and Experiment 2 were carried out using another two types of contrast, but not in the same experiment. Every contrast-control task was done in different days with different value of contrast in the same seven subjects. Experimental procedure and environment were same as those in Experiment 2 with only the contrast were changed. The orders of the three contrasts were randomized between subjects to avoid any kind of habituation. The task was carried out approximately one month after Experiment 2.

The result of contrast-control task is summarized in Figure 4.13. In all cases, the tendency of roughness proportion was all the same as Experiment 2 in every condition of contrast value.

4.5 Discussion

By designing two experiments accompanying both stimuli with and without spatial regularity, we expected to understand more about temporal roughness in visual textures. The results and discussions were divided into three parts.

4.5.1 Temporal roughness factor in grating and scramble

The visual texture studies mainly focus on the ability of the observer to effortlessly discriminate pairs of texture regions. As such, the distribution of properties, such as brightness, color, size, contour, slope, and contour termination were found to affect textural segmentation. In this study, we controlled all possible properties for subjects to discriminate stimulation roughness by their temporal factor.

The maximum frequency value for temporal roughness is around 16 to 32 Hz. There were limited studies on visual temporal roughness, but most literatures of haptic temporal roughness proved an optimum value for subjects to feel the surface as a vibration. Together, these results indicate that vibrotaction plays an important role in the visual perception of fine textures. However texture-elicited vibrations can be perceived in terms of either their temporal or intensive properties. Roughness can be determined temporally, as a function of the frequency of the texture-induced vibrations elicited on the skin during haptic, or roughness can be determined by the intensity of these vibrations visually.

4.5.2 Irregularity of spatial factor in temporal roughness

The perceptual representation of the spatial information present in irregular textures, such as those found in the real world, have often been examined using scatter-dot displays. These enable the investigation of the perception of spatial texture attributes in isolation from other properties of surfaces such as luminance, colour and spatial frequency. Visually, the texture density is a simple way of describing a textured area and is thus an important cue for surface isolation. By using visual grating, we suggested that the visual system represents texture roughness is unconnected than of density. Regular pattern in grating may cause subjects to percept less temporal roughness when the stimulation moved. By using visual scramble, we suggested that the temporal visual roughness system is highly associated with haptic vibrotaction rather than of density. The irregular spacing in scramble stimuli suggesting the significance of spatial coding, which also suggesting consecutive connection between visual and haptic during temporal roughness perception.

4.6 Conclusion

In this chapter, we designed a visual base stimulation to investigate the temporal factors of roughness perception. Visual stimulation with regularity and irregularity of spatial spacing were used in this study. In the present study, we used computer-assembled gratings and scrambles images to define time characteristics of visual roughness. The parameters of the grating including pixels per cycle, spatial frequency, and visible size were calculated and one single static grating image was generated. The actual sine grating and drift speed (in cycles per second) were then computed and the amount of pixels to be shifted is specified to perform a perception of movement. We then investigated the effects of changes in those gratings and scrambles parameters to subjects' roughness perception. In the first experiment, we investigated the effects of temporal frequency towards roughness perception by visual drifted grating stimuli. We could understand that gratings do have several limitations for roughness perception to human visual. In the second experiment, we changed our stimulation to scramble stimulation which originated from the grating stimuli. In order to examine the results of the second experiment, we carried out a magnitude estimation experiment on each of the difference temporal frequency of scramble stimuli. The results showed a more converged results during the perception of irregular spacing in scramble stimuli, suggesting the significance of spatial coding. However, we also found the evidence of how visual temporal factors influence the perception of roughness.

Chapter 5 Summary

To differentiate a surface texture, human apply both visual and haptic information for the perception. We are focusing in roughness, one of significant domain in the perception of textures. In addition, we generally recognize object's texture by using multisensory inputs, combining both modalities to produce final judgement into understanding the texture. During the processes, how do those different modalities affects each other? Are they integrated or disconnect inside our brain? Cognition of surface roughness at the same time in the two senses (tactile and visual) is still undeclared, and how both effects on each other could be intriguing. Moreover, human sensations during roughness perception always involve in interaction, but a lot of brain's response during the interaction is still unknown. Additionally, the perception of roughness has been studied primarily in the haptic domain. Plenty of psychological studies investigating tactile texture perception have been conducted using artificial stimuli such as dot surfaces, grating patterns or abrasive papers. In addition, a lot of research has been devoted to tactile roughness, in particular with respect to the role of vibration cues and to the neural mechanisms. Visual roughness is likely a factor that contributes to the perception of visual gloss, mainly focusing on spatial factors This raises the question on how the temporal factors affect the roughness perception. Does the spatial factors are more significance than temporal? How do we code the temporal code in visual roughness? Present thesis was divided into three studies to test these hypotheses.

1. The main objective of the first study was to explore how the two modalities influence each other during roughness perception of fine surface. Perception of textures can be divided into two; fine (spatial features smaller than 200 μm) and coarse textures. We designed two unimodal tasks and four bimodal tasks within both modalities using six different fine surfaces and six different grayscale photos. In unimodal visual task (V-V), subjects were asked to judge rougher visual stimuli between two stimuli that were presented in sequential order. In bimodal visual task, (V-

Vt), subjects needed to do the same visual roughness judgement while perceiving an interference tactile stimulus at the second order of the presented stimuli. We expected to measure the influence of each modality by considering how subjects were interrupted by the emergence of the tactile interference stimulus. Furthermore, bimodal visual task are divided into two tasks, which applied rough tactile interference stimulus (V-Vt-rough) and smooth one (V-Vt-smooth). Unimodal and bimodal tactile task (T-T, T-Tv-rough, and T-Tv-smooth) were the opposite, which subjects need to do tactile rough-ness judgement. We propose that the roughness of the interference stimulus from different modality may affects subjects judgment and different between the two types. We found that tactile sensory was dominant in the perception of roughness by fine surface. During cross modalities, visual information has almost no effects toward tactile sensory, but in the other hand tactile information had significance effects onto visual sensory. Furthermore, we found that stimuli with smaller particles bring more interference into subject's perception compared to bigger particles in fine surface. We suggest that particles sizes are as significant as the modalities in visual, tactile, or multisensory integration of both, in roughness perception of fine surface.

2. In the second study, we measured brain activity during pattern perception using functional magnetic resonance imaging (fMRI). Human sensations always involve in interaction, but a lot of brain's response during the interaction is still unknown. This study was designed to discover the unresolved part of the brain during performing visual and tactile interaction roughness recognition experiments. We designed four types of tasks: visual task (VV), tactile task (TT), visual - tactile task (VT), tactile - visual task (TV). The common area of each of the brain activation during each task was analyzed; and the results showed that activations located in the frontal and parietal, suggesting these regions were actively involved in the cross-modal processing. Specific activation for the information from the tactile and visual modality was seen in the frontal and parietal lobe, respectively, suggesting the particular activation in each at this region.

3. In the third study, we designed a visual base stimulation to investigate the temporal factors of roughness perception. Visual stimulation with regularity and irregularity of spatial spacing were used in this study. In the present study, we used computer-assembled gratings and scrambles images to define time characteristics of visual roughness. The parameters of the grating including pixels per cycle, spatial frequency, and visible size were calculated and one single static grating image was generated. The actual sine grating and drift speed (in cycles per second) were then computed and the amount of pixels to be shifted is specified to perform a perception of movement. We then investigated the effects of changes in those gratings and scrambles parameters to subjects' roughness perception. In the first experiment, we investigated the effects of temporal frequency towards roughness perception by visual drifted grating stimuli. We could understand that gratings do have several limitations for roughness perception to human visual. In the second experiment, we changed our stimulation to scramble stimulation which originated from the grating stimuli. In order to examine the results of the second experiment, we carried out a magnitude estimation experiment on each of the difference temporal frequency of scramble stimuli. The results showed a more converged results during the perception of irregular spacing in scramble stimuli, suggesting the significance of spatial coding. However, we also found the evidence of how visual temporal factors influence the perception of roughness.

The results of the three studies showed that the spatial and temporal factors modulate the visuo-tactile roughness processing differently, but partially overlapping between the modalities and factors. The present thesis investigated the mechanism of roughness perception in visual and tactile. Future tasks for present thesis include approaching spatial and temporal factors in each of both modalities and also in cross-modalities perception to understand more of multisensory integration by behavioral and fMRI methods.

Publications

1. Bigger influence by smaller particles in tactile-visual cross-modal roughness perception of fine surface
Mohd Usairy Syafiq, Jiajia Yang, Yinghua Yu, Jinglong Wu
Neuroscience and Biomedical Engineering, In Press (2017).

2. Development of a tactile angle stimuli presentation device for tactile cognitive function discrimination
Mohd Usairy Syafiq ,Yinghua Yu, Jiajia Yang, Jinglong Wu
Proceedings of 2013 IEEE International Conference on Mechatronics and Automation (ICMA 2013), pp.116-121(2013).

3. Development and evaluation of a tactile cognitive function test device for Alzheimer's Disease early detection
Jiajia Yang, **Mohd Usairy Syafiq** , Yinghua Yu, Satoshi Takahashi, Zhenxin Zhang, and Jinglong Wu
Neuroscience and Biomedical Engineering, Vol. 3, No. 2, pp. 58-65 (2015).

4. Human characteristics of tactile-visual cross-modal on roughness perception
Mohd Usairy Syafiq, Jiajia Yang, Yinghua Yu, Hiroki Matsumoto, Satoshi Takahashi, Jinglong Wu
IEEE/WIC/ACM Web Intelligence Conference 2015, International Workshop on Complex Methods for Data and Web Mining (CMDWM), pp. 1-4 (2015).

5. 臨床用の触覚角度弁別装置の開発および認知症早期発見への応用
Mohd Usairy Syafiq，　于　英花，楊　家家，阿部　康二，呉　景龍
第 3 回日本血管性認知障害研究会 (VAS-COG Japan 2012) 東京，2012-9.

6. Applicability in screening tests for cognitive impairment and consideration towards decreases in tactile discrimination
Mohd Usairy Syafiq, Jiajia Yang, Jinglong Wu
2015 ICME International Conference on Complex Medical Engineering (CME 2015), OS12-3, p. 62, (Okayama, 2015-6).

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