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**Controlled emotional tactile stimulation during functional magnetic resonance imaging
and electroencephalography.**

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Abstract

Background: Tactile stimulation used to induce emotional responses is often not well-controlled. Replicating the same tactile stimulations across studies is difficult, compared to replicating visual and auditory modalities, which have standardized stimulus sets. Standardizing a stimulation method by replicating stimuli across studies is necessary to further elucidate emotional responses in neuroscience research using tactile stimulation.

The new method: We developed a tactile stimulation device. The device's ultrasonic motor and optical force sensor have the following criteria: (1) controls the physical property of stimuli, pressure, and stroking speed; (2) measures actual touch timing; (3) is safe to use in a magnetic resonance imaging (MRI) scanner; and (4) produces low noise in electroencephalography (EEG) and MRI.

Results: The noise level of the device's drive was sufficiently low. For the EEG experiment, we successfully used signal processing to diminish the commercial power supply noise. For functional MRI (fMRI) scans, we found <5% signal loss occurred during device rotation.

Comparison with existing method(s): We found no previous report about the noise level of a tactile stimulation device used to induce emotional responses during EEG and fMRI

recordings. The signal loss rate was comparable with that of other robotic devices used in fMRI scanners. Emotional feelings induced by this stimulation method were comparable with those elicited in other sensory modalities.

Conclusions: The developed device could be used for cognitive-affective neuroscience research when conducting EEG and fMRI scans. The device should aid in standardizing affective tactile stimulation for research in psychology and cognitive neuroscience.

Keywords: Emotion, Affective touch, Tactile stimulation device, Electroencephalography, Functional magnetic resonance imaging, Cognetics

49 1. Introduction

50 Tactile perception is considerably important for investigating human emotions.
51 Infants have immature vision (Braddick & Atkinson, 2011) and an immature digestive system.
52 They touch their mothers' skin and breasts, and feel the warmth of the parents' body when
53 they are held in their parents' arms. These events should be closely associated with survival
54 instincts because human infants must be under parental care for their nutrition and safety.
55 Tactile perception is the primary sensory modality for emotion, which acts as an alerting
56 system to avoid a dangerous state, especially in a newborn baby. Harlow (1958) investigated
57 daily contact duration to a surrogate mother in rhesus infants and found a significant increase
58 in contact duration when the surrogate mother was made of cloth rather than wire,
59 irrespective of the feeding ability. When using ≥ 15 -day-old rhesus infants, he also found longer
60 daily contact duration to the cloth surrogate mother even when the wire mother was heated
61 to a comfortable temperature (Harlow & Suomi, 1970). These findings suggest that tactile
62 comfort is fundamental for infants to get attached to a familiar individual.

63 Cognitive neuroscience research on emotion is mostly conducted using visual and
64 auditory stimuli. Except for pain and itchiness, the number of studies using tactile stimuli is
65 fewer than that of studies using visual and auditory stimuli. By using the International
66 Affective Picture Systems (IAPS), an epoch-making stimulus set, cognitive scientists and
67 neuroscientists can share identical stimuli across studies conducted worldwide (Lang, Bradley,

68 & Cuthbert, 1997). This dataset is used broadly in the cognitive and neuroscience research
 69 field, and has inspired researchers to develop additional stimulus sets such as Geneva
 70 Affective Picture Database (GAPED) (Dan-Glauser & Scherer, 2011), Nencki Affective Picture
 71 System (NAPS) (Marchewka, Zurawski, Jednoróg, & Grabowska, 2014), Open Affective
 72 Standardized Image Set (OASIS) (Kurdi, Lozano, & Banaji, 2017), and the revised version of
 73 IAPS published 2008 (Lang, Bradley, & Cuthbert, 2008). The auditory version of IAPS, called
 74 the International Affective Digitized Sounds (IADS), was subsequently published in 1999
 75 (Bradley & Lang, 1999), revised in 2007 (Bradley & Lang, 2007), and extended in 2018 (Yang
 76 et al., 2018). Despite these efforts to standardize visual and auditory stimuli for emotion
 77 studies, standardized tactile stimulus sets have not been developed because of differences
 78 between audiovisual and tactile stimuli. First, tactile stimuli have not been semantically
 79 categorized. Some studies using Japanese sound symbolic words called "onomatopoeia" have
 80 demonstrated that categorizing phonemes used for tactile evaluation on any materials could
 81 correspond to a tactile perceptual space including affective evaluation (Sakamoto &
 82 Watanabe, 2017). However, onomatopoeia is not completely identical across cultures, which
 83 prevents standardization. Second, the physical properties of a tactile stimulus have a greater
 84 impact on emotion, compared to other sensory modalities. In the modality of tactile sensation,
 85 physical property (e.g., stroking speed) is significantly important for inducing an emotional
 86 response. Löken et al. (2009) demonstrated that the C-tactile fiber, which is a candidate nerve

87 fiber for processing the emotional aspect of tactile sensory input, most strongly responds to a
88 stroking speed of 3 cm/s than to other stroking speeds. In addition, the subjective rating of
89 comfort was maximum for the 3 cm/s brush stroke stimulation than for other stroking speeds.
90 This finding has been replicated numerous times by using brush stroking (Ackerley, Carlsson,
91 Wester, Olausson, & Backlund Wasling, 2014; Essick et al., 2010; Essick, James, & McGlone,
92 1999; Löken, Evert, & Wessberg, 2011), which suggests that stroking speed is a very important
93 property for inducing an emotional response. However, in some neuroscience studies using
94 tactile stimuli, the experimenter manually delivers the touching stimulation (Case et al.,
95 2016; Kitada et al., 2005; McCabe, Rolls, Bilderbeck, & McGlone, 2008). Some automated and
96 controllable tactile stimulation devices have been developed (Lederman & Klatzky, 1997;
97 Lederman, Klatzky, Hamilton, & Ramsay, 1999), but are not MRI- or EEG-compatible. As in
98 gustatory research (Kobayakawa et al., 1996; Kobayakawa et al., 2005; Ogawa et al., 2005)
99 and olfactory research (Gotow & Kobayakawa, 2014; Toda & Kobayakawa, 2008; Toda, Saito,
100 Yamada, & Kobayakawa, 2006), stimulus timing needs to be controlled using a computer and
101 robotic device because stimulation timing was not controlled when tactile stimulation is
102 administered manually. For the timing control, an electric pulse (Allen et al., 2016;
103 Blankenburg, Ruff, Deichmann, Rees, & Driver, 2006) or vibration using a speaker (Asai &
104 Kanayama, 2012; Kanayama, Morandi, Hiraki, & Pavani, 2017; Kanayama, Tamè, Ohira, &
105 Pavani, 2012), or tapping or vibration using a piezostimulator (Wacker et al., 2011; Tamè et

al., 2012; Tamè et al., 2015a; Tamè et al., 2015b) could be used. However, it is unnatural to induce an emotional response using these types of tactile input.

Previous work has measured neural responses to a tactile stimulus that is applied using a customized rotating device [e.g., rotating drum stimulator (Johnson & Phillips, 1988; Manfredi et al., 2014); cylinder rotation device for gratings presentation (Burton et al., 1999); rotary tactile stimulator (RTS; Dancer Design, St. Helens, United Kingdom; Ackerley et al., 2013; McGlone et al., 2012), or a tactile spinning wheel (patent no. P200801805; Muñoz et al., 2014)], which allows the use of multiple materials to induce an emotional response (e.g., IAPS or IADS). Ackerley et al. (2013) attempted to use an RTS for an EEG study and reported that the RTS sent a signal to an EEG trigger channel at the onset of each brush motion. Muñoz et al. (2014) described their triggering method to mark the timing of the touching event for EEG analysis as a set of pins that codifies the stimulus in the corresponding socket. Each pin set is read by a linear array of photoelectrical sensors. Furthermore, McGlone et al. (2012) used RTS in positron emission tomography studies. This type of stimulator should be standardized so that the stimulation method can be replicated across studies. Hence, in this study, we attempted to develop a similar stimulating device and verify its usability in inducing an emotional response. In addition, we aimed to confirm whether the device fulfilled the following requirements: (1) it controls physical properties, pressure, and speed; (2) it measures actual touch timing; (3) it is safe to use in MRI; and (4) it produces low noise in EEG and MRI. To

satisfy these requirements for psychology, cognitive neuroscience, and neuroimaging studies, we developed a tactile stimulation system using nonmagnetic materials for its frame and ultrasonic motors (USMs) as the actuators to control the touch experience between human skin and various materials. We measured the emotional response of participants touching various materials under the control of this device and compared their response with the emotional responses in the same set of participants induced by other sensory modalities. We also evaluated noise contamination of the device in MRI signals and EEG waveforms.

2. Methods

2.1 Tactile stimulation device

2.1.1 Design of the MRI-compatible tactile stimulation device

A custom-made tactile stimulation device was designed and developed to present well-controlled tactile stimulation to an experimental participant's hand or to other body parts in a normal environment and in the MRI environment. Figure 1 illustrates the tactile stimulation device. The device has 2 degrees of freedom. It primarily consist of an elevating part and a rotational part. Each part is driven by an ultrasonic motor (USM: USR30-E3NT; amplifier: D6060E; Shinsei Corp., Tokyo, Japan) on which an optical rotary encoder with 1000 PPR resolution was mounted. The employed USM was an MRI-compatible mechatronics component. The elevating part moves the rotational part up and down with a rack-and-pinion

mechanism; the stroke in the vertical direction is approximately 80 mm. The rotational part has eight contact parts at the tips, and it rotates around the center. Various tactile materials (described later) can be attached to each contact part; therefore, different tactile stimulations can be realized by changing and reciprocating the contact parts on a participant's body part. In addition, because the contact parts can be easily attached and removed, tactile stimulations can be quickly exchanged, depending on the experimental objectives. Two pinion gears reduce the rotational velocity. One gear has 20 teeth, and the other gear has 80 teeth. To increase the generative torque at the rotational part, the two pinion gears reduce the rotational velocity. In the present device, the gear with 20 teeth is attached to a USM, and the gear with 80 teeth is attached to a shaft connected to the rotational part (i.e., the reduction ratio is 1/4) to ensure lateral movement of the contact part on the participant's body. Hence, the resolution of rotation measurement becomes theoretically 0.0225 degree at the rotating part.

A custom-made optical force sensor was implemented in the base of the rotating part. The rotational part is supported by parallel leaf springs composed of phosphor bronze, and the springs are slightly bent when a contact part touches the participant's body (Figure 2). The deflection changes because of the magnitude of applied force to the body part; therefore, the measurement of deflection allows the contact force to be estimated. In our force sensor, the deflection is measured with an optical displacement sensor (FWDK10U84Y0 amplifier; Baumer, Frauenfeld, Switzerland). Stiffness (i.e., the relationship between the applied force

and deflection) is necessary to calculate the contact force in Hooke's law, and can be experimentally obtained by comparing the sensor value with that of a digital scale when moving the contact part downward and pushing it onto the digital scale. The precision of the force measurement can be improved by conducting this calibration before the experiment. The minimum measurable force of the force sensor is approximately 0.1 N. The use of this force sensor allows the administration of the contact force and detection of the contact moment that can be used as an onset for brain functional measurement and analysis.

The device itself has very simple mechanics and structure from an engineering viewpoint, but it can be constructed by integrating conventional mechatronics technologies, based on a cognetics approach (Rognini & Blanke, 2016). The device enabled various renderings of well-controlled tactile stimulation (even in a very limited MRI environment) that were linked with functional brain measurements.

The prototype device cost approximately 500,000 Japanese yen (JPY). The USM and driver were 150,000 JPY, the optical sensor system was 80,000 JPY, and the other mechanical and electrical components were 10,000 JPY.

Figure 1. Schematic diagram and pictures of the MRI-compatible tactile stimulation device.

The panels show (a) the front view, (b) back view, and (c) dimensions of the device.

Figure 2. The principle of force measurements by the custom-made optical force sensor. The panels show (a) the noncontact condition and (b) the contact condition. The deflection of the leaf springs are obtained by comparing the distances from an upper leaf spring between the noncontact and contact conditions. By using the deflection, the contact force can be estimated in Hooke's law.

2.2 Basic performance and functions

The elevating part can vertically move the rotational part by 8.0 cm under a velocity <19.6 cm/s, and can apply a rated force <6.7 N to the participant's body. This movement allowed us to adjust the contact height of the device with respect to the thickness of each material. Thus, because of this elevating function and the optical force sensor, all eight materials can come into contact with the participant's body under the same contact condition, even if the materials have different thicknesses. In addition, this function was used to escape the contact part from the participant's body when changing the tactile stimuli. The maximum rotational velocity of the rotation part is approximately 60 rpm because of the decelerator. Therefore, tactile stimuli can be theoretically rendered to a participant's body at a velocity <50.2 cm/s; the rated shear force applied to a body part is <2.5 N.

The movements of the elevating and rotational parts were controlled by the rotations of USMs with a proportional-differential controller, which was programmed in Visual C++ (Microsoft, Redmond, WA, USA). The I/O control (e.g., transferring the control command to the USM [in voltage] and acquiring the displacement [in voltage]) was conducted via a data acquisition card (NI PCIe-6323; National Instruments, Austin, TX, USA) installed in a desktop computer. The sampling rate was set at 1 ms (i.e., 1 kHz sampling frequency); thus, the device conditions (e.g., position, velocity, contact force) can be recorded/logged every 1 ms. With this function, the moment the device physically touches the participant's body can be

detected by observing the contact force; it can then be used as an onset trigger to link with certain brain activities.

2.3 Safety and MRI compatibility

The tactile stimulation device was composed of nonmagnetic materials (e.g., polyacetal, acrylonitrile butadiene styrene, polyoxymethylene (POM), aluminum, and brass) to ensure its safety in the MRI environment. Heat caused by the eddy current in the MRI environment was negligible because the conductive parts (e.g., brass screws and shafts) used in the moving parts were very small. During the experiment, an experimenter can observe the device's state and the applied force on a monitor, and can immediately disable the device by pressing emergency buttons when any problem occurs or unexpected values are displayed. The generative force was not very large (<6.7 N in the vertical direction and <2.5 N in the lateral direction); therefore, the device should not cause serious harm to a participant's body, even in the worst case scenario. The strong and time-varying magnetic field may affect the driving of the device (e.g., force, velocity). However, it is difficult to directly observe the influence in real time because additional MRI-compatible sensors have to be implemented into the device. The influence can instead be estimated by monitoring the magnitude of error between the desired and the real positions of the device. A large error indicates a breakdown in the device's control because the implemented controller works to minimize error. The influence of the magnetic

field on the tactile stimulation can be considered negligible because the analysis of the device behavior revealed that the error for an experimental block was less than 0.07 degree on average even if the device contacted a human body part during the EPI sequence; manual tactile stimulation with this precision is not feasible. Observing of the error also allows an estimation of the heat state on the USMs due to the long-time because it degrades performance in the position control. In addition, the participant's body part was not completely fixed on the device. The device was basically well-controlled in not harming the participant. However, we instructed the participants to remove their body part from the device if they feared for their physical safety.

The MRI compatibility of the device [i.e., safety, negligible influence of running the device during MRI scanning, and no influence of radiofrequency radiation and the magnetic field on the device (Gassert, Moser, Burdet, & Bleuler, 2006; Hara et al., 2014)] was confirmed using a 3T MRI scanner (Verio; Siemens, Erlangen, Germany) and water phantoms while running the device in various modes in the MRI environment. The details of the MRI-compatibility test are described later in sections “2.11 Functional MRI-compatibility test scan with spherical phantoms” and “2.12 Functional MRI-compatibility test scan with human participants.”

2.4 Psychological experiments

We conducted psychological experiments to confirm that the emotional responses were

distributed from strongly negative to strongly positive to tactile stimulations delivered by the developed device. In addition, we conducted identical psychological experiments by using visual and auditory emotional stimuli to compare the sensory modalities.

2.5 Participants

Fifty-one healthy individuals [28 men, 23 women; mean age (standard deviation), 21.94 (2.89) years] without any injury on their hands participated in the series of experiments. The participants did not have any neurological and/or psychiatric disorders. Two individuals were excluded from the analysis because a software error occurred during the tactile experiment. They therefore did not complete all experiments. All participants had normal vision or corrected vision with glasses or contact lens and reported no hearing problem. This study was conducted in accordance with the recommendations of Human Research Ethics Committee of Hiroshima University (Hiroshima, Japan). All participants gave written informed consent.

2.6 Visual stimulus

Positive, neutral, and negative pictures were selected, based on their valence values from original reports by Lang et al. (2008). The item numbers were 2039, 2208, 2211, 2311, 2345.1, 2795, 4619, 5250, 5621, 6831, 7018, 7233, 7499, 8467, 8475, 9190, 9342, and 9930. The

valence values ranged from 2.26 (item no. 2345.1) to 7.57 (item no. 5621), as illustrated in Figure 3a (open gray circles). Some mild positive and negative stimuli were used in training the participants to press the button and rate their emotion.

2.7 Auditory stimulus

Positive, neutral, and negative pictures were selected, based on the valence values originally reported by Bradley and Lang (2007). The item numbers were 242, 244, 254, 262, 320, 351, 368, 373, 375, 380, 410, 699, 712, 723, 725, 802, 811, and 815. The valence values ranged from 2.42 (item no. 712) to 7.9 (item no. 815). The valence distribution is illustrated in Figure 3b (open gray rectangles). Some mild positive and negative stimuli were used to train the participants to press the button and rate their emotion.

Figure 3. Valence scores averaged across all participants for (a) visual stimuli (circles) and (b) auditory emotional stimuli (rectangles). The filled black symbols indicate the scores acquired in this experiment and the open gray symbols indicate the scores acquired in the original

publication of the International Affective Picture Systems (IAPS) and International Affective Digitized Sounds (IADS). The x axis indicates each item in IAPS and IADS, ordered in ascending manner of the valence values acquired in the original reports.

2.8 Materials used to induce tactile stimulus

Based on a previous study (Sakamoto & Watanabe, 2017), we selected eight materials to induce positive and negative emotions when touching them. Satin, fur, Poron sponge (a type of urethane foam), urethane, human skin gel (EXSEAL Co., Ltd., Gifu, Japan), GelGems (Kameyama Co., Ltd., Osaka, Japan), plastic turf, and bristle were selected (Figure 4c). To differentiate the sensations of sticky and slippery, we chose human skin gel with hardness level 5 as the strong sticky material. In addition, GelGems, which consists of a thermoplastic polymer and liquid paraffin, was adopted as the weak sticky material; it feels sticky but does not become attached to the fingers when stroking it. Human skin gel includes polyol (>90%) and diisononyl phthalate (>7%) as a plasticizer. Hardness was measured with a durometer (Asker C-type; Kobunshi Keiki, Co., Ltd., Kyoto, Japan). Both of these gel-type materials leave no residue after touching them on the human skin surface. Bristles stimulus was made by boar (i.e., pig) hair brush. All materials used in this study were not metallic or magnetic, and were isolated from the device by styrene foam and thermoplastic polymer. These features confirmed its MRI compatibility and that it causes no additional noise in an EEG recording

when touching the materials.

2.9 Procedures

The order of the experiments using each sensory modality was counterbalanced across all participants. Owing to the constraint of the experimental room settings, the visual (V) and auditory (A) experiments were conducted in one session, and the tactile (T) experiment was conducted in another session. The order of visual and auditory experiment in the audiovisual session were counterbalanced (i.e., VA or AV). Therefore, the order of the experiments was as follows: VA-T, AV-T, T-VA, and T-AV.

First, the participants sat in a comfortable chair. The details of the experiment were explained to them. In particular, the instructions emphasized that the participants would be presented with an emotional stimulus and that the touch of the experimental materials with pressure to the skin may cause slight pain for some individuals. The participants could cancel their participation in this experiment at their discretion.

Participants viewed a display on a 24-inch liquid crystal display computer monitor (model E2416Hb; Dell, Inc., Round Rock, TX, USA) that was placed before them. The distance between the participant and the display was maintained at 60 cm. The resolution of the display was 1366×768 pixels, and the refresh rate was 60 Hz. Before the experiment, the participants underwent some training trials to become familiar with the task flow.

At the beginning of the experiment, a black background with a white fixation cross was displayed on the monitor. The participant viewed the fixation cross in the center of the display, and then waited for the stimulus, which induced an emotional response for 2 seconds. The stimulus was presented for 4 seconds. After the 4-second presentation, the participants evaluated their emotional state in the AV session, based on six items: valence, arousal, dominance, happiness, sadness, and fear. In the T session, the participants evaluated 10 items: valence, arousal, hardness, roughness, dryness, warmth, sticky/slippery, sharpness, quality (high/low), and naturalness. In this study, we focused only on the emotional responses (valence and arousal). After obtaining all responses to the stimulus, the next trial began with a 1-second blank.

2.9.1 Visual experiment

One of the selected IAPS pictures was presented as a stimulus to induce an emotional state. While the visual stimulus was presented, the fixation cross disappeared. Participants viewed the presented picture and maintained their eye gaze on the place where the fixation cross had been placed. The order of presented pictures was counterbalanced, based on their valence values. The stimulus presentation was controlled by using Presentation software (version 18.1, Build 03.31.15; Neurobehavioral Systems, Inc., Albany, CA, USA).

2.9.2 Auditory experiment

The auditory experiment was conducted in settings that were nearly identical to those of the visual experiment. The auditory stimulus was presented via speakers (GX-70HD II; Onkyo, Corp., Osaka, Japan), which were placed on the left and right side of the display monitor. The other settings for the auditory stimuli were identical to the settings used in a previous study (Yang et al., 2018).

2.9.3 Tactile experiment

The experimental settings and procedures of the tactile experiment were similar to those previously described in the visual and auditory stimuli experiments. However, the design for the tactile experiment was more complex than that of the visual and auditory experiments. This factor required some additional experimental settings. First, the participants sat in a height-adjustable chair and adjusted the height of the chair so that they could comfortably place their arm on the table with no tension in their arm muscles, even if they were required to maintain their posture for 30 minutes. Under the participant's arm, an arm rest board was attached to the edge of the desk to extend the area for the participant to place the arm backward to the desk. The participants could freely decide where to position their arm, based on comfort. A sponge board was on the arm rest and towels covered it.

A black cardboard box occluded all of the left hand area from their wrist. The tactile

stimulation device was in the cardboard box, and its movement and contact on the hand within the cardboard box were monitored by a camera (TS-PTCAM; I-O Data Device, Inc., Kanazawa, Japan). Under the participants' wrist, an additional sponge was placed as a hand rest at the participants' request. The position of the stimulation device was adjusted so that the tip of the stimulation rod was in contact with the surface of the participants' palm or back of hand (i.e., the dorsal part of the palm). Before the training session in this experiment, the contact pressure was calibrated, as described previously in section "2.1 Tactile stimulation device," to maintain a maximum pressure of <250 g (≈ 2.5 N).

In this experiment, we used two types of pressure (i.e., intense pressure [approximately 250 g at calibration] and weak pressure [approximately 30 g at calibration]) and three stimulation speeds (i.e., quick [30 cm/s], middle [3 cm/s], and slow [1 cm/s]). There were 96 stimulation patterns (i.e., 8 materials $\times$ 2 positions $\times$ 2 pressures $\times$ 3 speeds).

The practice session involved a one-time stimulation for each material. In total, eight stimulations were delivered to familiarize the participants with the task flow and in evaluating a stimulus. Intense stimulation pressure and the 10 cm/s speed were used only in the practice session. Thus, in the practice session, the participants experienced all materials that were used in the experiment, whereas all stimulations in the experiment were new with regard to the combination of speed, pressure, and material.

After the practice session, the participants performed the tactile evaluation task for

two separate blocks: the palm or the back of the hand. The order of the two blocks was counterbalanced. Pictures of the device are shown in Figure 4, and a video of the device rotation can be found in the Electronic Supplementary materials (TacDev01_S01_Device_Movement.mp4).

Figure 4. Photographs of the device developed and tested in this study. The panels show (a) the device, (b) the device in a functional magnetic resonance imaging (fMRI) scanner, and (c) the materials used in the sequence of experiments; the left upper to bottom panels show, respectively, fur, Poron sponge, GelGems, and plastic turf, and the right upper to bottom panels show, respectively, satin, urethane, human skin gel, and bristles.

2.10 Electroencephalogram recording experiment

We conducted an EEG recording during the tactile stimulation delivered by the tactile stimulation device to confirm that noise reduction and the stimulus timing control were sufficient. First, we recorded EEG waveforms in a completely noise-free shield room (i.e., in an area with a 50-Hz commercial power supply) with the device. We also recorded the EEG activity of three participants who did not participate in the psychological experiments in a normal EEG shield room (i.e., in an area with a 60-Hz commercial power supply). Most procedures were the same as those previously described in subsection “2.9.3 Tactile experiment.” Only two materials, fur and plastic turf, and the same speed (i.e., middle) and pressure (i.e., intense) were used in this experiment. The participants’ EEGs were recorded using the BrainAmp DC amplifier (Brainproducts, GmbH, Munich, Germany) and an EEG recording cap (EasyCap, GmbH, Herrsching, Germany) with 64 channel electrodes (using the 10-10 international standard position) referenced to the nose tip. The sampling rate was 500 Hz, and the online hardware filter was 1 Hz at the lower edge.

2.11 Functional MRI-compatibility test scan with spherical phantoms

We conducted functional MRI (fMRI) scans of a vendor-supplied spherical phantom (Siemens) to confirm that the developed device could safely operate in an MRI scanner without producing noise on the scanned images by using the Verio 3T scanner (Siemens) with a 32-

channel head coil. Typical echo planar images (EPIs) of the phantoms were acquired with repetition time 1 (TR1). The acquisition parameters for the EPIs were set, as follows: the slice orientation was axial; flip angle, 90 degrees; slice thickness, 3 mm; slice gap, 3.6 mm; slice orientation, axial; TR, 1 second; echo time, 30 ms; and acquisition matrix, 64×64 . Sixteen slices were acquired.

In this experiment, the tactile stimulation device was driven near the isocenter of the magnet in the following modes: “mode 1” was the “no-device condition” in which the EPI scans were obtained without the device; “mode 2” was the “device off condition” in which the EPI scans were obtained with the device but without a power supply; “mode 3” was the “device on condition” in which the EPI scans were obtained with the device on and the power switch on; and “mode 4” was the “device rotating condition” in which the device rotated for 4 seconds with various interstimulus intervals with an interval ranging 9–16 seconds. Each run consisted of 40 rotations.

2.12 Functional MRI-compatibility test scan with human participants

We conducted functional MRI (fMRI) scans of three healthy individuals to confirm that the developed device could safely operate in an MRI scanner without producing noise on the scanned images. The scanner was the Verio 3T scanner (Siemens) with a 32-channel head coil. Typical EPIs were acquired with repetition time 3 (TR3). The acquisition parameters for the

EPIs were set, as follows: slice orientation was axial; flip angle, 90 degrees; slice thickness, 3 mm; slice gap, 3.6 mm; slice orientation, axial; TR, 3 seconds; echo time, 30 ms; and acquisition matrix, 64×64 . Forty-nine slices were acquired. The other settings are the same as those used in the phantom scan. To compare the noise level with the device with that without device, we analyzed EPI images from 20 individuals during a resting task and from 13 individuals while viewing images by using an MRI-compatible monitor (NNL MRI In Room Viewing Device, NordicNeuroLab, Bergen, Norway). The timing and duration of visual stimulus presentation was exactly the same as that of the tactile stimulation.

3. Results

3.1 Confirmation of the emotional responses for each sensory modality

To confirm that the emotional response of the participants in this experiment were typical and comparable to those reported in previous studies (Bradley & Lang, 1999; Lang et al., 1997), the averaged valence scores were calculated and plotted with the original scores reported in previous studies. Figure 5 shows the averaged valence scores from this experiment and from previous experiments for each stimulus in ascending order of valence scores reported in the original experiment. This finding suggested that the difference was within one point for the IAPS and within 1.5 points for the IADS. Statistical tests on the averaged valence values across participants (repetition was 18 pictures for IAPS and 18 sounds for IADS) for the

difference between scores acquired from the two studies revealed no significant difference for the IAPS ($t(17) = -0.004$, n.s.) and a significant difference for IADS ($t(17) = -3.20$, $p < .01$). The valence value for IADS in this experiment was lower than that of the original report. However, as illustrated in Figure 5, the distribution of the scores in this experiment ranged from 1.98 to 7.26, which suggested a normal range of valence values among the participants, compared to the values in the original report (which ranged from 2.42 to 7.9).

We then compared the participants' emotional responses to audiovisual emotional stimuli with responses to tactile emotional stimuli by plotting them in ascending order by the expected valence value for each material (e.g. bristles can induce a low valence score [i.e., negative response] because it is prickly and uncomfortable). Figure 5 shows that the slope for negative items to positive items was similar for each sensory modality. The score range of the tactile stimuli was slightly narrow but similar to that of other sensory modalities: IAPS, 2.10–7.24; IADS, 1.98–7.26; tactile stimulus set, 2.44–6.67).

Moreover, the correlations between valence and arousal were calculated. For the IAPS, the correlation for the acquired data was -0.19 , whereas the correlation for the original data was 0.16 . Both results were not significant ($p > .10$). For the IADS, the correlation for the acquired data was -0.02 , whereas the correlation for the original data was -0.33 . Both results were not significant ($p > .10$). For tactile emotional stimuli, the correlation was -0.88 and significant ($p < .001$). Figure 6 reveals a trend of a low valence value when the participants

464 felt a stronger arousal. The averaged valence and arousal value for each stimulation are
 465 available in the Supplementary materials
 466 (TacDev01_S02_Emotional_Response_Ratings.xlsx).

467
 468 Figure 5. The valence scores, which are averaged across all participants, for emotional stimuli
 469 for each sensory modality, and their standard deviations. The x axis presents each item of the
 470 IAPS and IADS, ordered in ascending manner of the valence values acquired in the original
 471 reports for visual and auditory stimuli. For tactile stimuli, the x axis presents each time of 96
 472 stimulation patterns, which are ordered by the expected valence value.

474

Figure 6. Scatter plots of the valence scores versus the arousal scores for each sensory stimulus set used in the psychological experiments. The filled black symbols represent the data acquired in this experiment, and the open gray symbols represent the data from previous studies.

3.2 Modulation factors of the emotional valence and arousal scores

To determine which aspect of the tactile stimulation modulates the emotional valence and arousal, we conducted repeated-measures analysis of variance (ANOVA) with four within factors: material (fur, satin, urethane, Poron sponge, GelGems, human skin gel, plastic turf, and bristle); speed (1 cm/s, 3 cm/s, and 30 cm/s); pressure (intense or weak), and location (palm or back of the hand). Multiple comparisons were conducted with p-value correction by the modified sequentially rejective Bonferroni method.

3.3 Valence scores

For the valence scores, the following features were observed: the main effect of material [$F(7,336) = 74.26$, $p < .001$] and pressure [$F(1,48) = 29.61$, $p < .001$], and significant interactions between material and speed [$F(14,672) = 4.05$, $p < .001$] and between material and location ($F(7,336) = 6.07$, $p < .001$). Multiple comparison for the main effect of material revealed that most combinations were significant ($p < .01$), whereas the differences between

GelGems and human skin gel, urethane and Poron sponge, satin and urethane, and satin and Poron sponge were not significant. The averaged values of valence scores are illustrated in Figure 7 (left panel, black bars). The main effect of pressure revealed that intense pressure tended to induce negative valence scores, irrespective of the other factors, although the difference did not exceed 1 point (Figure 7; right panel, black bars).

To determine the simple main effects of speed and pressure for each material, we conducted multiple comparisons. For speed, significant effects were observed for fur, GelGems, urethane, Poron sponge, plastic turf, and bristle. When the device stroked the fur against the participants' hand, the slowest stimulation speed induced a less positive emotional response than did the other two speed conditions (for 1 cm/s < 3 cm/s: $t(48) = 3.19$, $p < .01$; for 1 cm/s < 30 cm/s: $t(48) = 2.46$, $p < .05$). By contrast, the slowest stimulation speed using plastic turf induced a more positive emotional response than did the other two speed conditions (1 cm/s > 3 cm/s: $t(48) = 2.92$, $p < .05$; 1 cm/s > 30 cm/s: $t(48) = 2.37$, $p < .05$). When the device stroked the participant's hand with GemGel, the middle speed stimulation induced a less positive emotional response than did the other two speed conditions (for 3 cm/s < 1 cm/s: $t(48) = 2.09$, $p < .05$; for 3 cm/s < 30 cm/s: $t(48) = 2.73$, $p < .05$). For Poron sponge and bristle, a significant difference between the 1 cm/s and 3 cm/s speeds was observed (Poron sponge: $t(48) = 2.53$, $p < 0.05$; bristle: $t(48) = 3.10$, $p < 0.01$), whereas the direction was opposite (Poron: 3 cm/s > 1 cm/s; bristle: 1 cm/s > 3 cm/s). When the device stroked the participants' hand with urethane,

the fastest stimulation induced a more positive emotional response than did the other two speed conditions (for 1 cm/s < 30 cm/s: $t(48) = 3.05$, $p < .05$; for 3 cm/s < 30 cm/s: $t(48) = 2.95$, $p < .05$). For the other materials (e.g., satin and human skin gel), the stroke speed had no significant effect. All valence scores for each speed condition are illustrated in Figure 8.

With regard to location, significant effects were observed only for bristle. When the device stroked the back of the participants' hand with bristle, a more negative emotional response was induced than it was with a touch on the palm ($F(1,48) = 27.38$, $p < .001$).

Figure 7. The averaged values of the valence and arousal scores across all participants for each material and pressure condition.

Hum.Gel, human skin gel

Figure 8. The averaged values of valence scores across all participants for each speed condition (upper graph) and location condition (lower graph) nested in each material.

* $p < .05$ and ** $p < .01$.

Hum.Gel, human skin gel

3.4 Arousal scores

The arousal scores indicated a main effect of material ($F(7,336) = 53.59, p < 0.001$), speed ($F(2,96) = 18.01, p < .001$), and pressure ($F(1,48) = 22.30, p < 0.001$). The scores also indicated significant interactions between material and pressure ($F(7,336) = 2.78, p < 0.01$), and between material and location ($F(7,336) = 3.79, p < 0.001$).

Multiple comparisons for the main effect of materials revealed that many combinations were significant ($p < 0.01$), whereas the scores for satin were not significantly different from urethane, Poron sponge, GelGems, or human skin gel. The averaged values of the arousal scores are illustrated in Figure 7 (left panel, gray bars). Moreover, three pairs of similar materials were not significantly different: urethane and Poron sponge, GelGems and human skin gel (i.e., sticky materials), and plastic turf and bristle (i.e., prickly materials). Multiple comparisons for the main effect of speed revealed that all combinations were significant ($p < 0.01$) and a faster stroke speed induced greater arousal scores (for $1 \text{ cm/s} < 3 \text{ cm/s}$: $t(48) = 4.92, p < 0.001$; for $1 \text{ cm/s} < 30 \text{ cm/s}$: $t(48) = 4.73, p < 0.001$; for $3 \text{ cm/s} < 30 \text{ cm/s}$, $t(48) = 2.83, p < 0.001$) (Figure 9a).

To determine the simple main effects of pressure and location for each material, we conducted multiple comparisons. For pressure, significant effects were observed for human skin gel, urethane, plastic turf, and bristle ($p < 0.01$). In all participants, the intense pressure condition induced higher arousal responses (Figure 9b). For location, significant effects were observed only for bristle. When the bristles were touched to the back of the participants' hand,

a higher arousal state was induced than it was with a touch on the palm ($F(1,48) = 16.46$, $p < .001$) (Figure 9c).

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Figure 9. Averaged values of the arousal scores across all participants for (a) speed (upper left),

(b) pressure (upper right), and (c) location (lower) conditions, nested in each material.

* $p < .05$ and ** $p < .01$.

Hum.Gel, human skin gel

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3.5 Electroencephalogram noise contamination with saline solution

We recorded one minute of EEG waveforms for each condition (i.e., with the device

off, with the device on, and with the device rotating) by using a container of saline solution. We also recorded an EEG when we connected a power cable for a personal computer to a commercial power supply near the container. All electrodes were dipped into the saline solution and carefully fixed on the table with mending tape. To evaluate continuous power supply noise contamination, we calculated the spectrum power for each electrode, based on the data of the whole recording period (Figure 10a) using fast Fourier transformation with Welch's method (window size: 1024; number of fast Fourier transformation points: 1024; overlap: 50%). As illustrated in Figure 10, the device off condition showed no clear peak at 60 Hz, which suggested the commercial power supply produced no noise contamination when the power of the device was off. In the device on condition and in the rotating condition, we observed a clear but very small peak at 50 Hz. The mean values were calculated for five frequency bins: 43–45 Hz, 46–48 Hz, 49–51 Hz, 52–54 Hz, and 55–57 Hz, which are illustrated in the lower part of Figure 10. We found that the power only at 49–51 Hz was prominent under the noise contamination condition, whereas the power value at 49–51 Hz for the other conditions were typically 5 dB smaller than the noise contamination.

Figure 10. Spectrum powers with saline solution for each condition. (a) Spectrograms for all electrodes are illustrated for each condition. (b) The spectrum powers are averaged across electrodes and frequencies in five frequency bins for each condition.

3.6 Electroencephalogram noise contamination with human participants

We recorded 5 minutes of EEG waveforms for each condition with the device off and with the device rotating. To evaluate continuous power supply noise contamination, we calculated the spectrum power for each electrode, based on the data of the whole recording period (Figure 11a), by using the same recording criteria as used for the saline solution. As illustrated in Figure 11, the device off condition shows no clear peak at 60 Hz, which suggested no noise contamination by the commercial power supply when the power of the device was off.

In the device rotating condition, we observed a clear peak at 60 Hz. Using noise removal twice with the CleanLine plugin (parameter, 60 Hz and 120 Hz, 0.05, sliding 4 ms), the power at 60 Hz was diminished and no peak existed on visual inspection. The mean values were calculated for five frequency bins: 53–55 Hz, 56–58 Hz, 59–61 Hz, 62–64 Hz, and 65–67 Hz, which are illustrated in the lower part of Figure 11. We found that power only at 59–61 Hz was prominent under the device rotating condition without noise removal, whereas the power value at 59–61 Hz was diminished by twice noise removal and had a very slight impact on the power values at other frequencies. The data from the other two participants are illustrated in Supplementary Figures 1 and 2.

To confirm that no additional transient noise occurred when the actuators of the device were rotating, we calculated the event-related spectrum power (ERSP) before, during, and after actuator rotation. The CleanLine plugin could not remove any transient noise. Therefore, if the transient noise induced by actuator rotation contaminated the waveform, then we would have seen a power increase along with the actuator rotations, even after removing noise by using the CleanLine plugin. We segmented the noise-removed waveforms into 40 epochs lasting 8 seconds (2 seconds (-2) before the actuator rotation period, 4 seconds of rotation period, and 2 seconds (+2) after the actuator rotation period), and calculated the ERSP for each frequency (i.e., Morlet wavelet with minimum cycle 8 at 50 Hz and maximum cycle 10 at 70 Hz; baseline period, -2 seconds to 0 second). For the baseline comparison, the waveforms of

the device off condition were also segmented at the identical time points, although no actual actuator rotation occurred. The ERSPs at the Fz, Cz, and Pz electrodes for each condition are illustrated in Figures 12a and 12b. The data from two other participants are illustrated in Supplementary Figures 3 and 4. The ERSPs showed no prominent power increase under the device rotation condition. The spectrum powers at all electrodes for the three periods are shown in Figure 12c. The findings also demonstrated no prominent increase or decrease in the device rotation condition, compared to the device off condition.

Figure 11. Spectrum powers with a human participant for each condition. (a) Spectrograms for all electrodes are illustrated for each condition. (b) The spectrum powers are averaged across electrodes and frequencies in five frequency bins for each condition.

Figure 12. The ERSPs from a participant in time-frequency maps at three midline electrodes during (a) the device off condition and (b) the device rotation condition. (c) The spectrum powers at 60 Hz are averaged across each time period and depicted in bar graphs for each condition.

ERSP, event-related spectrum power

3.7 Magnetic resonance imaging noise contamination with phantoms

We recorded phantom images for 52 times. We acquired 500 volumes for each run, using 8 minutes per run. In the no device condition, we obtained 26 recordings as a baseline. We acquired 11 recordings for the device off condition and 13 recordings for the device on condition to confirm the signal-to-noise ratio (SNR) as a stability index of image acquisition.

Four other recordings of the device rotating condition were used to evaluate whether transient noise was induced by actuator movement in the device.

First, we calculated the temporal SNR (tSNR) for each voxel (Krüger and Glover, 2001; van Der Zwaag et al., 2012). From the acquired tSNR, 20 voxels $\times$ 20 voxels $\times$ 4 voxels of the fifth slice in the center of a phantom were used as the stable center voxels for feature analysis because the values at the edge of the phantoms would not be stable across scans. In addition, the loss ratio was calculated by dividing the tSNR in the target condition by tSNR in the baseline condition. The tSNR and the loss ratio versus those of the baseline for each condition are listed in Table 1. We found that the loss ratio for each condition fell by 10%, compared to the baseline value (Hara et al., 2014). Figure 13 depicts the images of the phantoms, which were averaged for all scans for each condition, and the difference in the images, compared to the baseline image.

By using a similar approach, described in section “4.2 Electroencephalogram noise contamination,” we confirmed that no additional transient noise occurred when the actuators of the device were rotating. We calculated the averaged raw values across all 40 rotations, with each period lasting 4 seconds, for all four runs. No actual rotation occurred in the no-device, device off, or device on conditions. For these conditions, we used the same time period that was used for the device rotating condition such as the pseudo-rotation period, and calculated the average raw values across all pseudo-rotations. To obtain the baseline values,

we calculated the averaged values across all repetitions during the 4-second period preceding the rotation and pseudo-rotation periods. Figure 14a depicts the difference in values between 4 seconds for rotation (or pseudo-rotation) and 4 seconds before rotation. The difference was very low, typically lower than 0.1. In addition, we illustrated the waveforms for each condition, and found no strong value changes in the four times under the device rotating condition (i.e., they are averaged across all scans for the no-device, device off, and device on conditions).

Table 1. Temporal signal-to-noise ratio in the echo planar images for each condition

Condition	No.	tSNR (SD)	Loss (%)	Range
No device	26	235.30 (6.98)	-	218.40–245.67
Device off	13	234.53 (12.29)	0.33	206.16–252.54
Device on	11	231.52 (10.51)	1.61	215.43–247.09
Device rotating	4	242.98 (9.37)	-3.26	227.97–250.92

SD, standard deviation; tSNR, temporal signal-to-noise ratio

Figure 13. Acquired images of vendor-supplied spherical phantoms (Siemens Erlangen, Germany). At the top row, the images averaged across all scans are depicted for each condition. The middle row depicts the difference images, compared to the baseline images. For the baseline condition, the difference image was produced by subtraction between images for the odd scan numbers and images for the even scan numbers. At the bottom, the scale of the difference images was changed to 1/10 to detect any slight change from the baseline.

Figure 14. Raw value changes in the rotation and pseudo-rotation periods from the values before rotation for each condition. (a) Raw value changes during and before the rotation periods are averaged across all (i.e., pseudo) rotations. The schematic illustration of the target time period is on the right. (b) Raw value time courses for each condition. The period for 100–300 seconds is illustrated. Gray periods are the (pseudo) rotation periods.

3.8 Magnetic resonance imaging noise contamination with human participants

We recorded EPI images on participants for 36 times. We acquired 200 volumes for each run, using approximately 10 minutes per run. In the resting condition, we obtained 20 recordings as a baseline. We acquired 13 recordings during a visual task for the no device condition as a task-baseline, and three recordings for the device rotating condition to confirm

the SNR as a stability index of image acquisition. The recordings of the device rotating condition were used to evaluate whether transient noise was induced by actuator movement in the device.

First, we calculated the temporal SNR (tSNR) for each voxel (Krüger and Glover, 2001; van Der Zwaag et al., 2012). From the acquired tSNR, 10×10 pixels of the 24th slice in the upper left and right corners of image were used as the stable voxels for feature analysis because the values at the center of the image should include the participant's brain, which has strong individual differences across participants. A loss ratio was also calculated by dividing the tSNR in the target condition by the tSNR in the baseline (i.e., resting) condition. The tSNR and the loss ratio versus those of the baseline for each condition are listed in Table 2. We found that the loss ratio for each condition fell by 10%, compared to the baseline value (Hara et al., 2014).

By using a similar approach, described in section “4.2 Electroencephalogram noise contamination,” we confirmed that no additional transient noise occurred when the actuators of the device were rotating. We calculated the averaged raw values across all 40 rotations, with each period lasting 4 seconds, for all four runs. No actual rotation occurred in the no device, device off, or device on conditions. For these conditions, we used the same time period that was used for the device rotating condition such as the pseudo-rotation period, and calculated the average raw values across all pseudo-rotations. To obtain the baseline values,

we calculated the averaged values across all repetitions during the 4-second period preceding the rotation and pseudo-rotation periods. Figure 15a depicts the difference in values between 4 seconds for rotation (or pseudo-rotation) and 4 seconds before rotation. The difference was very low, typically lower than 0.2. In addition, we illustrated the waveforms for each condition, and found no strong value change under the device rotating condition (i.e., they are averaged across all scans for the resting and visual task conditions).

Table 2

Temporal signal-to-noise ratio in the echo planar images for each condition

Condition	No.	tSNR (SD)	Loss (%)	Range
Resting	20	9.93 (5.85)	—	8.65–12.85
Visual Task	13	8.98 (3.40)	9.56	8.21–10.17
Device rotating	3	9.28 (5.94)	6.54	9.02–9.50

SD, standard deviation; tSNR, temporal signal-to-noise ratio

a) Raw values during and before rotation periods and raw value between during and before rotation periods

b) Raw value time courses for each condition

Figure 15. Raw value changes in the rotation and pseudo-rotation periods from the values before rotation for each condition. (a) Raw value changes between during rotation and before rotation periods averaged across all (pseudo) rotations. (b) Raw value time courses for each condition. The period for 100–300 seconds is illustrated as an example. Gray colored periods are the (pseudo) rotation periods.

4. Discussion

The aim of this study was to develop a tactile stimulation device that can be used in cognitive neuroscience EEG and fMRI experiments of emotion. To this end, we confirmed the developed device met the three requirements: (1) the stimuli used to induce positive and negative emotions could be automatically changed; (2) power supply noise contamination on

the recorded EEG waveforms was sufficiently small so that it was negligible or removable by a signal processing; and (3) the tSNR in the EPIs of water phantoms were <10%. Based on these findings, the developed device fulfilled the required conditions.

4.1 Usability of various natural stimuli

Various materials can be attached to the tip of the developed device by using any bonding agent. The tip of the device was easily removable and disposable by using brass screws. The device can also be easily produced on a large scale. This capability allows various materials to be used in a series of experiments in an identical fashion. In fact, during the experiment, we could replace any deteriorated material with a new sample to maintain a material's properties such as the stickiness of a gel.

In this study, we used eight materials in one experiment: satin, fur, Poron sponge, urethane, human skin gel, GelGems, plastic turf, and bristle. We also modified three stroking speeds, two pressure strengths, and two touch locations. In total, we used 96 types of tactile stimulation, and successfully induced positive and negative emotional responses by stroking the hand. These tactile stimuli were comparable with the emotional stimulus sets used in the other sensory modalities. However, a limitation of a tactile stimulus is that we could not determine orthogonality between valence and arousal scores. The very high correlation score between valence and arousal also suggested that valence and arousal, in principle, were not

orthogonal when touching something induced any emotion. In this study, we attempted to control the arousal score by modifying stroking speed and obtained a significant main effect of speed on arousal score. This finding suggested that high-speed stroking can be used to increase the arousal score. In addition, the ANOVA demonstrated that high-speed stroking did not always induce a negative valence (e.g., opposite direction on fur and urethane, no speed effect on satin and human gel), which supported the possibility that the arousal score can be controlled without affecting the valence score, if the proper material is selected. However, the correlations between valence and arousal rating in the IAPS was not stable across experiments (reviewed in Grühn and Scheibe, 2008) and across cultures (Ribeiro, Pompéia, & Bueno, 2005). In addition, there were strong correlations occasionally, which suggested that continuous investigations with various materials and samples are required in a tactile modality. Another point to be discussed is that we have observed that tactile stimulation on the back of hand elicited a more negative emotional response than it did when applied to the palm. The dorsal part of the arm is a hairy place and typically has more C-tactile fibers, which respond to comfortable stimulation (Löken et al., 2009). We postulated that stimulation on the back of the hand would show a stronger positive valence. However, the back of hand is hairy but does not have very much muscle and fat. A stroking stimulus could then be a pushing stimulus on the skin surface on both (i.e., dorsal and ventral) sides of the hand by the material and the bones of the hand. This type of stimulation could cause most people to feel discomfort.

4.2 Electroencephalogram noise contamination

We confirmed that the commercial power supply used for controlling the device produced noise contamination in the recorded EEG. The commercial power supply noise could often create contamination in EEG waveforms because most EEG experiments use electrical control in stimulus presentation timing. The developed device also adopted electrical control of actuators to control touch timing automatically in milliseconds, which suggested that using the device makes any contamination of commercial power supply noise inevitable in a specific frequency band. In this study, the level of noise contamination was sufficiently low for recordings with saline solution and the human scalp; therefore, it could be removed by signal processing. The time-frequency analysis on the segmented waveforms also revealed that no prominent power increase occurred at 60 Hz during actuator rotation. In Figure 12, we observed stronger fluctuation in the spectrum power at 60 Hz in device off condition, compared to the device rotation condition. However, we believe that this type of fluctuation could be an individual difference because this fluctuation was not true for two other participants (Supplementary Figures 3 and 4). This finding suggested that this device could be used in any study investigating the high-frequency bands associated with emotion (Luo et al., 2009; Matsumoto, Ichikawa, Kanayama, Ohira, & Iidaka, 2006; Müller, Keil, Gruber, & Elbert, 1999). However, this confirmation was obtained using an active electrode, which is better for

avoiding commercial power supply noise. Under some conditions that required the use of passive type electrodes (e.g., EEG measurements in an MRI scanner), the device affected the recorded EEG waveform to a greater degree.

4.3 Functional MRI noise contamination

To evaluate the usability of the developed device during an fMRI scan, we conducted test EPI scans of vendor-supplied spherical phantoms. Based on findings of previous studies of noise level confirmation in an MRI scanner room (Krüger & Glover, 2001; W. Van Der Zwaag et al., 2012; Wietske Van Der Zwaag et al., 2009) and the development of a device that is usable in an MRI scanner room (Chinzei, Hata, Jolesz, & Kikinis, 2000; Hara et al., 2014), we calculated the SNR for each scan and adopted the tSNR for the noise level check. Compared to the baseline value (i.e., the no-device condition), the loss of the tSNR for the device off and device on conditions was smaller than the standard deviation across all scans without the device. This finding suggested that the noise contamination level was negligible. As illustrated in Figure 12, we did not find any transient noise induced by the actuator rotation. In addition, the difference between before actuator rotation and during actuator rotation was not larger than the difference in the other conditions in which the actuators were not all activated for the whole period (Figure 12). Similar results are also obtained when we conducted EPI scan with human participants. Based on these results, the device had no impact or very little

impact on the acquired images obtained by echo planar imaging with regard to device-induced noise contamination. However, as Table 1 shows, the minimum tSNR in the device off condition was substantially low and the standard deviations in all device conditions (i.e., off, on, and rotating) were relatively high, compared to the baseline values. These findings suggested that noise contamination from the device was small but not zero; therefore, it is necessary to monitor the noise contamination level when using the device.

4.4 Limitations

In this study, we developed a tactile stimulation device to induce an emotional response during EEG and fMRI recordings. However, in addition to the limitations previously described, other limitations exist with regard to orthogonality between valence and arousal, noise contamination in the passive electrode, and high standard deviations in the tSNR when the device is placed inside the scanner room.

One problem that needs to be solved to standardize an emotional tactile stimulus set such as the IAPS or IADS is a stable supply of materials. For visual and auditory stimuli, we used digitized picture and auditory files with a computer display and speaker. The materials used as the tactile stimuli are not digitized, and no vendor supplies the same materials throughout the world whenever researchers want a material. It would therefore be necessary to continuously attempt to find a stable supply system of the presented materials. Also, the

participants' characteristics should be important for standardization. In this study, the participants' age was limited to young adults. The physical properties of human skin surface alters with aging (Diridollou et al., 2001), which suggest that the results obtained in this experiment should be tested in various populations. Moreover, we adopted stroking as the touching mode in this experiment, which limited the participants' ability to sense warmth and softness. The findings also should be tested in various stimulation modes. One possibility for a standardized control for individual differences and stimulation modes is to measure and control the physical properties at the skin-surface contact. For example, vibrations on the skin surface can be associated with the emotional evaluation of the materials (Natsume et al., 2017), which suggests that the materials used in the experiment were controlled, based on their physical properties, at the skin-surface contact, not the material itself.

Another concern is the limited number of materials tested in this experiment. The current device allowed us to use eight materials in one experiment, whereas some studies have introduced 120 materials for the tactile perception dimension (Sakamoto & Watanabe, 2017). Moreover, if we use this device for behavior, EEG, and fMRI experiments, some restrictions exists in selecting the materials. First, metallic and magnetic materials must not be used because their safety use and noise level in the MRI experiment were not confirmed. For EEG experiments, metallic and magnetic materials can be safely used, whereas the noise level was not confirmed because touch on the metallic materials could increase noise

839 contamination if the room is not a fully noise-free environment. For each new material, we
840 have to confirm whether the noise level is not problematic for a study's aim, especially when
841 a researcher is interested in the EEG waveforms around the frequency of a commercial power
842 supply (i.e., 50 or 60 Hz, depending on the country and the area). In addition, water and gel,
843 which leave a residue after touch, are not highly compatible with this device. If we want to
844 use such a thing, we have to use one of eight rods for a small towel to wipe any residue away
845 in an automated manner. For increasing the number of possible materials for this device, we
846 will also continue to test more materials using this device for emotion research.

847 Another limitation, especially for the fMRI study, was the size and space of the device.
848 The device is small and easily portable; however, the available space in the gantry of an MRI
849 scanner is limited and varies by the scanner type. When we used the device in the MRI scanner,
850 we had to place the device at the side of the participant's waist or hip to deliver stroke
851 stimulation on the hand. We sometimes could not create sufficient space to place the device
852 when a participant's waist and hip widths were too broad. To pull the material away from the
853 participant's hand surface, the actuator must elevate the rotational part. The elevation length
854 was limited when the participant's arm was not sufficiently long so that the device could be
855 placed outside the gantry. In this situation, if the participant's hand was very thick, the top of
856 the rotational part could possibly touch the gantry. In the fMRI study, we could not use the
857 device if the space between the participant's body and gantry was insufficient to allow rotation

and elevation. In this situation, we had to omit using some of the eight stimulation rods.

4.5 Conclusion

We successfully developed an automatically controlled tactile stimulation device. The actuator movement and touch timing could be controlled in milliseconds. In addition, the stroking speed and touch pressure could be modulated and recorded in real time. These specifications enabled us to use this device in the EEG experiment, which requires touch onset recording in milliseconds. The actuator was an ultrasonic motor, which enabled the use of this device in an MRI scanner room. In the EEG and fMRI recordings, we confirmed that very low noise contamination was maintained. With this device, research on emotion in the cognitive neuroscience field could be advanced using tactile stimulation in a controlled manner.

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