Automatic Estimation of Multidimensional Ratings from a Single Sound-Symbolic Word and Word-Based Visualization of Tactile Perceptual Space

Ryuichi Doizaki, Junji Watanabe, and Maki Sakamoto

Abstract—Several pairs of Japanese adjective words pertaining to material's properties, such as roughness and hardness, have been used in Japanese studies to quantitatively evaluate variations in tactile sensations. This method asks observers to analyze their perceptual experiences one by one. An alternative notion is that human perceptual recognition is performed as a whole rather than by using fragmented factors. Based on this notion, we propose a system that can automatically estimate multidimensional ratings of touch from a single sound-symbolic word that has been spontaneously and intuitively expressed by a user. When a user inputs a sound-symbolic word into the system, the system refers to a database of phonemes and their auditory impressions, and calculates ratings in terms of 26 pairs of fundamental scales of touch. The estimated ratings of sound-symbolic words enable us to visualize a tactile perceptual space. Our study provides an alternative method for estimating the fine quality of tactile sensations.

Index Terms—Distribution diagram, system construction, sound-symbolic words, tactile sensation

1 Introduction

Quantitative assessments of sensations can be made based on subjective ratings using several pairs of adjective words (the semantic differential [SD] method) [1], and many studies have applied this method to analyze perception of textures [2], [3], [4], [5], [6], [7], [8]. The observer quantifies the perceived material properties of touch using scales whose ends represent two adjectives in an opposing pair, such as "rough–smooth" and "hard–soft." Because this method requires observers to analyze each of their perceptual experiences individually using bipolar adjective scales prepared in advance by the experimenter, it is well suited for interpreting fundamental dimensions of tactile perception [9].

In this paper, unlike in many previous studies, we explore a method of estimating evaluations of touch that only uses a single word. Specifically, we constructed a system that can convert a word that intuitively expresses tactile sensations into information equivalent to evaluations derived from 26 pairs of touch adjectives. This system can obtain the information from 26 adjective scales with a single word instead of asking many questions directly.

To achieve this capability, we focused on a word class of Japanese onomatopoeia referred to as "sound-symbolic words," which involves the association between linguistic sounds and sensory experiences [10]. We did this for two major reasons. First, this word class can describe differences in tactile sensation at a fine resolution. In Japanese, there are more than 300 touch-related sound-symbolic words, which is more than twice the number of adjectives that describe touch experiences [11]. For example, according to the Japanese sound-symbolic words dictionary [12], a soft texture can be described by "huwa-huwa," "puru-puru," "buyo-buyo," and "gunya-gunya." These four words express different qualities of a soft texture. The word "huwa-huwa" expresses softness and a light and fluffy texture like a down quilt, while "puru-puru" expresses a warm, soft, and wet texture like a gel emulsion. The word "buyo-buyo" expresses the qualities of something like a rubber ball with a soft, wet, and bumpy texture, while "gunya-gunya" expresses a sticky, limp, squashy, and unfavorable texture, like that of slime. In addition, we can create a new word easily by combining Japanese sound-symbolic words. For example, we can make "punya-punya" by combining "puru-puru" and "gunya-gunya" to express a comfortable stickiness.

The other reason is that Japanese sound-symbolic words evoke strong and systematic sensory-sound associations [13], and the phonemes of Japanese sound-symbolic words may characterize categories of tactile sensations. For example, "basa-basa" and "pasa-pasa" are different only in one sound: /b/ or /p/. The difference of only one sound can convey a

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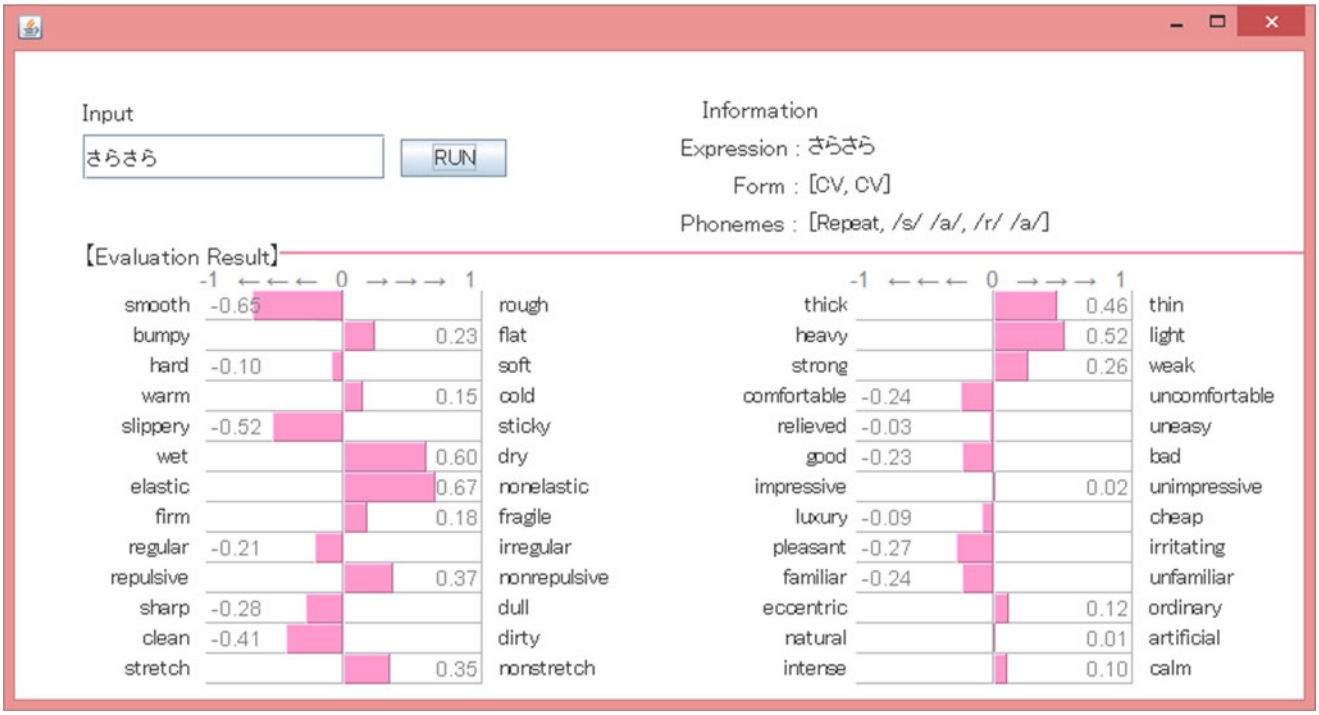

Fig. 1. Evaluation results for “sara-sara”.

critical difference in the perceptual and affective evaluations of tactile textures.

In summary, the word class of tactile sensations, at least in Japanese, has a large body of vocabulary that can express the complex and minute quality of sensations regarding multiple fundamental dimensions in touch, and the meanings of sound-symbolic words are typically characterized by phonetic features associated with multiple sensory experiences.

These features led us to the idea that we can calculate the multidimensional ratings of a word by integrating each phoneme’s impression, and we have proposed a system that can convert a sound-symbolic word in Japanese into quantitative ratings in multiple tactile dimensions (26 pairs of adjectives) [14]. In our system, when a word that intuitively expresses a tactile sensation is input into the text field, information equivalent to evaluations against the 26 pairs of touch adjectives is obtained based on an analysis of the sounds of

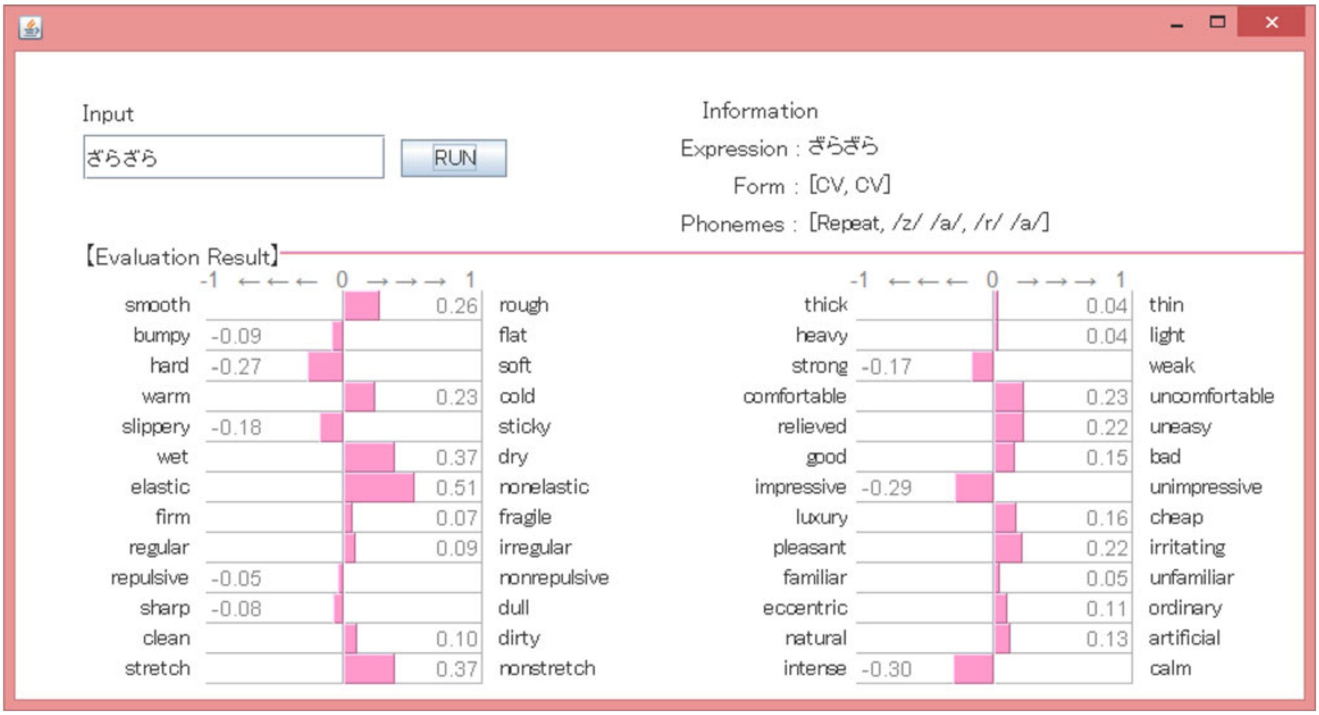

Fig. 2. Evaluation results for “zara-zara”.

TABLE 1
Twenty-Six Tactile Rating Scales

Basic tactile evaluation	Material-oriented evaluation	Affective evaluation
smooth–rough	elastic–nonelastic	comfortable–uncomfortable
bumpy–flat	firm–fragile	relieved–uneasy
hard–soft	regular–irregular	good–bad
warm–cold	repulsive–nonrepulsive	impressive–unimpressive
slippery–sticky	sharp–dull	luxury–cheap
wet–dry	clean–dirty	pleasant–irritating
	stretchy–nonstretchy	familiar–unfamiliar
	thick–thin	eccentric–ordinary
	heavy–light	natural–artificial
	strong–weak	intense–calm

the word. Figs. 1 and 2 show examples of outputs from our system for "sara-sara" and "zara-zara," respectively. "Sara-sara" shows higher ratings for "smooth," "slippery," "dry," "nonelastic," "clean," "thin," and "light" feelings, while "zara-zara" shows higher ratings for "rough," "hard," "dry," "nonelastic," "nonstretchy," "impressive," and "intense" feelings. This system enables us to analyze tactile sensations with many criteria by expressing the sensation with only a single word, and this idea can be applied to any combination of phonemes (even to newly created words) in Japanese. To estimate the quantitative information of every possible sound-symbolic word, we built a database of sound-symbolic associations for each phoneme with the 26 pairs of adjectives through psychological experiments.

Japanese has a large body of vocabulary for expressing tactile sensations in detail, and the multidimensional ratings of words can be predicted by combining the evaluations of each phoneme in these words, which are potential advantages of our system. Section 2 describes the construction and evaluation of the proposed system in detail. Section 3 shows how we apply the results of the system to visualize a tactile perceptual space expressed by the Japanese language. In Section 4, we summarize the results of our study, and discuss the future possibilities of our method.

2 System Construction

In this section, we describe in detail the procedure for constructing the automatic estimation system [14], and its evaluations. First, we discuss an experiment that we performed to analyze the sound-symbolic associations of phonemes and the 26 pairs of adjectives. Referring to 12 studies of tactile perception and 14 studies of visual perception, in our previous study [15] we collected 43 pairs of adjectives frequently related to Japanese sound-symbolic words. In the current study, we picked 26 pairs of adjectives from the 43 pairs except for visually related scales, as shown in Table 1. Among these, six pairs of adjectives in the left column relate to basic tactile dimensions [9]. The other 20 pairs of adjectives are related to material-oriented evaluations and affective evaluations. Most of the 26 pairs of adjectives are included in the 262 English words used by a previous study [16], which was the first attempt to collect words for a touch lexicon in English.

2.1 Experiment to Build Sound-Symbolic Database

In the experiment, participants viewed sound-symbolic words displayed on a monitor and rated their impressions in terms of the 26 bipolar adjective scales. From the results, we obtained a quantitative rating database for each phoneme, which enables us to estimate impressions of a word by analyzing only the phonemes of the word.

2.1.1 Participants

Seventy-eight paid participants, aged 20 to 24 years (51 men and 27 women), participated in this experiment. They had no linguistics knowledge and were all native Japanese speakers. They had normal or corrected-to-normal vision, and none of them reported any visual or linguistic abnormalities. They were unaware of the purpose of the experiments, and informed consent was obtained from all the participants before the experiment started. The experiments, including those for system evaluation (see Section 2.3), were performed at the University of Electro-Communications. Recruitment of the participants and experimental procedures were conducted in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki.

2.1.2 Stimuli

To obtain sound-symbolic associations of all Japanese phonemes with the 26 pairs of adjectives, we selected words that included all varieties of Japanese phonemes in the first syllable. First, we made a list of 14,584 sound-symbolic expressions by combining all sounds in the Japanese syllabary as two-syllable forms (i.e., /sara/). Then, we also created repetition expressions of the two-syllable forms (i.e., /sara-sara/). In addition, we made another list of expressions by adding words with all types of special phonemes used in Japanese sound-symbolic words (syllabic nasals /N/, choked sounds /Q/, long vowels /R/, and adverbs ending in /Li/ [17]) to the two-syllable forms (i.e., /saraLi/) (see Table A1 in the Appendix, which can be found on the Computer Society Digital Library at http://doi.ieeecomputersociety.org/10.1109/TOH.2016.2615923). Second, from this large word list, 312 words that could be used as tactile sound-symbolic words were selected by three experts (including one author) in psychology and linguistics. The 312 words, whose first syllables cover all Japanese phonemes, are shown in Table A2 in the Appendix, available in the online supplemental material.

The participant sat in front of a 23-inch LCD monitor. The sound-symbolic words were presented on the monitor with a resolution of $1{,}024 \times 768$ pixels and a refresh rate of 60 Hz. The sound-symbolic words were presented in 11 pt MS PGothic font. The distance between the participant's eyes and the screen was approximately 50 cm. The bipolar scales were presented in the form of an answer matrix on the monitor. The rating scales included 26 pairs of adjectives that would be used for expressing material properties of objects and their evaluations (Table 1).

Because of the large number of trials, we divided the 78 participants into six groups of 13 people and the 312 word stimuli into six groups of 52 words. Each participant gave their impressions of 52 words.

2.1.3 Procedure

The trials started with the presentation of a sound-symbolic word on the monitor, and participants were asked to report how they felt about the sound-symbolic word on a seven-point SD scale (e.g., for the comfortable–uncomfortable scale,

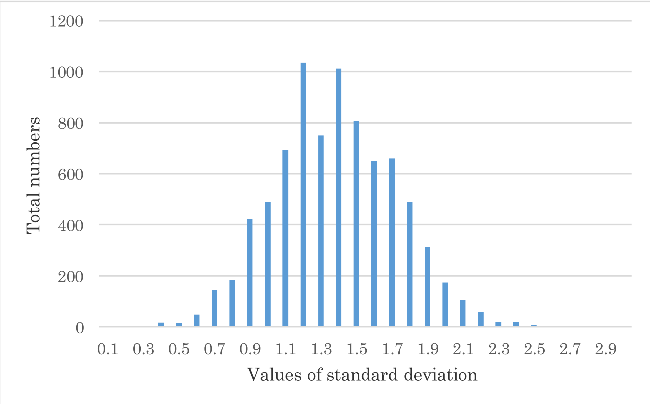

Fig. 3. Bar graph of the distributions for standard deviations for each scale for all words.

participants selected one of the following seven points: 1, very comfortable; 2, comfortable; 3, slightly comfortable; 4, neither; 5, slightly uncomfortable; 6, uncomfortable; and, 7, very uncomfortable). The participants responded by pushing one of seven buttons. The time allotted for answering was unlimited, but almost all trials took less than 1 minute. The presentation order of sound-symbolic words was randomized among participants. The orders and polarities of the bipolar scales were also randomized in the answer matrix.

2.1.4 Analysis and Modeling

The experimental results produced 105,456 items of data (26 rating scales × 312 words × 13 participants). Then, we calculated the averages and standard deviations of rating values for each scale of all words. The average of the standard deviation was 1.31. We displayed the bar graphs of the distributions for all 8,112 cases of standard deviation (26 rating scales × 312 words) in Fig. 3. Ninety-eight percent of all data (105,181 items of data) were within standard deviations of less than 2.0. In the analysis process below, we used these 105,181 items of data.

2.2 Sensory Image Estimation Model

2.2.1 Model to Estimate Sensory Impression

To estimate the sensory impressions of sound-symbolic words, we created a model in which the following equation was used to predict each rating value:

$$Y = \sum_{i=1}^{13} X_i + Const. \quad (1)$$

where Y represents the rating values of the respective 26 scales, and $X_1 - X_{13}$ are the corresponding values defined in Table 2. $X_1 - X_6$ respectively are the mean values of the specific consonant, voiced sound/p-sound, contracted sounds, vowels, semivowels, and special phonemes in the first syllable. $X_7 - X_{12}$ are the same categories for the second syllable, respectively, and X_{13} denotes the presence or absence of repetitions in the word. Using the average of the rating values as the objective variables and the variation of phonemes as the predictor variables, we conducted mathematical quantification theory class I, which is a type of multiple regression analysis. Table 3 shows examples of the results of the analysis for each scale. According to (1), the rating values of a sound-symbolic word can be calculated by the linear sum of the values ($X_1 - X_{13}$) of the word. For example, the expression "sara" is composed of the first syllable /sa/ (/s/ + /a/) and the second syllable /ra/ (/r/ + /a/). Therefore, the value of the "rough–smooth" scale on a seven-point scale (smooth 1 to rough 7) is estimated by the following equation (see Equation (1) and Table 3).

$$\begin{aligned} Y = {} & /s/(X_1) + \text{absence}(X_2) + \text{absence}(X_3) + /a/(X_4) \\ & + \text{absence}(X_5) + \text{absence}(X_6) + /r/(X_7) + \text{absence}(X_8) \\ & + \text{absence}(X_9) + /a/(X_{10}) + \text{absence}(X_{11}) + \text{absence}(X_{12}) \\ & + \text{absence}(X_{13}) + \text{Const.} \\ = {} & (-0.05) + (-0.32) + (-0.05) + (0.46) + (-0.02) + (-0.03) \\ & + (-0.14) + (-0.1) + (0.05) + (-2.19) + (0.2) + (-0.02) \\ & + (0.05) + (0.01) + (3.75) \\ = {} & 2.05 \end{aligned}$$

The estimated value of 2.05 suggests that "sara" is associated with a smooth impression.

The multiple correlation coefficients R^2 between the predicted values and the mean values of the actual ratings (the values obtained from the participants) were used as indicators of prediction accuracy. For 20 scales, the R^2 values were in the range of 0.80 to 0.90, and for the other six scales, they were higher than 0.90 (Table 3). Therefore, we considered our model to be sufficient for estimating impressions of sound-symbolic words by analyzing the phonemes and forms of the words.

2.2.2 User Interface and Information Processing

Our system comprises a user interface module, a sound-symbolic word-parsing module, an analyzing module, and

TABLE 2
Correspondences between Variables and Phonemes

First syllable	Second syllable	Phonological Characteristics	Variation of Phonemes
X_1	X_7	consonants	/k/, /s/, /t/, /n/, /h/, /m/, /y/, /r/, /w/ or absence
X_2	X_8	voiced sounds /p-sounds	presence (/g/, /z/, /d/, /b/, /p/) or absence
X_3	X_9	contracted sounds	presence(/ky/, /sy/, /ty/, /ny/, /hy/, /my/, /ry/, /gy/, /zy/, /by/, /py/) or absence
X_4	X_{10}	vowels	/a/, /i/, /u/, /e/, /o/
X_5	X_{11}	semi-vowels	/a/, /i/, /u/, /e/, /o/ or absence
X_6	X_{12}	special sounds [17]	/N/, /Q/, /R/, /Li/ or absence
X_{13}		repetition	presence(ex. huwa-huwa) or absence

TABLE 3
Examples of Category Quantities for 26 Rating Scales

Rating scales	Consonants		Vowels		R^2
	/s/ (X_1)	/r/ (X_7)	/a/ (X_4)	/a/ (X_{10})	
smooth–rough	−0.05	−0.14	0.46	0.20	0.88
bumpy–flat	0.56	0.08	0.18	0.05	0.84
hard–soft	−0.33	−0.26	−0.35	0.07	0.91
warm–cold	0.52	0.06	0.28	0.10	0.88
slippery–sticky	−0.50	−0.36	−0.10	0.08	0.89
wet–dry	0.49	−0.05	0.93	0.21	0.88
elastic–nonelastic	0.80	0.34	0.47	0.19	0.91
firm–fragile	0.02	0.07	0.23	0.08	0.85
regular–irregular	−0.53	0.09	0.01	0.17	0.89
repulsive–nonrepulsive	0.48	0.11	0.24	0.09	0.88
sharp–dull	−0.62	−0.06	−0.12	0.01	0.92
clean–dirty	−0.51	0.05	−0.14	−0.02	0.90
stretchy–nonstretchy	0.30	0.01	0.57	0.07	0.92
thick–thin	0.73	0.19	0.37	0.12	0.89
heavy–light	0.47	0.15	0.37	0.23	0.91
strong–weak	0.21	0.18	0.23	−0.02	0.89
comfortable–uncomfortable	−0.41	0.15	−0.13	0.03	0.87
relieved–uneasy	−0.05	0.12	0.02	−0.01	0.87
good–bad	−0.28	0.06	0.01	0.01	0.87
impressive–unimpressive	0.30	0.06	0.15	0.00	0.87
luxury–cheap	−0.23	−0.07	0.13	0.03	0.89
pleasant–irritating	−0.60	0.05	−0.07	0.04	0.89
familiar–unfamiliar	−0.06	0.02	0.12	−0.07	0.86
eccentric–ordinary	0.29	0.08	0.30	0.13	0.85
natural–artificial	0.05	0.06	0.10	0.08	0.84
intense–calm	0.04	0.00	0.03	−0.03	0.90

a database. Figs. 1 and 2 show the system's estimation values for "sara-sara" and "zara-zara." When a user inputs a sound-symbolic word into the text field in the upper-left frame of a window and presses the "Run" button, the parsing module automatically divides the word into each phoneme and classifies its form. According to (1) and the database, the analyzing module calculates the rating values of the word for the 26 scales. Then, the module converts the calculated values from 1 to 7 into values from −1 to 1 as shown in Figs. 1 and 2. Finally, graphs of the estimated values of the word are displayed in the lower frame. The form and phonemic elements of the word are displayed in the upper-right frame.

2.3 Evaluation of Our System

To verify that our system can estimate human tactile impressions expressed by sound-symbolic words, we asked participants to evaluate impressions of conventional and novel words in terms of the 26 SD scales, and compared the results obtained from the participants with those estimated by our system.

2.3.1 Participants

Eleven paid participants, aged 21 to 28 years (nine men and two women), participated in the experiment with conventional sound-symbolic words. Nine paid participants, aged 21 to 25 years (eight men and one women), participated in the experiment with novel sound-symbolic words. They had no linguistics knowledge and were all native Japanese speakers. They had normal or corrected-to-normal vision, and none reported any visual or linguistic abnormalities.

TABLE 4
Correlation Coefficients for the 30 Conventional Sound Symbolic Words

gasi-gasi	0.89^{***}	tuya-tuya	0.44^{**}	punyu-punyu	0.86^{***}
gyuru-gyuru	0.83^{***}	tero-tero	0.39^{**}	betya-betya	0.83^{***}
kusya-kusya	0.63^{***}	deko-deko	0.54^{***}	betoQ	0.88^{***}
gosi-gosi	0.71^{***}	toge-toge	0.83^{***}	petaQ	0.41^{**}
gowaQ	0.80^{***}	nuruQ	0.72^{***}	boso-boso	0.72^{***}
saraQ	0.85^{***}	neQtori	0.89^{***}	bowaQ	0.50^{***}
zaraQ	0.74^{***}	pari-pari	0.45^{**}	muniQ	0.92^{***}
syagu-syagu	0.53^{***}	pitaQ	0.35^{*}	mosaQ	0.60^{***}
zyuru-zyuru	0.61^{***}	humo-humo	0.62^{***}	mowa-mowa	0.80^{***}
tyuru-tyuru	0.76^{***}	puniQ	0.91^{***}	huwa-huwa	0.85^{***}

* $p < 0.05$, $^{**}p < 0.01$, *** $p < 0.001$.

They were unaware of the purpose of the experiments, and informed consent was obtained from all the participants before the experiments.

2.3.2 Stimuli

The experimental environment and procedure were the same as in the previous experiment except for the displayed words. For the conventional word experiment, we selected 30 sound-symbolic words with wide variations in their first phonemes (Table 4). The 30 sound-symbolic words are different from the words used to build the sound-symbolic database in Section 2.1. For the novel word experiment, we created various kinds of novel sound-symbolic expressions by combining phonemes randomly. Then, we showed the novel sound-symbolic words to three male participants whose average age was 30 years, and asked them to rate the novelty of each expression on a seven-point scale (1–7). They did not participate in the experiment in Section 2.1. Finally, we selected 18 novel sound-symbolic expressions (Table 6) that had received an average value of novelty higher than 5.0. The average value of the standard deviation for 18 words was 0.88.

2.3.3 Procedure

The participants evaluated the impressions of 30 conventional words or 18 newly created sound-symbolic expressions using the 26 SD scales. The order of words was randomized among participants.

2.3.4 Results

We calculated the correlation coefficient between the values obtained from the experiment and the values estimated by our system for each word using the 26 scales. For the conventional words, as shown in Table 4, there were six words with a correlation value of $0.30 - 0.50(p < 0.05)$, six words with that of $0.50 - 0.70(p < 0.001)$, and eighteen words with that of $0.70 - 1.00(p < 0.001)$. The word "pitaQ" obtained the lowest correlation value ($r = 0.35$, $p < 0.05$), and the word "muniQ" obtained the highest correlation value ($r = 0.92, p < 0.001$). In addition, we also calculated the correlation coefficient for the 26 SD scales. For each SD scale, we compared two data sets consisting of 30 values for the 30 sound-symbolic words. As shown in Table 5, there were three scales with a correlation value of $0.20 - 0.50$, 11 scales with that of $0.50 - 0.70(p < 0.01)$, and 12 scales with that of $0.70 - 0.90(p < 0.001)$. The scale of

TABLE 5
Correlation Coefficients of the 30 Conventional Sound Symbolic Words for the 26 SD Scales

smooth–rough	0.71^{***}	elastic–nonelastic	0.76^{***}	comfortable–uncomfortable	0.73^{***}
bumpy–flat	0.82^{***}	firm–fragile	0.62^{***}	relieved–uneasy	0.60^{**}
hard–soft	0.75^{***}	regular–irregular	0.59^{**}	good–bad	0.69^{***}
warm–cold	0.73^{***}	repulsive–nonrepulsive	0.53^{**}	impressive–unimpressive	0.41^{*}
slippery–sticky	0.73^{***}	sharp–dull	0.67^{***}	luxury–cheap	0.56^{**}
wet–dry	0.78^{***}	clean–dirty	0.71^{***}	pleasant–irritating	0.24
		stretchy–nonstretchy	0.54^{**}	familiar–unfamiliar	0.31
		thick–thin	0.65^{***}	eccentric–ordinary	0.60^{**}
		heavy–light	0.74^{***}	natural–artificial	0.76^{***}
		strong–weak	0.66^{***}	intense–calm	0.79^{***}

* *p < 0.05*, ** *p < 0.01*, *** *p < 0.001*.

"pleasant to irritating" obtained the lowest correlation value ($r = 0.24, n.s.$); the scale of "bumpy to flat" obtained the highest ($r = 0.82, p < 0.001$).

For the novel expressions, as shown in Table 6, there were 10 words with a correlation value of $0.60 - 0.80$ and eight words with that of $0.80 - 1.0 (p < 0.001)$. The word "bore-bore" obtained the lowest correlation value ($r = 0.65$, $p < 0.001$), and the word "muyo-muyo" obtained the highest correlation value ($r = 0.96, p < 0.001$). For each SD scale, we compared two data sets consisting of 18 values for the 18 sound-symbolic expressions. As shown in Table 7, there were 12 scales with a correlation value of $0.50 - 0.70$ ($p < 0.05$), 13 scales with that of $0.70 - 0.90 (p < 0.001)$, and one scale with that of over $0.90 (p < 0.001)$. The scale of "natural to artificial" obtained the lowest correlation value ($r = 0.52, p < 0.05$), while the scale of "smooth to rough" obtained the highest correlation value ($r = 0.95, p < 0.001$).

The results (Tables 4, 5, 6, and 7) suggest that our system can estimate impressions not only of sound-symbolic words established as Japanese vocabulary, but also of newly created novel sound-symbolic expressions.

3 Application of Our System

3.1 Word-Based Visualization of Tactile Sensation Categories

In this section, we introduce a word-based visualization of tactile perceptual space as an application of our system. Analyzing the relationship between words for expressing sensations is one method that can be used to investigate sensation categorization. The exploration of color naming has helped us to understand the constituents of perceptual color space [18], [19]. In addition, typical color spaces tagged with color lexicons, such as the Munsell color system, have been used for sharing and conveying color information in the world. Here we focus on sound-symbolic words as a rich inventory of touch lexicons, and attempt to visualize the tactile perceptual space systematically and automatically using our system.

We collected the sound-symbolic words frequently used for expressing tactile sensations, and input all words into our system to obtain ratings of 26 adjective scales for the words. We applied a principal component analysis to the outputs of the system, and generated a distribution diagram of the words (see Fig. 4 for an example of the diagram). The distribution diagram is a word-based visualization of how the tactile sensation is categorized in the Japanese language. In previous studies, tactile perceptual spaces have been constructed using ratings of tactile materials (material-based visualization (e.g., [2], [20])), and therefore, the space could be changed depending on the difference in materials used. Conversely, the word-based visualization is independent of the materials used for an experiment.

3.2 Methods

We collected Japanese sound-symbolic words using a Google search. The Google search was conducted on June 6th, 2014 using Microsoft Internet Explorer 11 for Windows 7. We found 76 words for which the number of phrase search results for "touch sensation like ****" was more than 100. We regarded the 76 words as those used frequently to express tactile sensations. We input each of the 76 sound-symbolic words into our system and obtained their rating scores. Using the scores of the six basic perceptual dimensions ("hard to soft," "rough to smooth," "bumpy to flat," "sticky to slippery," "wet to dry," and "warm to cold") [9], we performed a principal component analysis.

3.3 Results

We generated a distribution diagram of the sound-symbolic words using the first and second principal components as the horizontal axis and the vertical axis, respectively (Fig. 4). The cumulative contribution ratio of the first and second principal components was 80.0 percent. In this diagram, sound-symbolic words that express closely related sensations are also located close to each other. Additionally, we drew the six pairs of adjectives in the diagram based on the principal component loadings. The distribution diagram enables us to grasp the tactile perceptual space intuitively through the relationships among sound-symbolic words, and allows us to identify the categorization of tactile sensations in a detailed way.

TABLE 6
Correlation Coefficients for the 18 Novel Sound Symbolic Expressions

kase-kase	0.74^{***}	zume-zume	0.84^{***}	muyo-muyo	0.96^{***}
gatoQ	0.82^{***}	tiru-tiru	0.69^{***}	mokyuN	0.80^{***}
zyuka-zyuka	0.85^{***}	togyo-togyo	0.71^{***}	rigiQ	0.81^{***}
syumeri	0.71^{***}	nopoR	0.76^{***}	ruki-ruki	0.72^{***}
zyogari	0.95^{***}	hiro-hiro	0.80^{***}	retoQ	0.78^{***}
siri-siri	0.75^{***}	bore-bore	0.65^{***}	wane-wane	0.71^{***}

*** *p < 0.001*.

TABLE 7
Correlation Coefficients of the 18 Novel Sound Symbolic Expressions for the 26 SD Scales

smooth–rough	0.95***	elastic–nonelastic	0.87***	comfortable–uncomfortable	0.52*
bumpy–flat	0.71***	firm–fragile	0.54*	relieved–uneasy	0.59*
hard–soft	0.90***	regular–irregular	0.55*	good–bad	0.69***
warm–cold	0.77***	repulsive–nonrepulsive	0.83***	impressive–unimpressive	0.86***
slippery–sticky	0.54*	sharp–dull	0.72***	luxury–cheap	0.55*
wet–dry	0.56*	clean–dirty	0.74***	pleasant–irritating	0.63***
		stretchy–nonstretchy	0.87***	familiar–unfamiliar	0.60***
		thick–thin	0.84***	eccentric–ordinary	0.65***
		heavy–light	0.75***	natural–artificial	0.50*
		strong–weak	0.89***	intense–calm	0.88***

* $p < 0.05$, *** $p < 0.001$.

Furthermore, we applied a hierarchical cluster analysis (Ward's method) to the six values of the outputs of the words to visualize the structure of tactile perceptual space. We chose six categories because the cross-validated value of grouped words reached almost 90 percent and saturated at six categories (85.4 percent for four categories; 89.5 percent for six; 89.5 percent for ten; 92.5 percent for twelve). In Fig. 4, the bifurcations of the six categories are shown by black circles. The category circles help us to understand the connections or bifurcations among sound-symbolic words. The distribution diagram with category circles is useful for developing a new material/product.

3.4 Tactile Material Collection using Word-based Visualization

The distribution diagram (word-based visualization) can also be used to visualize the relationships among tactile materials. The tactile materials can be placed on the diagram by using the connections between how the materials are felt and the sound-symbolic words. The way in which the sound-symbolic words are spatially distributed on the diagram guides people to locate materials precisely and intuitively. People can locate materials directly on the words, or between words referring to impressions of the words. After locating many materials on the diagram, we can easily grasp the relationships between the diagrammed materials.

For example, when you need to collect 50 tactile materials that have a wide range of tactile qualities, you can place materials on the diagram and see what kind of tactile quality is lacking. If your collection of 40 materials are placed as in Fig. 5, it is obvious that the category including "gori-gori," "goso-goso," and "gisi-gisi" and the category including "gunya-gunya," "beto-beto," and "beta-beta" are needed for the other 10 materials as in Fig. 6. The specifications of 50 materials and corresponding sound-symbolic words are shown in a previous study [21] (see Table A3 in the Appendix, available in the online supplemental material).

Although material-based visualization can be changed depending on the variety of materials, the word-based diagram remains unchanged regardless of the number and variety of materials, and therefore the diagram is a useful way to explore the relationships among materials. In addition,

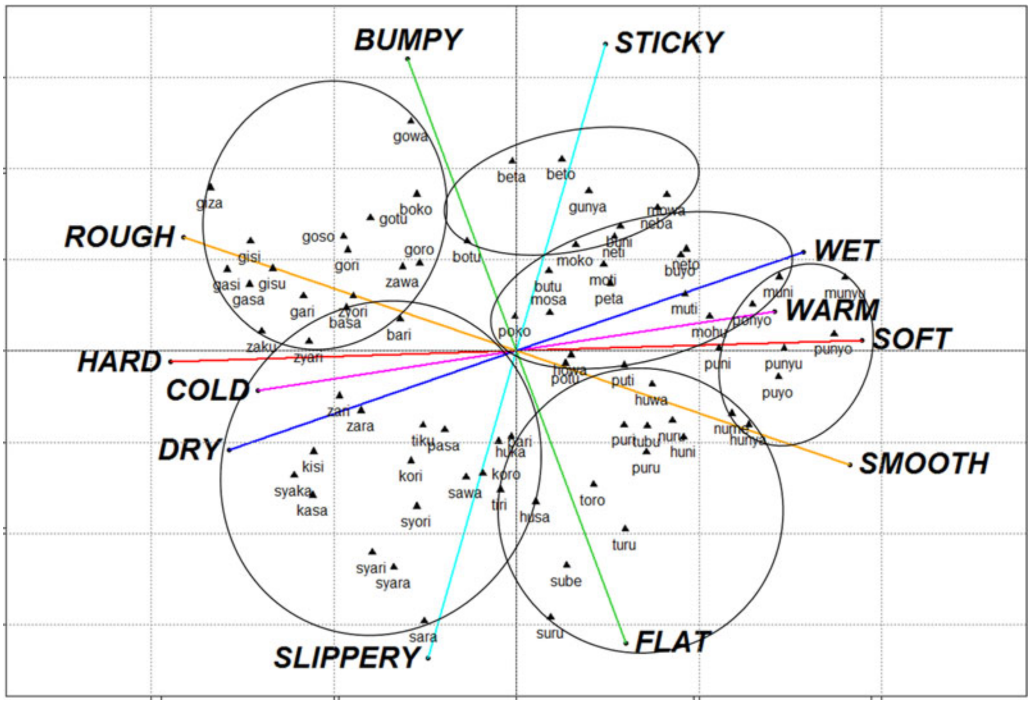

Fig. 4. Distribution diagram of 76 sound symbolic expressions. In the diagram, the repetitions in the sound symbolic expressions are omitted. Each circle represents bifurcations of six categories based on the cluster analysis.

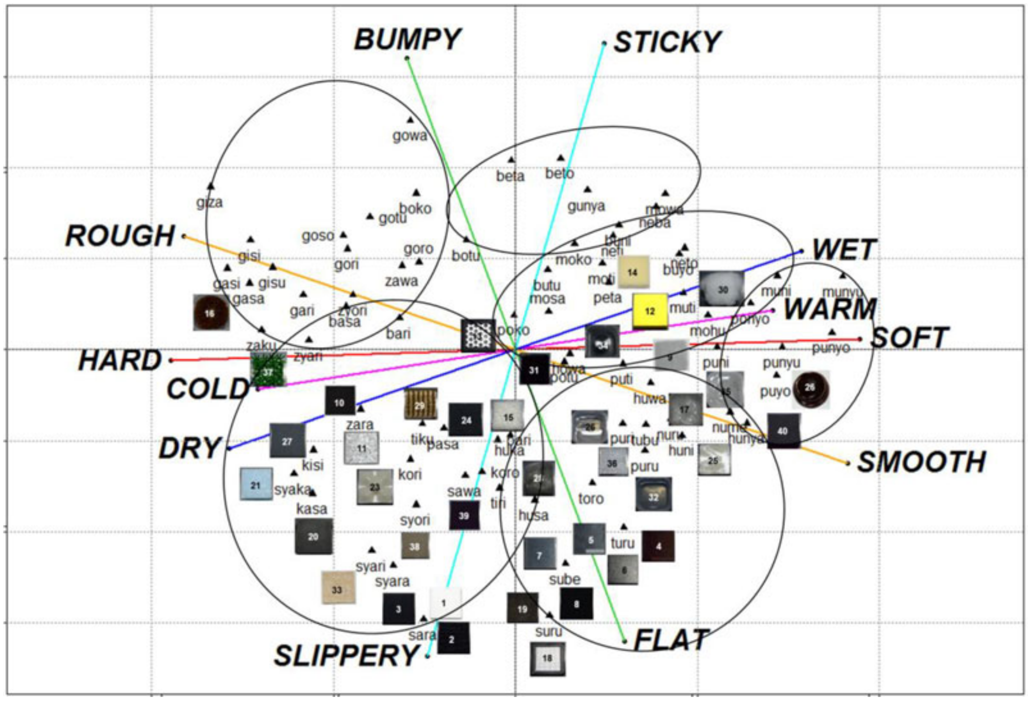

Fig. 5. Distribution diagram of 40 tactile materials (see Table A3 in the Appendix, available in the online supplemental material). The diagram indicates that the cactegory including "gori-gori," "goso-goso," and "gisi-gisi" and the category including "gunya-gunya," "beto-beto," and "beta-beta" are lacking corresponding materials.

because, at least in Japanese, the number of sound-symbolic words is larger than the number of adjectives, and because sound-symbolic words are trivially different from each other, we can visualize the detailed differences among materials.

This word-based visualization might be used for product design (see an example of fabric texture design inspired by sound-symbolic words [22]) and communication between designers and customers in the field of product design. If a customer requests tactile feeling by indicating a location on the diagram, a designer can develop a new material/product referring to the location of the sound-symbolic word, and/or an existing material/product located nearby on the diagram. If this kind of visualization is used for a specific product, such as cosmetics or fabrics, only a collection of words is needed to make a new diagram suitable for the product. After collecting sound-symbolic words that are used to express the product, the words are automatically converted into rating scores of

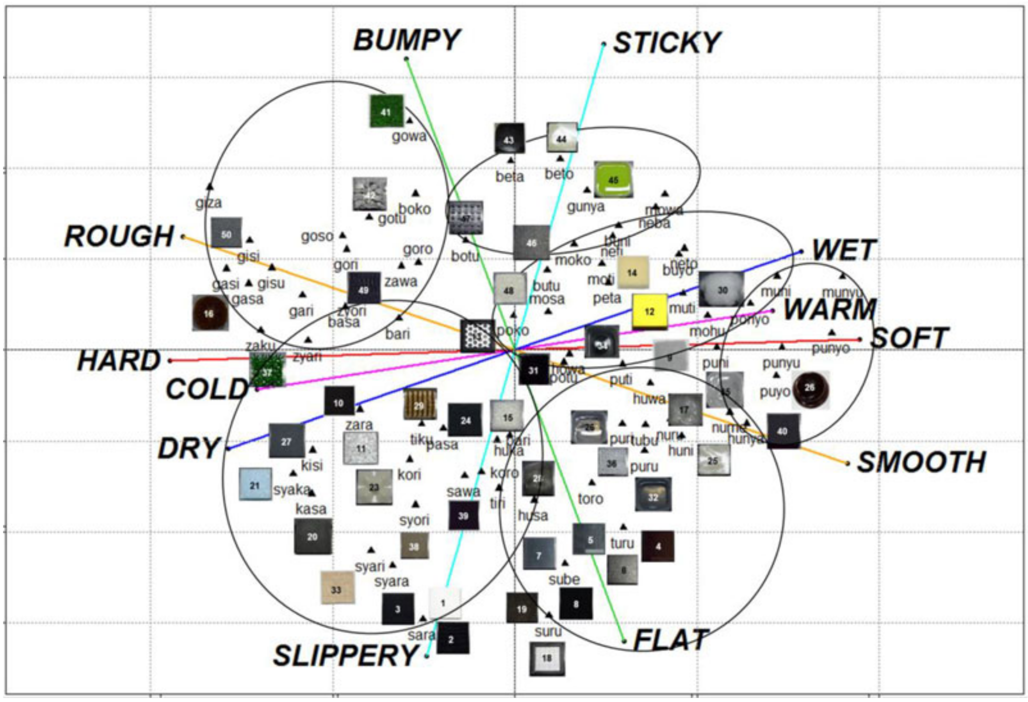

Fig. 6. Distribution diagram of 50 tactile materials. According to Fig. 5, we added 10 materials (no. 41-50).

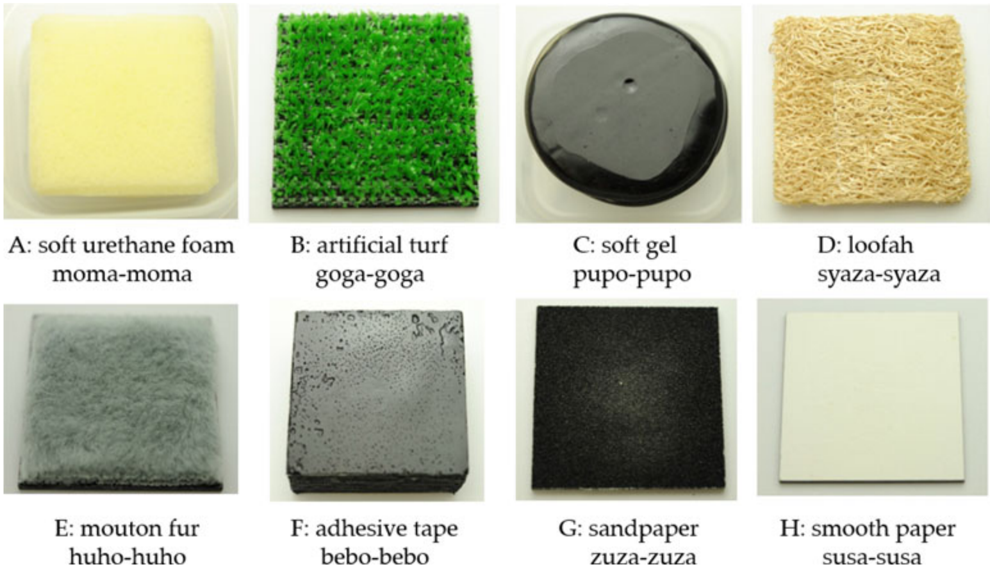

Fig. 7. Materials A-H used in the workshop [24].

26 adjectives by our system, and a new word-based diagram can be constructed.

4 Discussion

We described how we constructed a system that could estimate multidimensional rating scores from a single sound-symbolic word based on sensory–sound associations. Our system can transform any kind of sound-symbolic expression into information equivalent to evaluations against 26 pairs of touch adjectives. The results of the experiments conducted to verify our system showed that it could estimate not only sound-symbolic words established as Japanese vocabulary, but also newly created novel sound-symbolic expressions. As an application of our system, we introduced word-based visualization of the tactile sensation categories based on the outputs of our system.

Another application of our system based on the sound-symbolic association between linguistic sounds and sensory impressions is for inventing effective brand names in the product categories related to haptics (e.g., cosmetics, fabrics, car interiors, and foods). A previous study demonstrated that people expected a creamier, richer, and smoother ice cream when it was named “Frosh” rather than “Frish” [23]. Previous studies [24], [25] have pointed out that consumers associate fictitious brand names with product-related information, e.g., its size, speed, strength, weight. Our system quantifies the impression of sound-symbolic words in perceptual tactile dimensions, and can contribute to the invention of effective brand names to convey tactile impressions to consumers.

Our system can estimate the rating score of newly created words based on the sound symbolism (the “bouba-kiki” effect is a well-known example). At a workshop held at the World Haptics 2013 conference [26], we attempted to observe the “bouba-kiki” effect in touch using eight tactile stimuli selected from tactile materials [21]. Around 60 people participated in the workshop, and more than half of the participants were from Europe, the United States, and other countries. In the workshop, participants were asked: When two materials are described as “moma-moma” or “goga-goga,” which one is “goga-goga”? The materials A–H shown in Fig. 7 were used in the workshop. Participants touched two materials in a box without being able to see them and put a sticker on the side (left or right) where they felt the material was “goga-goga.” They performed these tasks for four pairs of newly created expressions: “moma-moma” versus “goga-goga” (materials A and B), “pupo-pupo” versus “syaza-syaza” (materials C and D), “huho-huho” versus “bebo-bebo” (materials E and F), and “zusa-zusa” versus “suza-suza” (materials G and H). About 80 percent of the participants selected “moma-moma” as material A, about 75 percent selected “pupo-pupo” as material C, about 80 percent selected “huho-huho” as material E, and about 85 percent selected “zuza-zuza” as material G. The evaluations from our system for the eight sound-symbolic expressions (see Figs. A1–A8 in the Appendix, available in the online supplemental material) indicates that there are similarities between impressions of each material and evaluations predicted by our system. However, more formal and large-scale investigation is needed to further explore the universality of sound symbolism.

In conclusion, we have described a new system that uses sound-symbolic relationships to automatically convert a spontaneously expressed a single sound-symbolic word into quantitative ratings in multiple tactile dimensions. Because the database of our system is based on Japanese phonemes, and only Japanese people participated in the evaluation experiment (in Section 2.3), it would be interesting to investigate the differences in tactile sensation categories among different languages. In addition, as the validation experiment of our system was restricted to the language domain, validation experiments using actual materials would be a future direction for this work.

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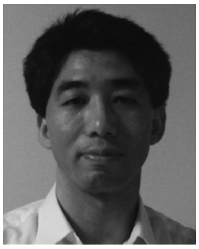

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