RESEARCH ARTICLE

Food-texture dimensions expressed by Japanese onomatopoeic words

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Abstract
This study examined perceptual dimensions of food texture using Japanese onomatopoeic words. Photographs of 56 foods were presented to the participants, and they reported onomatopoeic (mimetic) words suitable for the texture of the foods. The participants' responses were collated into a contingency table of photographs by onomatopoeic words. Correspondence analysis was applied to the table, and 15 dimensions were extracted. The biplot of the configurations was rotated by the technique of sparse coding. The obtained dimensions were smoothness/sounds in slurping noodles; adhesiveness; crumbliness/dryness/fluffiness of breads; popping/juiciness of spherical-shaped foods; soft elasticity/smoothness of gel, wateriness/creaminess; bendability of sticky foods; crispness/crunchiness of snacks; crispness of fruits; elasticity; crunchiness of vegetables; breakability of rod-like foods; sizzle (high temperature and oiliness); and two dimensions specifically expressing textures of lemon and pickled plum. These are considered to be basic food-texture dimensions expressed by Japanese onomatopoeic words.

KEYWORDS
correspondence analysis, food texture, onomatopoeia, sound symbolism

1 | INTRODUCTION

Texture is a food quality that is as important as flavor for consumers (Rohm, 1990; Szczesniak, 1971; Szczesniak & Kleyn, 1963), and there are many terms to describe food texture. Research on food texture is essential for efficient communication about foods, especially for people with different cultural backgrounds. The representative terms for texture in several languages have been presented; Szczesniak and Kleyn (1963) reported 77 English words for food texture, Rohm (1990) presented 105 German texture terms, and Lawless, Vanne, and Tuorila (1997) categorized 71 Finnish texture terms. Drake (1989) provided a polyglot list for 54 English terms for sensory, textural, and rheological properties of foods, and their equivalents in 22 other languages. Nishinari et al. (2008) selected 227 French terms and 144 Chinese terms as texture descriptive words, and categorized them. Yoshikawa, Nishimaru, Tashiro, and Yoshida (1970a) collected 406 Japanese texture terms, many of which were onomatopoeic words, and Hayakawa et al. (2005) collected 445 Japanese texture terms, ~70% of which were onomatopoeic. Since the other languages described above do not have many onomatopoeic words for expressing texture, the use of onomatopoeic words may be one of the reasons for the large number of texture terms in Japanese (Bourne, 2002).

Japanese onomatopoeic (mimetic) words are generally classified into two groups, Giongo, which imitates real sounds, and Gitaigo, which symbolically depicts sound manners in nonauditory sensory impressions, states, movement, or events. There are many onomatopoeic words in Japanese; there are ~2,000 words in the dictionary of onomatopoeic words edited by Yamaguchi (2015), and unconventional onomatopoeic words that are not included in ordinary dictionaries are often used in some circumstances. For example, many unconventional onomatopoeic words have been used in Japanese

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comics. Various derivatives of a Japanese onomatopoeic word can be generated by lengthening vowel, adding a geminate cluster (making a consonant a double consonant), and reduplicating it. The derivative families of onomatopoeic words often represent similar meanings with subtle different connotations.

While it has been believed that there is an independent category of onomatopoeic words in Japanese, Indo-European languages do not generally have such linguistic classes of onomatopoeic words, though there are some sound-symbolic words such as click, munch, murmur, pop, rattle, thump, and twinkle. In modern Chinese, there are few onomatopoeic words corresponding to Gitaigo in Japanese. In English, onomatopoeic expressions mimicking sounds are often considered to be childish, whereas onomatopoeic words are not regarded as immature expressions in Japanese, and are often used in newspaper articles and novels to express objects and events vividly, though they are sometimes considered to be colloquial and informal. These differences make it difficult to translate and understand Japanese documents that contain onomatopoeic words. Since a large share of texture terms in Japanese are onomatopoeic, there should be many non-Japanese speakers that find it difficult to understand Japanese expressions of food qualities. Thus, it would be helpful to classify and organize Japanese onomatopoeic words expressing food texture.

In this study, Japanese participants were asked to view photographs of foods, and to report onomatopoeic words suitable to the texture of the foods. The responses were collated into a contingency (cross-tabulated) table that consisted of foods by onomatopoeic words. Correspondence analysis was applied to the table, and a biplot was obtained. The axes of the biplot were rotated, and texture dimensions of Japanese onomatopoeic words expressing food texture were obtained. The texture dimensions can be interpreted to the classes of texture terms.

In this study, participants were asked to report Japanese onomatopoeic words rather than to rate food texture on predetermined scales, as in the study of Yoshikawa et al. (1970a). Voluntary reporting would reduce the influences of researchers’ assumptions, though it does not completely eliminate them. Associations of foods with Japanese onomatopoeic words were examined by Hayakawa, Hatae, and Shimada (2000) and Ikeda, Hayakawa, and Kohyama (2006), and Quantification Method III analyzed the associations, which is equivalent to correspondence analysis used in this study. In those studies, participants were asked to report foods whose texture matched a Japanese texture term. However, people usually use texture terms in eating foods or drinking to describe the texture, rather than think foods from texture terms. Thus, in this study, participants were asked to report onomatopoeic words from photographs of foods. This task would be more natural than the task in which foods are reported from texture terms, and it is expected to obtain more reliable texture space expressed by Japanese onomatopoeia. Another unique feature of this study is the extension of the correspondence analysis. The results obtained in this study were first analyzed by correspondence analysis in previous studies (Hayakawa et al., 2000; Ikeda et al., 2006). However, configurations obtained by correspondence analysis were rotated using a technique of machine learning termed sparse coding. The results described later suggested the potential usefulness of the rotation method for data analysis in food science. The same methodology was used to derive perceptual dimensions of visual material perceptions using Japanese onomatopoeic words, and meaningful perceptual dimensions were successfully obtained (Hanada, 2016).

Food names were used for the studies of Yoshikawa et al. (1970a); Yoshikawa, Nishimaru, Tashiro, and Yoshida (1970b) to examine the qualities of foods. However, what foods are imagined from the names may be different for different participants. Using photographs of foods would reduce those variations across participants, though not so well as in the cases of eating the actual foods. However, eating many foods and evaluating them are not practical for surveying many types of foods. Hence, we presented photographs of foods to participants.

## METHODS

### Apparatus

Stimuli were displayed on an organic electro-luminescence display (Sony PVM-A250). The viewing distance was about 95 cm. The display size was 1,920 pixels × 1,080 pixels (54.3 cm × 30.6 cm). Participants viewed the display in a dark room.

### Participants

Fifty Japanese undergraduate or graduate students (19–24 years old, 27 females, and 23 males) participated in the experiment. All of them were naive to its purpose and were majoring in information sciences.

### Stimuli

Fifty-six photographs of foods were used. They were collected from several image sites, or photographed by the author’s laboratory. The width of the photos was 1,024 pixels, except for one photograph (No. 29), in which the original image accidentally included the white frame in the image. The height varied depending on the original size of the image. Downsized images of the stimuli are shown in Figure 1. Foods included dishes that ordinary Japanese people often eat in addition to uncooked foods such as vegetables and fruits. Some of the dishes were selected from the foods that matched the representative Japanese onomatopoeic texture words described previously (Hayakawa et al., 2000), so that all the representative onomatopoeic words would presumably be reported. In addition, foods with characteristic food texture were added. The names of the foods for each image are shown in Table 1.
2.4 Procedure

The experiment consisted of two blocks. In the first block, the participants were asked to report onomatopoeic words suitable to express food textures. In each trial, one of the stimulus images was presented in the left side of the display with a white background. Ten empty text boxes were shown in the right side of the display. The participants were asked to write onomatopoeic words that were appropriate to describe the texture of the presented food. They were allowed to use the same response for different images. They were asked to report all the onomatopoeic words that came into mind, and had to write at least one onomatopoeic word to proceed into the next trial. The

FIGURE 1 Downsized images used in this study. The number on each image was omitted when it was presented to participants.
TABLE 1  Names of the photographed foods

| Image | Food | Image | Food |
|-------|------|-------|------|
| 1     | Celery | 29 | Chawanmushi (cup-steamed egg custard hotchpotch) |
| 2     | Broccoli | 30 | Ramen (Chinese noodles) |
| 3     | Asparagus | 31 | Tonkatsu (deep-fried breaded cutlet of pork) |
| 4     | Peas | 32 | White bread |
| 5     | Cucumber | 33 | Rice cracker |
| 6     | Indian corn | 34 | Pretzel |
| 7     | Lettuce | 35 | Baumkuchen |
| 8     | Tomato | 36 | Daifuku (soft rice cake with bean jam) |
| 9     | Cherry tomato | 37 | Pickled radish |
| 10    | Watermelon | 38 | Jelly |
| 11    | Muskmelon | 39 | Fermented soybeans |
| 12    | Grapes | 40 | Poaizu (Chinese-style steamed bun) |
| 13    | Apple | 41 | Roast salmon |
| 14    | Cherry | 42 | Grilled chicken |
| 15    | Strawberry | 43 | Kakuni (stewed cube of meat) |
| 16    | Kiwi | 44 | Cooked rice |
| 17    | Lemon | 45 | Ice cream |
| 18    | Pickled plum | 46 | Udon (thick white noodles) |
| 19    | Pizza | 47 | Caramels |
| 20    | Sausage | 48 | Sweet potato |
| 21    | Donut | 49 | Chocolate |
| 22    | Kimchi (Korean pickles) | 50 | Banana |
| 23    | Deep-fried chicken | 51 | Cookie |
| 24    | Boiled egg | 52 | Youkan (sweet jelly of adzuki beans) |
| 25    | Bean-jam bun | 53 | Gummy candies |
| 26    | Potato-chips | 54 | Inarizushi (flavored boiled rice wrapped in fried bean curd) |
| 27    | Okonomiyaki (Japanese-style pancake) | 55 | Tofu (soybean curd) |
| 28    | Green soybeans | 56 | Kiribosi-daikon (dried strips of Chinese radish) |

definition of Japanese onomatopoeia (Giongo and Gitaigo) as described in Section 1 was explained, and a few examples of onomatopoeic words were presented to remind them of Japanese onomatopoeia. The order in which the stimuli were presented was randomized. Each stimulus image was evaluated once. Before the experimental trials, two practice trials were performed using food photographs other than those used in the experiment to familiarize the participants with the task. In the second block, the participants were asked to answer the questions about the food of each image. In each trial, one of the stimulus images was presented in the left as in the first block, and the questions were displayed in the right. There were four questions: whether you know the food, the food name, the frequency of you eating it, and your preference for the food. Results of the latter block are not reported here.

3  RESULTS

The mean number of onomatopoeic words for a food photograph reported by a single participant was 2.4. Since differently written expressions can have the same pronunciation in Japanese, onomatopoeic words pronounced in the same way were grouped together in one category and transformed into a representative word. Two responses that were not onomatopoeic in any sense were excluded; Japanese onomatopoeic words have characteristic morphological features, and the excluded words were morphologically inconsistent. The remaining responses were transcribed into Roman alphabets using the Hepburn system except for the following exceptions; the geminate clusters (double consonants) are indicated by “Q” as in the studies of Japanese onomatopoeic words (Akiti, 2009; Hamano, 1986); the vowels unaccompanied by consonants (single vowels) are shown in uppercase, and the long vowels are represented by “–”; the mora nasal is represented by “N.” We obtained 771 onomatopoeic words, and all the onomatopoeic words that were reported 10 times and more than 10 times are shown in Table 2.

Using the responses of all participants, we created a contingency table of 56 food images (rows) by the 771 onomatopoeic words (columns). Next, 359 onomatopoeic words that appeared only once were eliminated and 412 onomatopoeic words were retained. Thus, a contingency table of 56 food images by 412 onomatopoeic words was obtained, and correspondence analysis was applied to that table using the R package “ca” (Nenadic & Greenacre, 2007). Figure 2 shows the inertia values (eigenvalues) of the analysis. The knee of the plot is not clear from the figure, and we cannot determine the appropriate number of components from it. We decided to extract 15 components. The 15 components seem to be fairly large, but we chose the number to avoid losing useful information. In addition, the 15 dimensions gave the clearest interpretations for the axes rotated by the procedure. The 15 dimensions explained ~60% of the total inertia.

The 15-dimensional configurations were then plotted as a symmetrical biplot, and the configurations in the first and second dimension are shown in Figure 3a, and those in the third and fourth dimensions in Figure 3b. The onomatopoeic words with absolute coordinates less than or equal to 1.0 on either the horizontal or vertical axis, or whose frequencies were less than five, were shown by dots in order to increase visibility. The arm-like structure of the configurations was clearly observed in Figure 3b, but the directions of the arms were not aligned to the dimensional axes. Correspondence analysis can be thought of as principal component analysis (PCA) with different standardization of data (Clausen, 1998). PCA determined the axes by selecting such directions that the data should be explained mostly in order. However, studies of signal processing and machine learning as well as studies of classical factor analysis showed that the axes derived by PCA would not
generally correspond to meaningful directions. Thus, in machine learning and signal processing, independent component analysis or sparse coding representation has been used for the rotation of PCA axes to extract source signals (Hyvärinen, Karhunen, & Oja, 2001; Stone, 2004). Hence, we decided to rotate the original configurations of the biplot using the technique of sparse coding. The configurations were rotated so the coordinates for the images and onomatopoeic words would be as sparse as possible. The following criterion for sparseness, which should be minimized for maximizing sparseness, was used.

$$J = \sum_{i,k} |b_{ik}| + \sum_{j,k} |m_{jk}|$$

Where $b_{ik}$ and $m_{jk}$ are the rotated coordinates in the $k$-th dimension of food $i$ and onomatopoeic word $j$, respectively. Equation (1) is the sum of the absolute coordinates after the rotation for both foods and onomatopoeic words. This criterion has been often used in the literature on sparse coding in image processing (e.g., Hyvärinen & Raju, 2002; Li, Cichocki, & Amari, 2004). This sparse-coding rotation was also used for the biplot obtained by correspondence analysis in the study of visual material perception, and basic dimensions of visual material perception were successfully extracted by this technique (Hanada, 2016).

The first of four-dimensional spaces of the rotated 15-dimensional biplot is shown in Figure 4, and the remaining spaces are shown in Figure S1. The onomatopoeias with absolute coordinates less than or equal to 1.0 on either the horizontal or vertical axis, or whose frequencies were less than five, were shown by dots as in Figure 3. Most of the items can be seen situated near the axes or around the origin, which resulted from the sparseness coding.

### Table 2: Reported onomatopoeic words and their frequency

| Onomatopoeia | Frequency | Onomatopoeia | Frequency | Onomatopoeia | Frequency | Onomatopoeia | Frequency | Onomatopoeia | Frequency |
|--------------|-----------|--------------|-----------|--------------|-----------|--------------|-----------|--------------|-----------|
| sakusaku     | 290       | nebaneba     | 51        | paku         | 24        | sharQ       | 14        |              |           |
| tsurutsuru   | 242       | pakipaki     | 51        | betobeto     | 23        | tsuruN      | 14        |              |           |
| shakishaki   | 224       | hokuhoku     | 50        | fuwa         | 23        | baribori    | 13        |              |           |
| paripari     | 205       | garigari     | 49        | monyumonyu   | 23        | boroboro    | 13        |              |           |
| mochimochi   | 196       | korikori     | 47        | kuchakucha   | 22        | bunibuni    | 13        |              |           |
| fuwafuwa     | 157       | pariQ        | 47        | pakiq        | 22        | guchuguchu  | 13        |              |           |
| zakuzaku     | 151       | poroporo     | 47        | petapeta     | 22        | gunyagunya  | 13        |              |           |
| karikari     | 137       | punipuni     | 43        | funyafunya   | 21        | ju-         | 13        |              |           |
| shakushaku   | 123       | jurujuru     | 39        | mokyumokyu   | 21        | jukujuku    | 13        |              |           |
| puchipuchi   | 121       | pasapasa     | 37        | kariQ        | 20        | mochumochu  | 13        |              |           |
| torotoro     | 101       | pakupaku     | 36        | pari         | 20        | munyumunyu  | 13        |              |           |
| poripori     | 98        | puripuri     | 36        | pokipoki     | 20        | nurunuru    | 13        |              |           |
| juwajuwa     | 89        | tekateka     | 36        | shitoshito   | 20        | suQ         | 13        |              |           |
| shiQtori     | 88        | dorodoro     | 35        | churuchuru   | 19        | doro        | 12        |              |           |
| mosamosa     | 85        | guniguni     | 35        | netoneto     | 19        | guchaguchu  | 12        |              |           |
| purupuru     | 82        | mushamusha   | 35        | bechabecha   | 17        | hiNyari     | 12        |              |           |
| juwa-        | 78        | moshamosha   | 33        | gorigori     | 17        | hitahtia    | 12        |              |           |
| tsutsububu   | 75        | puchiQ       | 33        | mogu         | 17        | motamota    | 12        |              |           |
| sharishari   | 69        | sarasara     | 33        | moshumoshu   | 17        | pori        | 12        |              |           |
| juwa         | 67        | nechanchea   | 31        | paki         | 17        | puchi       | 12        |              |           |
| mogumogu     | 67        | gunyugunyu   | 29        | poki         | 17        | moQchiri    | 11        |              |           |
| tsuyatsuya   | 67        | saku         | 29        | shaku        | 17        | pokiQ       | 11        |              |           |
| boribori     | 64        | sakusQ       | 29        | surusuru     | 17        | potapota    | 11        |              |           |
| betabeta     | 61        | juwaQ        | 28        | gitorito     | 16        | subsube     | 11        |              |           |
| mosomoso      | 60       | kuchukuchu   | 28        | juwa-        | 16        | bosoboso    | 10        |              |           |
| ju-ju        | 59        | mokumoku     | 26        | mofumufu     | 16        | fuQkura     | 10        |              |           |
| baribari      | 56       | munimuni     | 26        | toro         | 16        | hamuhamu    | 10        |              |           |
| zarazara      | 55       | horohoro     | 25        | korokoro     | 15        | kari        | 10        |              |           |
| hokahoka       | 54       | mochamochu   | 25        | nechonecho   | 15        | poriQ       | 10        |              |           |
| zuruzuru       | 54       | fukafuka     | 24        | jakujaku     | 14        | putsuputsu  | 10        |              |           |
| AtsuAtsu      | 53        | hafuhafu     | 24        | NkuNku       | 14        |              |           |
foods and onomatopoeic words related dominantly to each of the dimensions were summarized in Table 3. The dimensions were interpreted based on common features of foods related to each of the dimensions and the lexicographic meanings of the onomatopoeic words, which are shown in Table 3.

Dimensions 1 and 2 are shown in Figure 4a. Along the axis of Dimension 1, there were noodles udon and ramen, and onomatopoeic words zuru-zuru, zuzuQ, and gokugoku. Onomatopoeic words zuru-zuru, and zuzuQ generally indicates mimetic sounds and feelings when slurping long food like noodles with chopsticks. (These eating sounds are very unpopular for occidental people, but the slurping style is common for eating noodles in Japan.) Onomatopoeic word gokugoku generally indicates the sensation and sounds of gulping smooth foods or liquid. Onomatopoeic words that indicate slippery texture such as churuchuru and surusuru also have moderate values in Dimension 1. Hence, this dimension represents texture related to smoothness of noodles, as well as mimetic sounds when slurping them.

Foods such as baumkuchen, white bread, bean-jam bun, and donut, all of which consist of bread, and onomatopoeic words bosoboso, mofumofu, pasapasa, fuwafusa, and fukafuka were located on the positive side of Dimension 2. Also, the food pizza and onomatopoeic words toro-ri, perapera, and nobinobi were located on the negative side. Onomatopoeic words fukafuka and fuwafuwa indicate fluffiness and softness, respectively, and pasapasa and bosoboso indicate dryness and crumbliness, respectively. Since all these foods along this dimension consist of breads that can be fluffy as well as dry and crumby, the positive direction should indicate the fluffy texture of bread as well as dryness and crumbliness. Onomatopoeic word toro-ri on the negative side generally indicates thickness and viciousness, while nobinobi indicates stretchiness. The negative direction of Dimension 2 seems to indicate pastiness, which is antagonistic to dryness and crumbliness in a sense.

Figure 4b shows the projection of Dimensions 3–4. Dimension 3 related to fermented soybean (natto) and onomatopoeic words nebaneba, nuchanucha, nurururu, and betobeto indicated adhesiveness and viscosity. They corresponded well to previously described class of adhesiveness and viscosity (Hayakawa et al., 2013). On the positive side of Dimension 4 were tomato, cherry, grape, and strawberry, which are watery fruits or vegetables; onomatopoeic words

![FIGURE 2](image-url)  
**FIGURE 2** Inertias (eigenvalues) obtained via correspondence analysis against the component number

![FIGURE 3](image-url)  
**FIGURE 3** The original biplot obtained by correspondence analysis applied to the contingency table of foods × onomatopoeic words. Plots (a) and (b) are projections to the planes of dimensions 1–2 and 3–4, respectively. The onomatopoeias with absolute coordinates less than or equal to 1.0 on either the horizontal or vertical axis, or whose frequencies were less than five, were shown by dots.
FIGURE 4 The biplot rotated by the technique of sparse coding. Plots (a) and (b) are projections to the planes of dimensions 1–2 and 3–4, respectively. The onomatopoeias with absolute coordinates less than or equal to 1.0 on either the horizontal or vertical axis, or whose frequencies were less than five, were shown by dots.

- **Puchi(Q)** and **Gar(G)** that represent the sound and feeling of popping;
- **Gunyu**, which expresses the feeling of flexibility and squashiness; and
- **Gujuguju** that indicates water instability. This dimension is associated with popping and juiciness in breaking the spherical-shaped skin covering fruits or vegetables. Thus, Dimensions 3 and 4 should represent adhesiveness and popping/juiciness of spherical-shaped foods, respectively.

Along the axis of Dimension 5 were foods **Jelly**, **Tofu**, and **Chawanmushi** (cup-steamed egg custard hotpotch), which is made of gel or jelly-like materials, and onomatopoeic words **Purururu**, which indicates soft elasticity and wobbliness, and **TuruN**, **Turururu**, **Tururi**, and **Torusuru**, which implies smoothness and slipperiness (Figure S1a). This dimension would be the soft elasticity and smoothness of gel. Food ice cream and onomatopoeic words **Pechopeche** (wateriness), **Hichie** (coldness), and **Dorodorodo** (thickness and viscosity) were related to Dimension 6 (Figure S1a). Dimension 6 may be related to wateriness, and creaminess as well as coldness, or textures specific to ice cream.

Dimension 7 was related to confectionery **Caramel**, **Gummy candies**, and **Yokan** (sweet jelly of azuki beans), and onomatopoeic words **NeQtory** (stickness and viscosity), **Kachikachi** (firmness), **Gunyagunyu**, **Gunya**, **Guniguni**, and **Gunyugunyu** (flexibility and limpness, or bendability) (Figure S1b). Since the onomatopoeic words starting with “guny” that represent the manner of bending are dominant, this dimension would represent bendability of sticky foods. In the negative side of Dimension 8 were foods **Sweet potato**, **Roast salmon**, **Grilled lettuce**, and onomatopoeic words **Morimori**, **Hokuhoku**, **Chikuchiku**, **Hokohoko**, and **Hokahoko**, which would mostly be characterized by hotness or high temperature (Figure S1b). In the positive side were **Rice cracker**, **Potato-chips**, and **Cookies**, and onomatopoeic words **Paripari**, **Bosoboso**, **Nobinobi**, **Zakuzaku**, and **Garigari**, most of which are related to crispiness and crunchiness. We are not quite sure about what the negative side represents, but the positive direction should indicate crispness and crunchiness of snacks.

On the negative side of Dimension 9 was **Chocolate**, **Rice cracker**, and **Potato chips** (Figure S1c), which also appears in the positive side of Dimension 8. On the positive side were foods **Watermelon**, **Apple**, **Kiwi**, and **Muskmelon**, and onomatopoeic words **SyakiQ**, **Zaku**, **Syarisysi**, **Syaku**, and **Saku**, among others, which represent crispy texture. This dimension is related to the crispy texture of fruits. Dimension 10 was related to foods **Daihuku**, **Pizza**, and **Cooked rice**, and onomatopoeic words **Nobinobi**, **Toro-ri**, and **Mugyumugyu** (Figure S1c). Onomatopoeic words **Nobinobi** and **Toro-ri** express stretchiness and viscosity, respectively, and **Mochimochi** are used to express stickiness and elasticity, especially of mochi rice. Considering the onomatopoeic words expressing elasticity and very elastic foods mochi and pizza along this axis, this dimension should represent elasticity.

Dimension 11 represented the food **Lemon** and onomatopoeic word **ShuwaQ** (does not appear in Figure S1d because of the low frequency), and Dimension 12 was related to food **Kimchi** (Korean pickles), lettuce, **Celery**, and **Kiri-bosi-daikon** (dried strips of Chinese radish), and onomatopoeic words **Piripiri**, **Shinsashina**, **Jakijaki**, **KoriQ**, and **Shakishaki** (Figure S1d). Onomatopoeic word **Piripiri** indicates a piquant feeling, which may specifically be related to the spiciness of **Kimchi**, and **Shakishaki** and **Jakijaki** are related to the crispy and crunchy texture of some vegetables. As a whole, this dimension indicates crunchiness of vegetables.

Dimension 13 is related to the foods **pretzel**, **Chocolate**, **Cucumber**, and **Asparagus**, which are foods with rod or plate shape, and can be broken into two by bending them. Further, along this dimension are
| Represented texture                  | Direction | Food              | Onomatopoetic words                           |
|-------------------------------------|-----------|-------------------|------------------------------------------------|
| Dim. 1 Smoothness and sounds in slurping noodles | Positive  | Ramen             | zuruzuru                                      |
|                                     |           | Udon              | gokugoku                                      |
|                                     |           |                   | zuzuQ                                          |
|                                     |           |                   | churuchuru                                     |
|                                     |           |                   | surusuru                                       |
|                                     |           |                   | Slippery feeling and sound in slurping         |
| Dim. 2 Fluffiness, crumbliness, and dryness of breads | Positive  | Baumkuchen        | bosoboso                                       |
|                                     |           | White bread       | mofumofu                                       |
|                                     |           | Bean-jam bun      | pasapasa                                       |
|                                     |           | Donut             | fuwafuwa                                       |
|                                     |           |                   | fukafuka                                       |
|                                     |           |                   | toro-ri                                        |
|                                     |           |                   | Thick and viscous                              |
|                                     |           |                   | Stretchy                                       |
| Pastiness                           | Negative  | Pizza             | perapera                                       |
|                                     |           |                   | nobinobi                                       |
|                                     |           |                   | Thin and flimsy                                |
| Dim. 3 Adhesiveness                 | Positive  | Fermented soybeans| nebaneba                                       |
|                                     |           |                   | nuchanucha                                     |
|                                     |           |                   | nurunuru                                        |
|                                     |           |                   | betobeto                                       |
|                                     |           |                   | Sticky, adhesive, and viscous                  |
| Dim. 4 Popping and juiciness in breaking spherical-shaped fruits or vegetables | Positive  | Cherry tomato     | puchiQ                                         |
|                                     |           | Cherry            | puchi                                          |
|                                     |           | Tomato            | AkaAka                                         |
|                                     |           | Grapes            | gariQ                                          |
|                                     |           | Strawberry        | korokoro                                       |
|                                     |           |                   | teca                                           |
|                                     |           |                   | guyu                                           |
|                                     |           |                   | gujuguju                                       |
|                                     |           |                   | Unstable with a lot of water                   |
| Dim. 5 Soft elasticity and smoothness of gel | Positive  | Jelly             | purupuru                                       |
|                                     |           | Tofu              | tsuruN                                         |
|                                     |           | Chawanmushi       | tsururi                                        |
|                                     |           | Boiled egg        | churuchuru                                     |
|                                     |           |                   | surusuru                                       |
|                                     |           |                   | zuzuQ                                          |
|                                     |           |                   | Slippery feeling and sound in slurping         |
| Dim. 6 Wateriness, creaminess and coldness of ice cream | Positive  | Ice cream          | pechapecha                                     |
|                                     |           |                   | hiNyari                                        |
|                                     |           |                   | hiEhiE                                         |
|                                     |           |                   | dorodororo                                     |
|                                     |           |                   | bechabecha                                     |
|                                     |           |                   | Cold                                           |
|                                     |           |                   | Cold                                           |
|                                     |           |                   | Thick and viscous                              |
|                                     |           |                   | Soggy and viscous                              |
| Dim. 7 Bendability of sticky foods   | Positive  | Gummy candles     | neQtori                                        |
|                                     |           | Caramels          | kachikachi                                     |
|                                     |           | Youkan            | gunyagunya                                     |
|                                     |           |                   | Sticky and viscous                             |
|                                     |           |                   | Firm                                           |
|                                     |           |                   | Flexible and limp                              |
| Represented texture | Direction | Food | Onomatopoeic words |
|---------------------|-----------|------|--------------------|
| gunya               | Flexible and limp |
| guniguni            | Flexible and limp |
| gunyogunyo          | Flexible and limp |
| **Dim. 8**          |           |      |                    |
| Crispness and crunchiness of snacks | Positive | Rice cracker | paripori | Sound and feeling in biting crispy foods |
| Potato-chips        |           | baribari  | Sound and feeling in biting crunchy foods |
| Cookie              |           | nobinobi  | Stretchy          |
| gari                | Sound and feeling in popping |
| zakuzaku            | Crunchy   |
| garigari            | Sound and feeling in popping |
| boribori            | Sound and feeling in biting crunchy foods |
| Negative            | Sweet potato | morimori | Large in volume |
| Roast salmon        | hokuhoku  | Hot in temperature |
| Grilled chicken     | chikuchiku| Piquant and prickling |
| hokohoko            | Soft, hot and crumbly |
| hokahoka            | Hot in temperature |
| **Dim. 9**          |           |      |                    |
| Crispness of fruits | Positive | Watermelon | shakiQ | Crispy |
| Apple               | zakuQ    | Crunchy |
| Muskmelon           | sharishari | Crispy |
| Kiwi                | shakuQ   | Crispy |
| Strawberry          | sakuQ    | Crispy |
|                      | shaki    | Crispy |
| Negative            | Chocolate | koQteri | Thick and oily |
| Rice cracker        | paripori | Sound and feeling in biting crispy foods |
| Potato-chips        | gitogito | Oily |
| baribari            | Sound and feeling in biting crunchy foods |
| **Dim. 10**         |           |      |                    |
| Elasticity          | Positive | Daifuku | nobinobi | Stretchy |
| Pizza               | toro-ri  | Thick and viscous |
| Cooked rice         | mochimochi | Sticky, elastic and chewy |
|                      | mugyumugyu | Doughy |
| **Dim. 11**         |           |      |                    |
| Texture specific to lemon | Positive | Lemon | | |
| **Dim. 12**         |           |      |                    |
| Crunchiness of vegetables | Positive | Kimchi   | piripiri | Piquant and pungent |
| Lettuce             | shinashina | Shriveled and wilted (flexible and pliant in the formal situation) |
| Celery              | jakjaki  | Crunchy |
| Kiri-boshi-daikon   | koriQ    | Crunchy |
|                      | shakishaki | Crispy feeling and sound in biting hard food |
| **Dim. 13**         |           |      |                    |
| Breakability of rod-like foods | Positive | Pretzel | pokiQ | Sound and feeling in snapping |
| Chocolate           | pokipoki | Sound and feeling in snapping |
| Cucumber            | pakiki   | Sound and feeling in snapping |
| Asparagus           | pakipaki | Sound and feeling in snapping |
|                      | poriQ    | Sound and feeling in snapping |
|                      | poki     | Sound and feeling in snapping |
|                      | peki     | Sound and feeling in snapping |

(Continues)
the onomatopoeic words pokipoki, pakipaki, pokiQ, peki, and so on (Figure S1e). These onomatopoeic words express snapping of something long in two pieces. Hence, this dimension should express the texture of breakable rod-like foods. On the negative side of Dimension 14 were pea, green soybeans, Indian corn, banana, and broccoli, and onomatopoeic words mukimuki, putuputu, pakuQ, pokiQ, and mugyumugyu (Figure S1e). What this side represents is unclear. On the positive side, there were foods okonomiyaki (Japanese-style pancake), sausage, and kakuni (stewed cube of meat), and onomatopoeic words ju-ju-, ju-, AtsuAtsu, koQteri, teratera, hafuhafu, and gitogito. Onomatopoeic words ju-ju- and ju- are mimetics corresponding to sizzle (hissing sound of frying and cooking). AtsuAtsu, represent hotness in temperature, and gitogito implies oiliness. Hence, the positive direction of Dimension 14 can be summarized as sizzling that occurs at high temperatures, as well as oiliness.

Dimension 15 was related to pickled plum, and onomatopoeic words shiwashiwa, nuchunuchu, mugyumugyu, pecho, guchagucha, and so on (Figure S1f). This dimension seems to represent the texture specific to pickled plum.

As can be seen from the summary of Table 3, Dimensions 11 and 15 seem to represent textures of specific foods: lemon and pickled plum. Dimensions 2, and 6 were also related solely to foods (fermented soybeans, and ice cream), but these dimensions seem to represent generic characteristics of texture, adhesiveness and wateriness/creaminess, respectively, considering the onomatopoeic words relevant to these dimensions. The remaining dimensions are likely to express particular characteristics of food texture: smoothness/sounds in slurping noodles (Dim. 1) crumbliness/dryness/fluffiness of breads (Dim. 2), popping/juiciness of spherical-shaped foods (Dim. 4), soft elasticity/smoothness of gel (Dim. 5), bendability of sticky foods (Dim. 7), crispness/crunchiness of snacks (Dim. 8), crispness of fruits (Dim. 9), elasticity (Dim. 10), crunchiness of vegetables (Dim. 12), breakability of rod-like foods (Dim. 13), and sizzle (high temperature and oiliness) (Dim. 14).

4 | DISCUSSION

The participants reported a large number of onomatopoeic words. Hayakawa et al. (2005) noted that out of 446 representative Japanese texture terms, 312 terms are onomatopoeic. Yoshikawa et al. (1970a) also reported that a large part of texture terms consist of onomatopoeic words. Thus, onomatopoeic words are important elements for expressing textures in Japanese. Some onomatopoeic words such as sakusaku and shariQ represent not only the sound of mastication for crunchy foods but also the feeling involved in mastication. Many of the reported onomatopoeic words are not directly related to sound, but based on the sensations and feelings while eating these foods. It should be noted that many of the onomatopoeic words reported in this study are also used for describing tactile sensation; surusuru expresses smooth food texture as well as tactile sensation of a smooth surface.

The number of the dimensions obtained by correspondence analysis was fairly large, especially compared to the three dimensions that Lawless et al. (1997) obtained by multidimensional scaling (MDS) of Finnish and English texture terms, and the three dimensions that Toda, Wada, Yasumatsu, and Ishii (1971) extracted by
PCA on instrumental and sensory data. However, Lawless et al. (1997) applied the cluster analysis to classify the terms, and obtained 10–12 groups of texture terms for U.S. and Finnish consumers and food professionals, and Toda et al. (1971) focused only on gels and pastes for foods. On the other hand, Yoshikawa, Nishimaru, Tashiro, and Yoshida (1970c) extracted eight dimensions of textures using factor analysis. Nishinari et al. (2008) extracted six dimensions by correspondence analysis for Chinese texture terms. In the study of Hayakawa et al. (2013), six-, five-, and three-dimensional solutions were adopted for MDS and applied to three kinds of similarity data about Japanese texture terms representing mechanical attributes, geometrical attributes, and other attributes relating to moisture and fat/oil. Further, they categorized the terms into six, five, and three classes by cluster analysis of the configurations for those attributes obtained by MDS, and into many more sub-categories. Ikeda et al. (2006) extracted six dimensions by dual scaling (equivalent to correspondence analysis) from the table of food items by onomatopoeic words, which resulted in 16 groups of texture terms by cluster analysis. These studies suggest that a high dimensional space is required to describe the structure of texture terms because of the complexity of food textures. Thus, considering that this study obtained the term groups as dimensions in a multi-dimensional space rather than classes obtained by cluster analysis, 15 dimensions of textures obtained in this study do not seem unreasonable.

Textural characteristics for solid and semi-solid foods were generally classified into several categories: hardness, cohesiveness, viscosity, springiness, adhesiveness about mechanical characteristics, particle size and shape, particle shape-orientation about geometrical characteristics, and moisture and fat content (International Standard Organization, 1994; Szczesniak, 1963). Categories of geometrical characteristics were not related to the dimensions obtained in this study, but Dimensions 4 and 13 were somewhat related to spherical-shaped foods and rod-like foods, respectively. These suggest that Japanese onomatopoeic words are more suitable for expressing mechanical characteristics, oil/fat characteristics, and water contents than geometrical characteristics.

A mechanical attribute of hardness was not also distinctly represented as described above, probably because especially hard foods were not included in the food items. Hayakawa et al. (2013) also noted that no category specifically related to hardness and firmness was obtained. However, softness was partially related to Dimensions 2 and 5. Other mechanical attributes such as cohesiveness, viscosity, springiness, and adhesiveness, are substantially related to the dimensions obtained by our analysis, but these mechanical attributes did not correspond to the dimensions of Table 3 in the one-to-one manner. For example, Dimension 14, which was related to sizzle, somewhat represented oiliness, but the dimension was also related to hotness and juiciness. Brittleness, which was a sub-category of cohesiveness, was represented in Dimensions 2 and 9. Conversely, Dimension 5 was related to springiness or elasticity as well as softness, and Dimension 2 was related to softness and brittleness. This suggests that the dimensions obtained by this study do not represent specific physical attributes contributing to texture, but textures that arise by combined physical characteristics.

The following factors of food textures were extracted by Yoshikawa et al. (1970c): hard-soft, cold-warm, oily, juicy, elastic-flaky, heavy, viscous, and smooth. Each of these factors was related to multiple dimensions of the biplot in a distributed manner. Hard-soft factor was related to Dimensions 2 and 5; cold-warm factor to Dimensions 6, 8, and 14; oily factor to Dimension 14; juicy factor to Dimension 4; elastic-flaky to Dimensions 2, 5 and 10; heavy factor to Dimensions 10 and 14; viscous factor to Dimensions 2, 6, and 7; and smooth factor to Dimensions 1 and 5. Note also that Dimensions 2 and 5 were related to attributes of softness as well as elasticity, Dimension 2 to softness and elasticity, Dimension 14 to oiliness and wariness. These also suggest that the texture dimensions expressed by Japanese onomatopoeia represent combined properties of several basic texture characteristics.

Onomatopoeic words are sound-symbolic words that vocal sounds or phonemes contain meaning themselves. Onomatopoeic words related to most of the texture dimensions shown in Table 3 have some common characteristics. For example, the onomatopoeic words related to Dimension 3 of adhesiveness and fermented soybeans included the consonants "n" and "b" in the first syllable, which seem to represent stickiness. The first syllable for the onomatopoeic words that contributed to Dimension 5 was "p," "t," or "s." Syllable "p" is told to often symbolize the tearing of a surface with tension, "t" has weak tension and "s" is sliding on a smooth surface (Hamano, 1986). Many of the onomatopoeic words for Dimension 7 are related to the bendability of sticky foods and start with the consonant "g." The first consonant of the onomatopoeic words strongly related to Dimension 9 (most related to crispness of fruits) was "sh" or "z," which should symbolize crispness. Consonant "p" of the onomatopoeic words for Dimension 13 seems to represent snapping of rod-like foods. These illustrate the characteristics of sound symbolism in onomatopoeic expressions of food texture.

Sound symbolism has been studied in other fields of psychology; some phonemes match a visual form better than other visual forms (e.g., Köhler, 1929; Oyama & Haga, 1963; Ramachandran & Hubbard, 2003). Cross-modal correspondences between taste/texture and sound properties have been investigated (Crisinel, Jones, & Spence, 2012; Favalli, Skov, Spence, & Byrne, 2013; Gallace, Boschin, & Spence, 2011; Ngo, Misra, & Spence, 2011; Simner, Cuskley, & Kirby, 2010; Spence & Gallace, 2011). Some foodstuffs are reliably associated with nonsense words, such as "maluma/takete" (Gallace et al., 2011; Spence & Gallace, 2011). Sweet taste matches "maluma" and bitter taste is associated with "takete" (Crisinel et al., 2012). The flavor of chocolate are also consistently associated with non-words (Ngo et al., 2011). These findings illustrate the sound symbolism in gustatory sensation. Crispy foods tend to make sounds with higher pitches than crunchy foods, and it is also suggested that this difference in pitch is reflected in higher pitch of "f" and "sp" in "crisp" than that of "u" and "ch" in "crunch" (Vickers, 1984). Sound symbolisms in Japanese onomatopoeic words expressing gustatory sensation have also been examined. Sakamoto and Watanabe (2015) investigated sound
symbolism in Japanese onomatopoeic words expressing taste/texture that participants reported after tasting drinks. However, the study used only liquid drinks as stimuli, not solid or semi-solid foods, although there are many Japanese onomatopoeic words that express various food textures of solid and semi-solid foods. A similar study was conducted to sound symbolism in touch using Japanese onomatopoeic words (Sakamoto & Watanabe, 2018). Some commonalities in sound symbolism for touch and taste/texture were found. The consonants /s/ and /sy/ were related to good taste/texture and comfortable touch, and the consonant /b/ was related to bad taste/texture and uncomfortable tactile sensation. This study also confirmed that phonemic sounds symbolize food texture in systematic ways. The present findings may also provide useful data for further linguistic and psychological studies on sound symbolism. Many variants of onomatopoeic words can be easily produced in Japanese by changing short vowels to long ones, adding a geminate cluster, and reduplicating it. Further, new Japanese onomatopoeic words are often created for expressing unique and unfamiliar sensations, especially in the younger generations. Those characteristics of Japanese onomatopoeic words expand the expressiveness of food texture for the Japanese language while also creating difficulties for non-Japanese speakers to comprehend Japanese expressions of texture. Thus, the understanding of sound symbolism in Japanese texture terms would be helpful for the communication of food textures across different cultures.

Many languages have a distinct class of words with clear sound symbolism. There are many onomatopoeic words in Korean and Basque, and some East Asian languages have a distinct onomatopoeic system called “expressives” (Enfield, 2005). Some sub-Saharan African languages have a sound symbolic system called ideophones (Childs, 1994). It would be worthwhile to conduct a similar study using onomatopoeic words in such languages to reveal how food texture is expressed by onomatopoeia.

Although correspondence analysis and PCA have been used in several studies of food texture, the axes of the configurations were not rotated in those studies. Axes for correspondence analysis and PCA are generally selected such that dimensions accounting for the largest portion of variances are sequentially extracted; the first dimension explains the largest proportion of variances, and the second dimension the second largest proportion, and so on. However, recent studies of signal processing and machine learning have shown that the axial directions of PCA do not correspond to meaningful directions. It should be noted that this has been long known in psychometrics as factor indeterminacy of factor solution (Harman, 1976), and a large number of methods of factor rotation have been proposed. For signal processing, independent component analysis and sparse coding methods have been presented to derive meaningful directions. Several studies of food textures used MDS for visualizing the relations among texture terms (e.g., Hayakawa et al., 2013), but a MDS solution also has ambiguity about the axial rotation. The rotation method used in this study based on sparseness is potentially useful for texture research, and would be worth considering in the application of configurations obtained by MDS, PCA, and correspondence analysis.

The rotation method used in this study is a procedure to derive statistically meaningful axes in terms of sparseness. The dimensions derived by this rotation method should have some perceptual and psychological significance. However, although this technique of sparse coding shows statistically meaningful directions of data space, it does not reveal what the dimensions represent. Although the obtained dimensions were interpreted based on lexicographic meanings of onomatopoeic words and food properties, other interpretations of the dimensions than those presented in the results are indeed possible; the second dimension may represent texture specific to fermented soybeans, or adhesiveness of general sticky foods. Further work is required to clarify what those dimensions mean.

Participants in the experiments were university students that did not major in food science. Many studies showed that texture terms used by food professionals are considerably different from general consumers (e.g., Rohm, 1990; Szczesniak & Kleyn, 1963). Thus, it is not known that the results obtained by this study can be generalized to food professionals. However, onomatopoeic words are considered to be oral and rather colloquial, and are generally used in casual circumstances more than formal ones. Hence, the usage of onomatopoeic words for consumers may not be so different from that from food professionals. Another limitation of this study is that foods used for the experiment did not cover all foods that the Japanese eat in daily life. There could be other food-texture dimensions expressed by Japanese onomatopoeia than the dimensions obtained in this study. In addition, the photographs of foods were used as stimuli to reduce the variation of recalled foods, but different participants might imagine slightly different food textures depending on their different experiences with the foods. With this caveat, this study has revealed many texture characteristics expressed by Japanese onomatopoeic words, classified them into 15 texture dimensions, and provided information about the properties of sound symbolism in the expressions of food texture.

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AUTHOR CONTRIBUTIONS
The whole work for this study was performed by the author.

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Conflict of Interest: The author declares that he does not have any conflict of interest.
Ethical Review: This study was approved by the ethics committee of Future University Hakodate.
Informed Consent: Written informed consent was obtained from all study participants.

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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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