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Effects of ±2 °C cup rim temperature variations relative to beverage temperature on flavor perception

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ABSTRACT

Food temperature and temperature stimulation of areas around the tongue and nose can influence flavor perception. However, during mastication, the lower lip makes contact with cutlery and tableware, and temperature sensation in the lower lip is thought to play a significant role in flavor perception. In this study, a tumbler-type device that can apply a specific temperature to the lower lip without altering the beverage is utilized to investigate changes in flavor perception, including in-mouth aroma, aftertaste, intensity of taste, throat feeling, deliciousness, comfort, sweetness, saltiness, sourness, bitterness, and umami. The evaluation experiment revealed that cooling the cup rim by 2 °C relative to the beverage temperature led to a stronger perception of coldness, improved throat feeling, and significant increases in perceived deliciousness and comfort ($p < 0.05$). In addition, warming the cup rim for warmed green tea tended to enhance the perception of in-mouth aroma ($p = 0.055$). This study demonstrated that the temperature of the lower lip during drinking influences human flavor perception.

1. Introduction

Meals are delightful experiences that bring great joy and happiness, and savoring them contributes to living a fulfilling life (Macht et al., 2005); U.S. Department of Agriculture Staff and United States and Department of Agriculture and United States and Department of Health and Human Services, 2000). Humans do not perceive food flavors, such as deliciousness, based solely on chemical compounds. In addition to chemical stimuli, they experience flavors during food consumption through various sensory modalities, including vision, hearing, and touch (Zampini & Spence, 2012; Auvray & Spence, 2008). Therefore, flavor perception is not solely determined by taste but is influenced by the interaction of the five senses.

Recently, cross-modal technology that emphasizes sensory perception by combining multiple senses, such as visual and auditory stimuli, has gained attention and has been used in various research fields (Narumi et al., 2011, 2010; Weidner et al., 2023; Tanikawa & Hirose, 2012; Nakano et al., 2019; Zampini & Spence, 2005; Koizumi et al., 2011). Among the various senses, research focusing on temperature has attracted increasing interest. The temperature of food and beverages influences flavor perception (Stokes et al., 2016; Kim et al., 2015; Ross & Weller, 2008; Kähkönen et al., 1995; Drake et al., 2005; Yau & Huang, 1996; Singh & Seo, 2020). Therefore, the flavor perception of food and beverages can be influenced by providing temperature stimuli to the oral cavity. In addition to the food temperature, temperature stimulation around the nose or on the tongue has been shown to influence flavor perception. The "Affecting Tumbler" (Suzuki et al., 2014) study demonstrated that thermal sensations presented around the nose can alter the perceived intensity, aftertaste, comfort, and bitterness of beverages. Other studies have shown that direct temperature stimulation of the tongue, without food involvement, can also impact flavor perception (Cruz & Green, 2000; Karunanayaka et al., 2018). Furthermore, a spoon-shaped device with an adjustable temperature was proposed to modify the perception of spiciness (Yang et al., 2022). These findings suggest that temperature stimulation within and around the oral cavity can significantly influence flavor perception. However, studies on individually controlling the temperature of areas surrounding the mouth, such as the oral cavity excluding the tongue and lips, and the temperature of food or beverages to investigate their effects on changes in flavor perception have not been conducted. The lips, similar to the fingertips, exhibit high tactile sensitivity (Tsutsui et al., 2016), and research has shown that the mouth region has an especially high

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sensitivity to temperature (Stevens & Choo, 1998). In addition, during meals, the lower lip comes into contact with cutlery and tableware, suggesting that the temperature sensation of the lower lip is also important for flavor perception. Therefore, we focused on the effect of the lower lip temperature on flavor perception and aimed to individually control the temperature of the part of the cup touching the lower lip and the temperature of the beverage to elucidate their relationship with flavor perception. This study focuses primarily on beverages because of the lack of mastication effects and the ease of standardizing parameters such as throat feeling without interference. In this study, we developed a tumbler-type device that applies controlled temperature stimuli to the lower lip and examined the effects of these stimuli on beverage flavor perception. Peltier elements and heat pipes were used in the device to regulate the cup rim temperature between 0 °C and 65 °C, allowing direct thermal stimulation of the lower lip. Using this system, we investigated how temperature affects flavor perception. Since previous studies have shown that food and beverage temperatures affect flavor perception (Stokes et al., 2016; Kim et al., 2015; Ross & Weller, 2008; Kähkönen et al., 1995; Drake et al., 2005; Yau & Huang, 1996; Singh & Seo, 2020), we specifically focused on the cup rim temperature and its effects. In this work, flavor perception encompasses in-mouth aroma, aftertaste, intensity of taste, throat feeling, deliciousness, comfort, sweetness, saltiness, sourness, bitterness, and umami.

2. Material and methods

2.1. Method for applying a temperature stimulus to the lower lip

Fig. 1 shows the configuration of the tumbler-type device capable of providing a specific temperature to the lower lip. The tumbler-type device consists of a tumbler, an aluminum heat pipe, two thermal change modules, a thermistor to obtain the temperature of the cup rim, and a control board. The aluminum heat pipe is attached to the cup rim, which efficiently transfers heat. The two thermal change modules at the two ends of the heat pipe vary the heat pipe temperature. Each thermal change module comprises a Peltier device, a heat sink, and a fan to warm or cool by flowing a current in the forward or reverse direction from the motor driver to the Peltier device. We arranged a heat sink and a fan to cool the Peltier device, which releases the absorbed heat and consumed power to the heat radiation side.

Fig. 1 shows the configuration of the tumbler-type device. We implemented a prototype system of the device based on this configuration. The implemented system is shown in Fig. 2. We adopted a vacuum insulation structure in the tumbler (made by THERMOS) to maintain the beverage temperature and prevent heat from being transmitted to the outside. For the cup rim, we chose an aluminum heat pipe with high specific heat and thermal conductivity from materials used in tableware and cutlery. We inserted an insulation material between the tumbler and the heat pipe to prevent the temperature of the cup rim from being transmitted to the tumbler. We also used a neoprene-based adhesive

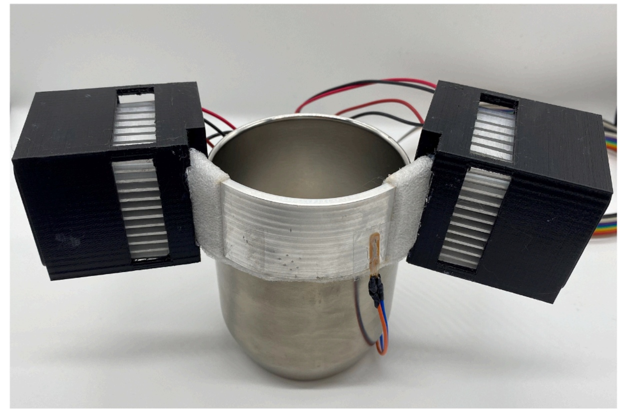

Fig. 2. Implementation of the tumbler-type device.

(made by AEROFLEX) to prevent the beverage from seeping through the gap.

We attached a heat pipe that protruded from the tumbler to provide the same temperature to both the lower lip and the corner of the mouth. The median thickness of an adult's upper lip is 13.87 mm, with a standard deviation of 2.13 mm (Isiekwe et al., 2012). Therefore, we affixed the heat pipe such that the cup rim extended 16 mm from the tumbler. Additionally, considering that the width of the mouth corner is greater in males, with an average of 49.7 mm and a standard deviation of 3.6 mm (Kouchi & Mochimaru, 2008), we attached insulation material to the heat pipe to achieve a width of 55 mm.

We implemented an Arduino and a motor driver on the control board for temperature control. Peltier devices were mounted to control the temperature of the cup rim, and a thermistor (made by SEMITEC, 103JT-025) provided feedback to the Peltier devices (made by NaRiKa).

In addition, a PID control system was adopted for driving the Peltier devices to change the temperature of the cup rim. After implementation, we conducted experiments to evaluate the cooling and warming capabilities of the device. Fig. 3 shows the temperature change in the cup rim during warming and cooling. The temperature of the cup rim can be precisely varied within the range of 0 °C to 65 °C by continuously warming and cooling it for 5 min.

Additionally, since the cup rim, with various temperatures, comes into contact with the beverage during drinking, we investigated the effect of the cup rim temperature on the beverage temperature during consumption. Before drinking, we placed cooled water (5 °C), room-temperature water (24 °C), and warmed water (45 °C) into the tumbler-type device. The cup rim temperature was adjusted by ±2 °C relative to the beverage temperature, following the same conditions as in the experiment. The beverage was then transferred to a separate cup via the cup rim. We measured the temperature of the beverage when it was in the tumbler-type device and after it was transferred to the other

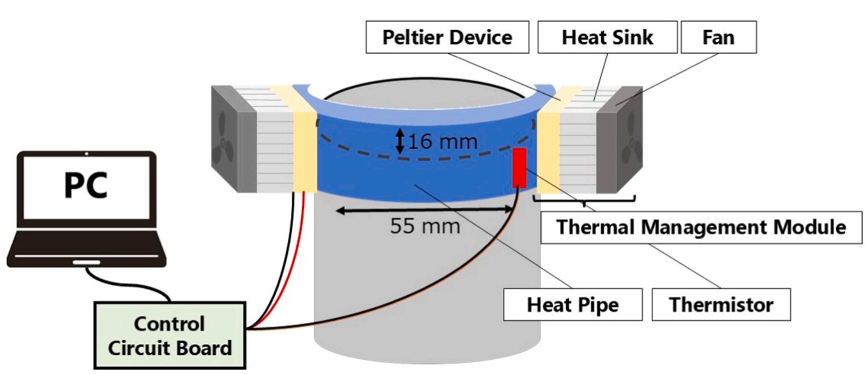

Fig. 1. Composition of the tumbler-type device.

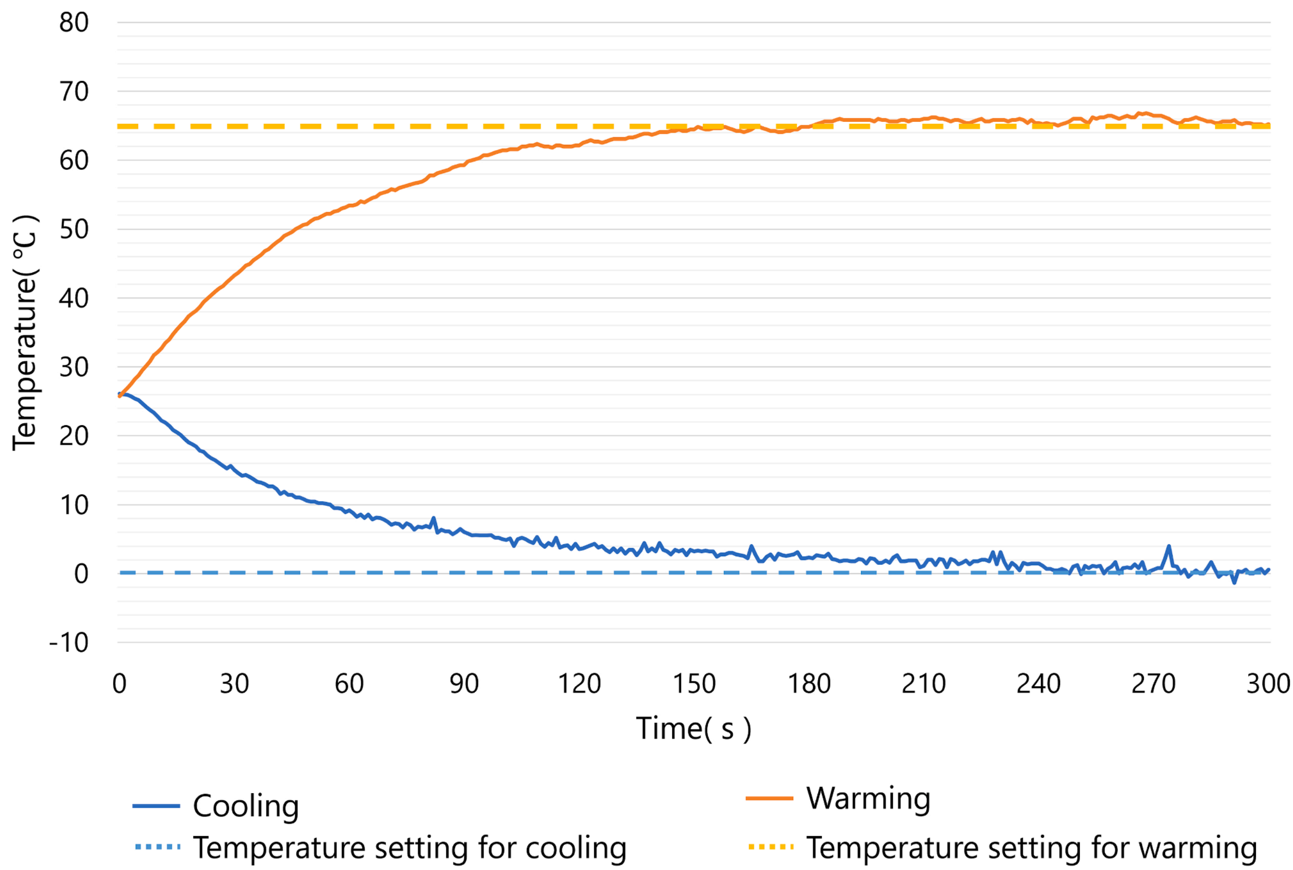

Fig. 3. Temperature change at the cup rim during warming and cooling.

cup. The maximum temperature change observed was 0.3 °C. Therefore, we confirmed that the cup rim temperature did not affect the beverage temperature.

2.2. Experimental conditions

Previous studies have shown that the change in flavor perception due to food temperature varies with the type of food (Stokes et al., 2016; Kim et al., 2015; Ross & Weller, 2008; Kähkönen et al., 1995; Drake et al., 2005; Yau & Huang, 1996; Singh & Seo, 2020). Additionally, in the "Affecting Tumbler" (Suzuki et al., 2014) study, researchers investigated the impact of temperature stimulation around the nose on flavor perception using orange juice and apple juice. In reference to these studies, our experiment included orange juice (made by Ehime Beverage), which is known to correspond to an enhanced perception of sourness; apple juice (made by Ehime Beverage), which is associated with a heightened perception of sweetness; green tea (made by HARUNA Produce), which is known for its strong bitterness; and water, which is tasteless and odorless.

The combination conditions of cup rim and beverage temperatures (nine conditions) are shown in Table 1. In the previous "Affecting Tumbler" study, the effect on flavor perception was investigated by

Table 1
Combination of beverage and cup rim temperatures.

	cooled conditions	standard	warmed conditions
cooled beverage (5 °C)	3 °C	5 °C	7 °C
room-temperature beverage (24 °C)	22 °C	24 °C	26 °C
warmed beverage (45 °C)	43 °C	45 °C	47 °C

varying the skin temperature around the nose by ±2 °C from room temperature (Suzuki et al., 2014). Taking this as a reference, in the present study, three temperature conditions were set for the cup rim: the same temperature as the beverage, −2 °C for the cooled condition, and +2 °C for the warmed condition. The beverage was maintained at three different temperatures: cooled, room temperature, and warmed. In the experiment, the cup rim at the same temperature as the beverage was set as the standard condition. The cup rim temperature was then varied by ±2 °C relative to the beverage temperature to investigate its effect on flavor perception.

The cooled beverage was set at 5 °C, and the room-temperature beverage was set at 24 °C, aligning with the ambient temperature. For warmed beverages, particularly considering the potential risk of significant tissue damage with temperatures exceeding 50 °C on the lower lip (Eliav & Gracely, 2008), the maximum temperature for the lower lip was set at 47 °C. Therefore, we set the temperature of the warmed beverages at 45 °C. The aroma and basic taste of food and beverages can change with temperature (Stokes et al., 2016; Kim et al., 2015; Ross & Weller, 2008; Kähkönen et al., 1995; Drake et al., 2005; Yau & Huang, 1996; Singh & Seo, 2020). Although juices are not usually warmed, this experiment included a warmed beverage condition to explore its potential effects. We prepared cooled and warmed beverages in separate cups. We regulated the temperature of the cooled beverages using a refrigerator. The cooled beverages were maintained at the target temperature using a refrigerator, while the warmed beverages were heated in a microwave and subsequently kept warm using a cup warmer. Immediately before tasting, the beverages were poured into the tumbler-type device designed to regulate the cup rim temperature.

We conducted the evaluation using the method of magnitude estimation, in which a scale with one as the reference point based on a cup rim at the same temperature as the beverage was used. We asked participants to compare the intensity of several factors in subsequent tastings. The evaluation criteria were as follows: temperature perceived by the lower lip, perceived temperature of the beverage, in-mouth aroma, aftertaste, intensity of taste, throat feeling, deliciousness, comfort, sweetness, saltiness, sourness, bitterness, and umami. The temperature evaluation included separate assessments for warm and cold. The “temperature perceived by the lower lip” and “perceived temperature of the beverage” were evaluated by asking, "How many times warmer/colder did it feel compared to the standard?" For the other items, the participants were asked, "How many times stronger did it feel compared to the standard?" For example, if participants perceived the temperature to be 1.5 times coldness, they reported it as “coldness: 1.5″; if the warmth remained unchanged, they reported it as “warmth: 1”.

We established the “temperature perceived by the lower lip” to evaluate how participants perceive the temperature of the cup rim through the lower lip. We used the “perceived temperature of the beverage” to assess whether participants perceive the beverage temperature differently because of the temperature stimulus applied on the lower lip. Additionally, based on previous research (Suzuki et al., 2014), we designed four items—“in-mouth aroma,” “aftertaste,” “intensity of taste,” and “throat feeling”—to assess the objective evaluation of flavor perception, while we designed two items—“deliciousness” and “comfort”—to evaluate participants’ personal preferences. We set five items to evaluate the five basic tastes, along with the above six flavor perception items. Finally, we asked the participants to freely report their impressions for each comparative stimulus.

2.3. Experimental procedures

According to an a priori power analysis conducted using G*Power software, at least 13 participants were required to detect a medium effect (dz = 0.5) with a power of 0.80. In the “Affecting Tumbler” (Suzuki et al., 2014) study, 14 participants were included. Therefore, we recruited 20 participants for this experiment. The experiments with orange juice, apple juice, and water involved 18 university and graduate students (9 males and 9 females, mean age of 22.1 ± 1.3 years), whereas the green tea conditions involved 20 participants (10 males and 10 females, mean age of 22.5 ± 1.1 years). The experiments with orange juice, apple juice, and water took approximately 1 h and 30 min, including breaks, and were conducted on the same day. The green tea experiment was conducted on a separate day and lasted approximately 30 min.

We explained the experiment to the participants before they began and obtained their signatures on an informed consent form. We informed the participants in advance that the experiment involved drinking and rating beverages and that they were free to withdraw from the study at any time. During this explanation, we confirmed that the participants had no aversion to the beverages provided and were free of allergies. Individuals with medical conditions or those taking medications that could substantially affect taste sensitivity were excluded from the experiment.

Before starting the experiment, we asked the participants to subjectively rate their current level of throat dryness using the visual analog scale method on a 100 mm line to minimize the potential impact of throat dryness on flavor perception ratings. The scale ranged from “not dry” at 0 to “very dry” at 100. If the rating was 70 or higher, the participants were given a small amount of water before the experiment.

First, participants were presented with a beverage with the cup rim at the same temperature as the beverage (standard). The participants subsequently verbally reported the perceived intensity of each evaluation item relative to the standard, providing positive real numbers without specifying significant figures, upper limits, or lower limits. This process was conducted as one set, and a total of six sets were performed, corresponding to the six experimental conditions. The beverage temperature was measured immediately before the beverage was presented to the participants using an infrared radiation thermometer, with each cup containing 10 g of the beverage. To control for order effects, the combinations of cup rim and beverage temperatures were presented in a randomized order. The participants were not informed of the specific cup rim and beverage temperature combinations.

To minimize individual differences, we presented each condition to all participants once. In this experiment, we employed the magnitude estimation method, where participants evaluated each condition relative to a reference using a ratio scale. This approach ensures that sensory evaluations are relative, which likely reduces the variance in evaluations due to the number of trials compared to absolute ratings.

We informed participants that they could taste the beverages as many times as they wished and that they were not obligated to consume all of the liquid in the cup and encouraged them to bring the cup to their mouths as soon as it was handed to them. In addition, to eliminate lingering tastes, we instructed the participants to take a sip of room-temperature water before drinking a beverage under a different condition, especially if the beverage was something other than water. We instructed the participants to drink by placing the heat pipe attached to the cup against their lower lip to achieve temperature stimulation of the lower lip. Participants were allowed to take breaks at any time during the experiment. This study was carried out according to the principles expressed in the Declaration of Helsinki and approved by the our University Research Ethics Review Committee.

The average room temperature during the experiment was 24.5 ± 0.5 °C, and the humidity was 11±11 %.

2.4. Statistical analyses

We standardized the data (n = 18 or n = 20) by calculating each participant’s mean and standard deviation. We subtracted the mean from each data point for each subjective evaluation and divided the result by the standard deviation. Next, we compared the evaluation differences between the standard, cooled, and warmed cup rims for each beverage condition. We conducted a Shapiro–Wilk test on the standardized evaluation data. Since none of the evaluation items followed a normal distribution, we employed the nonparametric Friedman test to assess whether there were significant differences in flavor perception items based on the cup rim temperature. We subsequently conducted multiple comparisons using Bonferroni correction to assess significant differences in the evaluation data based on the cup rim temperature. Although the evaluation value for the standard condition was set to 1 prior to log transformation and standardization, the evaluation values used in the statistical analysis varied for each participant based on their standard. Statistical significance was set at 0.05.

3. Results

In this study, changes in flavor perception were evaluated by placing beverages at three different temperatures (cool, room temperature, and warm) into the mouth, with the temperature of the cup rim differing by 2 °C from the beverage temperature. We conducted experiments with 18 to 20 participants, compared the results to those obtained under a standard condition in which the cup rim temperature matched the beverage temperature, and evaluated flavor perception using the magnitude estimation method. We used orange juice (sour), apple juice (sweet), green tea (bitter), and water (tasteless and odorless). Figs. 4 to 6 show the means and standard deviations of the differences between the log-transformed and standardized evaluation data and the standardized reference values for each beverage. Fig. 4 shows the results of the participants’ perceived lower lip temperature, beverage temperature and in-mouth aroma. Fig. 5 shows the results of the aftertaste, intensity of taste, throat feeling, deliciousness, and comfort. Fig. 6 shows the results of the five basic tastes.

3.1. Results of the cup rim temperature perceived by the lower lip

For room-temperature orange juice, room-temperature water, and

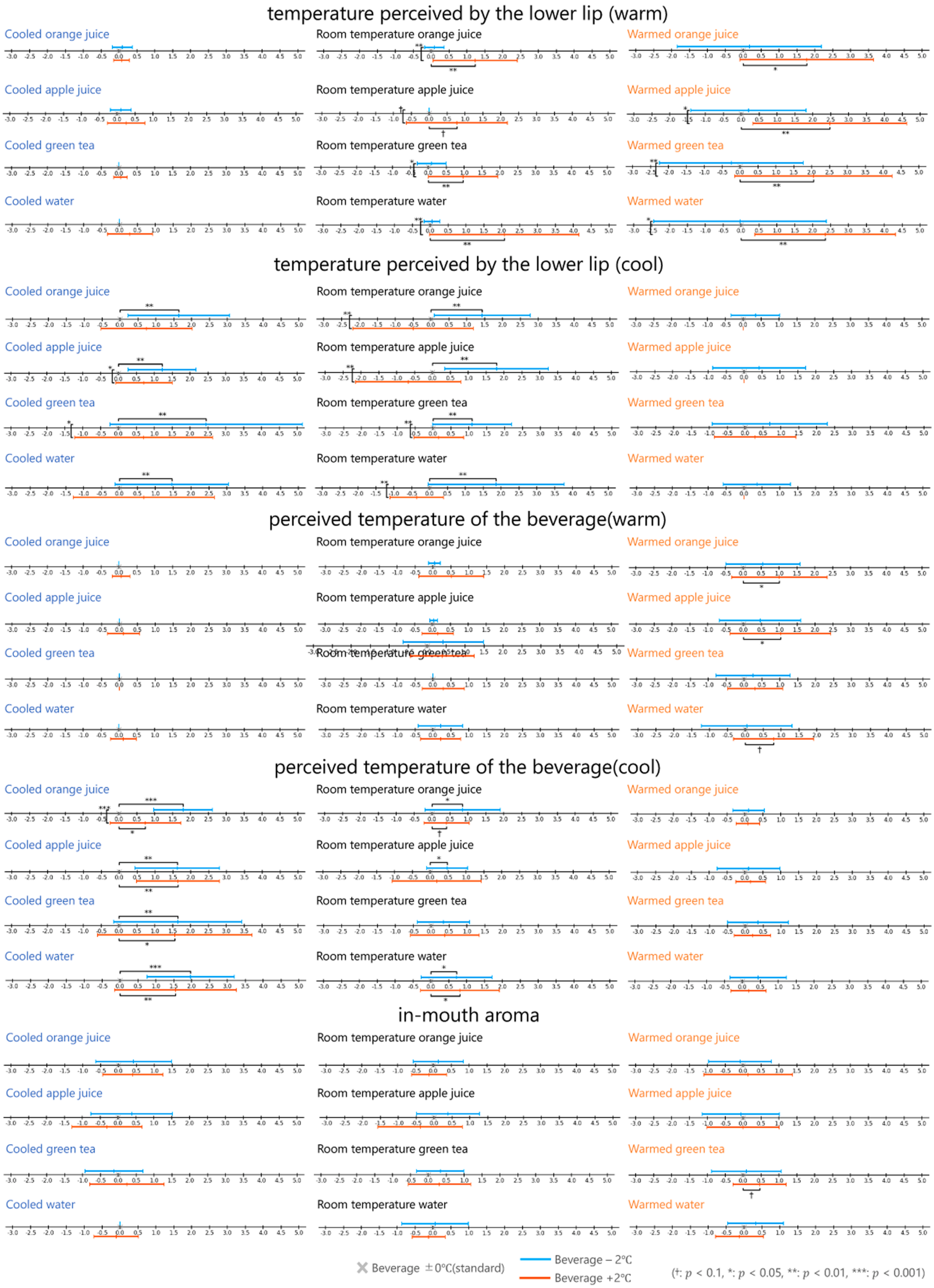

Fig. 4. Results of the participants' perceived lower lip temperature, beverage temperature and in-mouth aroma. This figure shows the means and standard deviations of the differences between the log-transformed and standardized evaluation data for each beverage compared with the standard condition and the significance of these differences.

Fig. 5. Results of the aftertaste, intensity of taste, throat feeling, deliciousness, and comfort. This figure shows the means and standard deviations of the differences between the log-transformed and standardized evaluation data for each beverage compared with the standard condition and the significance of these differences.

Fig. 6. Results of the five basic tastes. This figure shows the means and standard deviations of the differences between the log-transformed and standardized evaluation data for each beverage compared with the standard condition and the significance of these differences.

room-temperature green tea, a warmed cup rim resulted in a significantly higher temperature perceived by the lower lip than that in the standard condition ($p < 0.05$). Room-temperature apple juice & a warmed cup rim showed no significant difference, but there was a trend toward the temperature perceived by the lower lip as being warmer than that in the standard condition ($p = 0.063$). In all warmed beverage & warmed cup rim conditions, the temperature perceived by the lower lip was significantly warmer than that in the standard condition ($p < 0.05$). In all cooled beverage & cooled cup rim conditions, the temperature perceived by the lower lip was significantly colder than that in the standard condition ($p < 0.01$). For cooled apple juice & a warmed cup rim and cooled green tea & a warmed cup rim, the temperature perceived by the lower lip was significantly colder than that in the standard condition ($p < 0.05$). In all room-temperature beverage & cooled cup rim conditions, the temperature perceived by the lower lip was significantly colder than that in the standard and warmed cup rim conditions ($p < 0.01$).

These results indicate that participants could perceive *a* ± 2 °C difference in the lower lip temperature under cooled (3–5 °C), room-temperature (24–26 °C), and warmed (45–47 °C) conditions. However, for cooled beverages with a warmed cup rim (5–7 °C) and warmed beverages with a cooled cup rim (43–45 °C), participants did not accurately perceive the 2 °C difference compared with the standard condition.

3.2. Results of perceived beverage temperature

For warmed orange juice & a warmed cup rim and warmed apple juice & a warmed cup rim, a significantly warmer beverage temperature than that in the standard condition was perceived ($p < 0.05$). While there was no significant difference for cooled water & a cooled cup rim, there was a trend toward the beverage temperature being perceived as warmer than that in the standard condition ($p = 0.068$).

In all conditions with cooled beverages, under a cooled cup rim, the beverage temperature was perceived as being significantly colder than that in the standard condition ($p < 0.01$). For warmed orange juice & a cooled cup rim, the beverage temperature was perceived as being significantly colder than that in the standard condition ($p < 0.05$), and for a cooled cup rim, the beverage temperature was perceived as being significantly colder than that in the warmed cup rim condition ($p < 0.01$). Under a warmed cup rim, the beverage temperature was perceived as being significantly colder than that in the standard condition for cooled apple juice, cooled water, and cooled green tea ($p < 0.05$). In the conditions with room-temperature orange juice, room-temperature apple juice, and room-temperature water, under a cooled cup rim, the beverage temperature was perceived as being significantly colder than that in the standard condition ($p < 0.05$). For room-temperature water & a warmed cup rim, the beverage temperature was perceived as being significantly colder than that in the standard condition ($p < 0.05$).

These results indicate that warming the cup rim by +2 °C makes juice feel warmer when drinking juice at 45 °C. Additionally, for beverages cooled to 5 °C, a temperature difference between the beverage and the cup rim significantly enhances the perception of coldness of the beverage. In the case of room-temperature juice and water, cooling the cup rim by −2 °C significantly enhances the perception of coldness of the beverage.

3.3. Results of in-mouth aroma

Warmed green tea & a warmed cup rim showed a trend toward an increase in-mouth aroma compared with the standard condition, although this difference was not statistically significant ($p = 0.055$). In all the other conditions, there were no significant differences in the evaluation of in-mouth aroma based on the cup rim temperature.

These results indicate that changes in-mouth aroma were observed only under the green tea condition.

3.4. Results of aftertaste

Cooled orange juice & a cooled cup rim showed a trend toward an increase in aftertaste compared with the standard condition, although this difference was not statistically significant ($p = 0.076$). Room-temperature apple juice & a cooled cup rim showed a significant increase in aftertaste compared with the standard condition ($p < 0.05$). Warmed orange juice & a cooled cup rim showed a significant increase in aftertaste compared with the standard condition ($p < 0.05$) and a trend toward an increase compared with a warmed cup rim ($p = 0.063$). There were no significant differences in aftertaste for water and green tea based on the cup rim temperature.

These results clearly revealed that changes in aftertaste due to the temperature of the cup rim vary depending on the type of beverage.

3.5. Results of the intensity of taste

For room-temperature orange juice & a cooled cup rim, the perception of the intensity of taste significantly increased compared with a warmed cup rim ($p < 0.05$). Warmed orange juice & a cooled cup rim also showed a significant increase in the intensity of taste compared with the standard condition ($p < 0.05$). Conversely, warmed orange juice & a warmed cup rim exhibited a significant decrease in the intensity of taste compared with a cooled cup rim ($p < 0.05$). Warmed green tea & a warmed cup rim demonstrated a significant increase in the intensity of taste compared with the standard condition ($p < 0.05$). There were no significant differences in the intensity of taste for apple juice and water based on the cup rim temperature.

These results showed that cooling the cup rim when drinking orange juice at 24 °C or 45 °C increases the intensity of taste. Additionally, warming the cup rim when drinking green tea at 45 °C also increases the intensity of taste.

3.6. Results of throat feeling

Cooled orange juice & a cooled cup rim significantly improved throat feeling compared with the standard condition and a warmed cup rim ($p < 0.05$). Cooled apple juice & a cooled cup rim also significantly improved throat feeling compared with the standard condition ($p < 0.05$). Cooled apple juice & a warmed cup rim ($p = 0.057$) and cooled water & a cooled cup rim ($p = 0.062$) showed no significant differences compared with the standard condition, but there was a trend toward improved throat feeling. Cooled green tea & a cooled cup rim significantly improved throat feeling compared with the standard condition ($p < 0.01$). Cooled green tea & a warmed cup rim showed no significant difference compared with the standard condition ($p = 0.093$), but there was a trend toward improved throat feeling. Room-temperature orange juice & a cooled cup rim significantly improved throat feeling compared with a warmed cup rim ($p < 0.05$). Room-temperature apple juice & a cooled cup rim ($p = 0.09$) and room-temperature green tea & a cooled cup rim ($p = 0.063$) showed no significant differences compared with the standard condition, but there was a trend toward improved throat feeling.

These results showed that cooling the cup rim by −2 °C improved throat feeling for all beverages cooled at 5 °C and room-temperature beverages (24 °C) other than water.

3.7. Results of deliciousness

Cooled orange juice & a cooled cup rim ($p < 0.01$) and cooled green tea & a cooled cup rim ($p < 0.05$) significantly increased deliciousness compared with the standard condition. Cooled apple juice & a cooled cup rim showed no significant difference compared with the standard condition ($p = 0.064$) but exhibited a trend toward increased deliciousness. Cooled green tea & a cooled cup rim showed no significant difference compared with a warmed cup rim ($p = 0.071$) but tended toward an increase in deliciousness. Room-temperature orange juice & a cooled cup rim significantly increased deliciousness compared with a warmed cup rim ($p < 0.05$) and, although not significant, exhibited a trend toward increased deliciousness compared with the standard condition ($p = 0.075$). Room-temperature apple juice & a cooled cup rim significantly increased deliciousness compared with the standard condition ($p < 0.01$). Room- temperature green tea & a cooled cup rim showed no significant difference compared with the standard condition ($p = 0.090$) but displayed a trend toward increased deliciousness. Warmed green tea & a warmed cup rim significantly increased deliciousness compared with the standard condition ($p < 0.05$). There were no significant differences in deliciousness due to the cup rim temperature for water.

These results showed that cooling the cup rim when drinking juice or green tea at 5 °C or 24 °C increases deliciousness, and warming the cup rim when drinking 45 °C green tea also enhances deliciousness.

3.8. Results of comfort

Cooled orange juice & a cooled cup rim significantly increased comfort compared with the standard condition ($p < 0.05$), and there was a trend toward increased comfort compared with a warmed cup rim ($p = 0.053$). Cooled apple juice & a cooled cup rim showed a tendency toward increased comfort compared with both the standard condition ($p = 0.07$) and a warmed cup rim ($p = 0.091$). Room-temperature orange juice & a cooled cup rim exhibited a significant increase in comfort compared with both the standard condition and a warmed cup rim ($p < 0.05$). Similarly, room- temperature green tea & a cooled cup rim demonstrated a significant increase in comfort compared with the standard condition ($p < 0.05$). For warmed green tea & a warmed cup rim, although not statistically significant, there was a trend toward increased comfort compared with the standard condition ($p = 0.076$). There were no significant differences in comfort due to the cup rim temperature for water.

These results indicate that cooling the cup rim when drinking juices at 5 °C or 24 °C tends to increase comfort.

3.9. Results of sweetness

Although not statistically significant, cooled apple juice & a cooled cup rim showed a trend toward increased sweetness compared with the standard condition ($p = 0.088$). Room-temperature orange juice & a cooled cup rim also showed a nonsignificant trend toward increased sweetness compared with the standard condition ($p = 0.068$). Room-temperature apple juice & a cooled cup rim significantly increased sweetness compared with the standard condition ($p < 0.05$). There were no significant differences in sweetness due to the cup rim temperature for water and green tea.

3.10. Results of saltiness

There were no significant differences in saltiness due to differences in the cup rim temperature across all beverages.

3.11. Results of sourness

Cooled orange juice & a warmed cup rim significantly increased sourness compared with the standard condition ($p < 0.05$). Room-temperature orange juice & a warmed cup rim showed a trend toward increased sourness compared with the standard condition, although this difference was not statistically significant ($p = 0.076$). There were no significant differences in sourness due to the cup rim temperature for beverages other than orange juice.

3.12. Results of bitterness

Cooled green tea & a cooled cup rim significantly decreased bitterness compared with the standard condition ($p < 0.05$) and showed a trend toward decreased bitterness compared with a warmed cup rim ($p = 0.053$). Warmed green tea & a warmed cup rim did not show a significant difference compared with the standard condition ($p = 0.053$), but there was a trend toward increased bitterness. There were no significant differences in bitterness due to the cup rim temperature for beverages other than green tea.

3.13. Results of umami

There were no significant differences in umami due to differences in the cup rim temperature across all beverages.

4. Discussion

4.1. Discussion of the experimental results

Previous studies have reported that temperature stimulation to the tongue or nose affects flavor perception. This study demonstrated that temperature stimulation to the lower lip during drinking changes flavor perception. This finding aligns with the understanding that a single sensory modality does not govern flavor perception but is formed through multisensory integration, including visual, auditory, and tactile inputs (Spence, 2015). The lips, like the tongue, are innervated by the trigeminal nerve and can detect temperature stimuli (Kenshalo, 1960). Previous studies have reported that input from the trigeminal nerve contributes to flavor perception (Spence, 2015). Therefore, thermal stimulation to the lower lip likely activated thermoreceptors, which conveyed somatosensory information to the central nervous system via the trigeminal pathway. This somatosensory input may have been integrated with other sensory modalities, influencing flavor perception. The following paragraphs present discussions for each evaluation item.

The warmed cup rim (47 °C) was perceived as significantly warmer than the standard cup rim (45 °C) by the lower lip for all warmed beverages. However, the temperature perceived for the cooled cup rim (43 °C) and warmed beverages did not significantly differ from that in the standard condition. Previous studies have shown that individuals are susceptible to temperatures above 45 °C (LaMotte & Campbell, 1978). Therefore, participants could likely perceive the 2 °C difference between 45 °C and 47 °C but could not distinguish the difference between 43 °C and 45 °C.

The warmed cup rim (26 °C) was perceived as significantly warmer than the standard cup rim (24 °C) by the lower lip for all room-temperature beverages except for room-temperature orange juice. This difference may be due to variations in the temperature perceived by the lower lip depending on the type of beverage. When comparing the averages, room-temperature water was rated as having the warmest temperature for the lower lip. These results suggest that beverages such as juice and green tea, which contain more ingredients, may stimulate taste receptors during consumption, making it more difficult to perceive the temperature of the cup rim.

For all cooled beverages, the cooled cup rim (3 °C) was perceived as significantly colder by the lower lip than the standard cup rim (5 °C). However, the warmed cup rim (7 °C) for cooled apple juice was also perceived as significantly colder than the standard cup rim. This may be because cold sensations are less noticeable at approximately 5 °C (Stevens & Choo, 1998), suggesting that participants were unable to perceive the temperature difference between 5 °C and 7 °C.

The warmed cup rim was perceived as significantly warmer than the standard cup rim in the warmed juice condition. In contrast, there was no significant difference in perceived beverage temperatures in the warmed water and green tea conditions. Thus, the effects on temperature perception when the temperature of the cup rim changes likely depend on the beverage ingredients.

For all cooled beverages, both the cooled cup rim (3 °C) and the warmed cup rim (7 °C) were perceived as significantly colder than the standard cup rim (5 °C). In the case of the cooled cup rim, the presentation of a sensation colder than the beverage on the lower lip caused the beverage itself to feel colder. However, in the open-ended responses, the following was reported: "the warmed cup rim (7 °C) made the beverage (5 °C) feel colder because the beverage was brought to the mouth after the lower lip felt the warmer temperature." This result suggests that for the cooled beverage condition, the presentation of a temperature warmer than the beverage temperature (5 °C) on the lower lip through the warmed cup rim (7 °C) resulted in the lower lip being initially warmed by +2 °C, which made the beverage feel colder when the cooled beverage was subsequently brought to the mouth. These results demonstrate that the presentation of a temperature different from that of the beverage on the lower lip can alter the perceived temperature of the cooled beverage.

Under the warmed green tea conditions, the warmed cup rim tended to enhance the perceived in-mouth aroma compared to the reference condition. In contrast, no such effect was observed for the other beverages. This outcome may be attributed to the high-temperature sensitivity of aroma compounds present in green tea. Thermal stimulation around the lower lip may have increased the local skin temperature, thereby promoting the volatilization of aroma compounds during inhalation (Kumazawa & Masuda, 2005) and enhancing the perception of in-mouth aroma. In contrast, juice contains a higher baseline concentration of aroma compounds, which may have attenuated the perceptual impact of temperature-related changes. From a psychological and cultural perspective, Japanese participants may have held prior expectations that warm green tea produces a stronger aroma, potentially influencing their perception. Previous studies have also indicated that personality traits can affect the relationship between olfaction and flavor perception (Boesveldt & de Graaf, 2017), in addition to chemical stimuli. The warmed cup rim may have induced expectations of intensified aroma, contributing to the observed change in perception. Such expectations were likely absent from juice and water, which may explain the absence of a similar effect.

The cooled and warmed orange juice with the cooled cup rim tended to result in a stronger aftertaste compared with the standard condition, and the room-temperature apple juice with the cooled cup rim was significantly stronger in aftertaste than that in the standard condition. However, a significant difference in the intensity of taste was found only for the warmed orange juice with the cooled cup rim. These results indicate that the changes in aftertaste and the intensity of taste due to the cup rim temperature may vary depending on the inherent flavor perception of the beverage. Additionally, the combination of room-temperature orange juice & a cooled cup rim significantly increased the intensity of taste compared with the combination with a warmed cup rim. The combination of warmed green tea & a warmed cup rim significantly increased the intensity of taste compared with the combination with a cooled cup rim. While there was no significant difference at a temperature difference of 2 °C (cooled cup rim vs. standard cup rim, warmed cup rim vs. standard cup rim), there was a significant difference at a temperature difference of 4 °C. These results indicate that changing the set temperature of the cup rim can indeed change the perception of the intensity of taste.

Under cooled and room-temperature juice conditions, the cooled cup rim significantly increased throat feeling compared with that in the standard condition, with similar trends observed. For cooled apple juice, the warmed cup rim also tended to enhance throat feeling relative to the standard condition. Conditions that exhibited significant differences or trends in throat feeling for cooled and room-temperature juices also showed significant differences and a tendency to perceive both the cup rim and beverage temperatures as colder than that in the standard condition. These results suggest that the evaluation of throat feeling for juice may be influenced by the temperature of the cup rim as perceived by the lower lip and the beverage temperature.

In the warmed beverage condition, only green tea showed a significant increase in deliciousness and a tendency toward increased comfort with the warmed cup rim compared with the standard condition. The lack of significant differences or trends for the other warmed beverages may be due to the traditional consumption of hot green tea. Previous studies have shown that taste perception is influenced by individual preferences for the serving temperatures of food (Kim et al., 2015). Similarly, preferences for the serving temperature and habitual dietary practices may affect flavor perception based on the temperature of the cup rim.

In the room-temperature apple juice and cooled cup rim condition, the sweetness was significantly increased compared with that in the standard condition. Room-temperature orange juice and cooled apple juice with a cooled cup rim also showed a tendency toward increased sweetness compared with the standard condition. Previous studies have indicated that warming the front of the tongue from a cooled state enhances the perception of sweetness (Cruz & Green, 2000). However, the results of this experiment demonstrated that sweetness could also be perceived when the lower lip was cooled. Cooled solutions are well established to generally exhibit less sweetness than warmed solutions; nevertheless, trends in sweetness perception may vary when combined with other tastes, such as saltiness or sourness, or when the concentration of the solution changes (Calviño, 1986; Lipscomb et al., 2016). These findings suggest that the cooled cup rim may alter the sensitivity to the sweetness of beverages containing various food components, such as apple juice and orange juice. Moreover, the effect of temperature stimuli via the lower lip on taste perception may differ from that observed when temperature stimuli are applied on the tongue. Under cooled and room-temperature orange juice conditions, the warmed cup rim resulted in a significant increase in sourness compared with that in the standard condition. Previous studies have shown that cooling the tongue enhances the perception of sourness (Cruz & Green, 2000). However, similar to the results for sweetness, the findings of this experiment contradict those of prior studies. These results suggest that the effect of temperature stimuli via the lower lip on taste perception may differ from that via the tongue. In addition, since apple juice tends to be sweeter than orange juice and orange juice tends to be sourer than apple juice (Ivo et al., 2022), the application of temperature stimuli to the lower lip is hypothesized to cause changes in sweetness for apple juice and sourness for orange juice. The sensory characteristics of fruit juices are influenced by their sugar-to-acid ratio (Kelebek & Selli, 2011), and because orange juice is generally perceived as having stronger sweetness and sourness, cooling the cup rim in the case of orange juice likely leads to changes in both sweetness and sourness.

Under the cooled green tea conditions, the cooled cup rim significantly reduced the perception of bitterness compared with the standard condition. Previous studies have shown that bitter compounds such as caffeine, quinine, and naringin exhibit less bitterness at 10 °C and 40 °C than at 20 °C and 30 °C. In comparison, denatonium shows the greatest reduction in bitterness at 10 °C (Green & Andrew, 2017). These findings align with the results of the present experiment, in which the cooled cup rim significantly decreased the perception of bitterness in the cooled green tea condition. One possible explanation is that, with green tea at 5 °C and the cup rim cooled to 3 °C, participants perceived the cup and beverage as significantly colder than those in the standard condition, thus reducing the perception of bitterness. In other words, low-temperature stimulation may reduce the activation of bitter taste receptors, thereby decreasing bitterness perception. Additionally, under the warmed green tea condition, the warmed cup rim tended to increase the perception of bitterness compared with the cooled cup rim. Previous studies have demonstrated that bitter compounds can modulate sweetness and sourness and interact with volatile flavors (Drewnowski, 2001). Thus, further investigation is necessary to fully understand the factors contributing to the observed increase in bitterness.

Water exhibited a weaker influence of the lower lip temperature stimulus on flavor perception than juice or green tea. This difference can be attributed to the relatively simple composition of water, which is more tasteless and odorless than juice or green tea. In contrast, because the components in each juice and green tea differed, the texture and taste perception changes resulting from the temperature stimulus applied on the lower lip likely varied across the beverages. We observed changes in flavor perception between juice and green tea when presenting temperature to the lower lip.

These differences may be attributed to the compositional differences of the beverages and participants' expectations regarding beverage temperature. Regarding beverage composition, previous studies have reported that polyphenols in green tea interact with proteins, lipids, and other food components, thereby altering flavor perception (Niu et al., 2023). Furthermore, because the properties of polyphenols change depending on the temperature of green tea, thermal stimulation of the lower lip is likely to affect flavor perception differently (Zeng et al., 2017). Prior research has also shown that the serving temperature of green tea influences flavor perception (Pramudya & Seo, 2018). In addition, cultural background is known to contribute to flavor perception (Spence, 2015). In Japan, green tea is a familiar beverage consumed in cold, room-temperature, and hot forms, while juice is generally preferred cold. As a result, participants may have formed an expectation that "cold equals delicious" for juice, leading to different perceptual responses between juice and green tea.

4.2. Limitation and future work

For room-temperature juice and green tea, the cooled cup rim significantly increased throat feeling and deliciousness compared with those in the standard condition, with a tendency toward further enhancement. These results suggest that applying a temperature stimulus to the lower lip may enhance throat feeling and deliciousness when refrigeration is unavailable, such as during disasters. Additionally, a comparison of the mean throat feeling values between the cooled and room-temperature beverage conditions revealed that the cooled beverage condition resulted in higher throat feeling values. These findings suggest that the influence of temperature on flavor perception depends on the beverage temperature. Moreover, modification of the cup rim temperature may be particularly effective when combined with beverages typically consumed cold, such as juice or beer, as their flavor perception tends to be enhanced at lower temperatures.

Based on these results, the temperature around the lower lip may influence the basic taste of a beverage, suggesting the potential to enhance the inherent flavor of a beverage without relying on flavorings or additives.

However, the mechanisms underlying these phenomena remain unclear. Previous studies have demonstrated that flavor perception can be influenced by the temperature of foods (Stokes et al., 2016; Kim et al., 2015; Ross & Weller, 2008; Kähkönen et al., 1995; Drake et al., 2005; Yau & Huang, 1996; Singh & Seo, 2020). We hypothesize that the flavor perception obtained with the proposed method changes depending on the beverage temperature. Therefore, further investigations are needed to explore the influence of temperature on the components of various beverages.

Based on some evaluation items, while no significant differences were observed when a temperature difference of ± 2 °C was applied around the lower lip, a temperature difference of ± 4 °C could clearly affect flavor perception. Therefore, changing the temperature range by cooling or warming by at least 4 °C could lead to further changes in flavor perception. Consequently, future research will investigate changes in flavor perception across various temperature ranges.

Previous studies have reported that cultural background and past experiences play a significant role in cross-modal modulation of flavor perception (Wan et al., 2014). Therefore, we plan to include a broader and more diverse participant pool comprising individuals of different age groups, nationalities, and dietary habits. By increasing the sample size and diversity, we aim to examine the generalizability of the findings.

Furthermore, we aim to implement temperature-controlled utensils, such as spoons, and explore the application of the proposed method to food other than beverages. By using these devices, we expect smoother texture, enhanced flavor, and a more pleasant eating experience, allowing individuals to enjoy even foods they may find unpalatable. In addition, if it becomes possible to create the illusion of preferred temperatures for room-temperature foods, this could prove valuable in situations such as disasters with limited cooking capacity.

In addition to the standard serving of beverages, food service settings may offer novel eating and drinking experiences. For example, it is possible to control the temperature of the cup rim to maintain an optimal drinking temperature or to dynamically vary the temperature of the rim to modulate flavor perception, enabling the development of entirely new menu items. Furthermore, this approach may be applied to assistive tableware for older adults, with potential benefits in meal assistance and swallowing support.

5. Conclusions

In this study, we evaluated whether flavor perception could be altered by providing temperature stimulation to the lower lip while consuming a beverage. We used orange juice, apple juice, water, and green tea in the experiment. We presented three conditions for each beverage: cooled, room temperature, and warmed, and the drinking spout conditions: the same temperature as the beverage and a temperature within ± 2 °C. In addition, it was evident that the proposed method could influence the perception of beverage temperature and affect flavor perception. The effect of lower lip temperature stimulation on flavor perception varied depending on the type of beverage. In this experiment, we presented a constant temperature; however, we plan to verify the effect on flavor perception by changing the temperature during drinking. In addition, we plan to increase the number of participants and the variety of beverages to investigate further the relationship between lower lip temperature presentation and flavor perception, as well as to expand the temperature range presented at the cup rim.

Ethical statement - studies in humans and animals

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. This article does not contain any studies with animals performed by any of the authors. Informed consent was obtained from all individual participants included in the study.

Ethical statement

Ethical approval for the involvement of human subjects in this study was granted by the Aoyama Gakuin University Research Ethics Committee, reference number H22–032, dated Jan. 12, 2023.

CRediT authorship contribution statement

Mai Kamihori: Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Kodai Ito:** Writing – review & editing, Methodology, Investigation. **Yuichi Itoh:** Writing – review & editing, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Mai Kamihori reports financial support was provided by Japan Society for the Promotion of Science. Yuichi Itoh reports was provided by Japan Society for the Promotion of Science. Mai Kamihori reports financial support was provided by Japan Science and Technology Agency. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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