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# *Virtually tasty*: An investigation of the effect of ambient lighting and 3D-shaped taste stimuli on taste perception in virtual reality

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ABSTRACT

Taste perception is influenced by sensory information not only about the food itself but also about the external environment where the food is tasted. Prior studies have shown that both visual attributes of the environment (e.g., light colour, location) and the shape associated to food (e.g., plates, cutlery) can influence people's taste perception and expectations. However, previous studies are typically based on non-edible shapes usually shown as 2D images or presented as 3D tangible objects aimed to be perceived by subjects' hand. Therefore, the effect of mouthfeel of differently shaped foods on taste perception remains unclear. Capitalising on the advantages of virtual reality (VR) to manipulate multisensory features, we explore the effects of coloured (red, blue, neutral) virtual environments on the taste (sweet, neutral) perception of differently shaped taste samples (rounded/spiky shapes according to the *Kiki-Bouba* paradigm). Overall, our results showed increased ratings of sweetness when participants tasted Bouba-shaped samples (rounded) relative to Kiki-shaped samples (spiky) suggesting that tactile attributes perceived inside the mouth can influence sweetness perception. Furthermore, we concluded that lighting colour in a virtual setting might dampen experiences of sweetness. However, this effect may only be present when there is a cross-modal correspondence with taste. Based on our findings, we conclude by describing considerations for designing eating experiences in VR.

## 1. Introduction

Taste and flavour are often considered interchangeable, but they are different. The sense of taste, often called the gustatory system, refers to the five basic tastes – sweet, sour, bitter, salty and umami (Trivedi, 2012), whilst flavour refers to an integrated experience including taste, odour, and chemical sensations (Lundström et al., 2011). Taste perception is influenced not only by gustation sensations (Spence, 2013) and the characteristics of the food itself such as its colour (Huang et al., 2019), but also environmental characteristics unrelated to the food being tasted, such as the texture or colour of a food container (Spence and Van Doorn, 2017) or the location where the food is tasted (Chen et al., 2020). For example, one might avoid eating meat that looks green and a glass of wine may taste nicer during a classical music concert with friends than when being alone in one's office (Nakata & Kawai, 2017). In this paper, we focus particularly on how sweet taste experiences can be influenced by visual cues and especially mouthfeel (tactile shape), due to its critical relevance to evaluating taste experiences (Tournier et al., 2007).

### 1.1. Cross-modal correspondences between taste and shape

Mouthfeel (shape) is the tactile sensation of objects within the mouth and includes sensory attributes such as texture, perceived viscosity, and chewing frequency, which can affect people's taste experience. For example, previous research has shown that satiety can be influenced by mouthfeel viscosity (Stribitcaia et al., 2020) and chewing time (Lin et al., 2020). Food texture can also play an important role in the

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emotional, hedonic and affective modulation of the gustatory experience, since it can activate the reward circuits located in the orbitofrontal cortex and amygdala (Stoeckel et al., 2009). For example, fat texture (more viscous) can increase the attractiveness of food (Rolls, 2012).

Shape also plays an important role on taste perception more broadly. People often describe flavours by means of shape attributes, e.g., "round wine", or a "sharp taste" (Spence and Deroy, 2013). Studies also show that the shape of containers used to eat or drink can influence the perception of taste (Spence and Van Doorn, 2017), affecting for instance the taste expectation of coffee (Van Doorn et al., 2017) or alcoholic drinks (Spence and Wan, 2015). Also, the weight, size, shape and colour of cutlery used to eat can modulate food taste (Harrar and Spence, 2013) and eating experiences (Michel et al., 2015). For instance, the material of spoons can modulate the taste attributes of cream (Piqueras-Fiszman et al., 2012b) and yogurt (Piqueras-Fiszman and Spence, 2011), the shape and colour of plates can influence the sweetness and intensity of a desert (Piqueras-Fiszman et al., 2012a; Stewart and Goss, 2013), and the shape features of food packages may influence the customer taste expectation (Velasco et al., 2016). Particularly, prior studies show that the shapes associated with food affect people's expectations of taste, often using experimental paradigms such as the *Kiki-Bouba* effect (Köhler, 1940).

The *Kiki-Bouba* effect (Köhler, 1940) explores perceptions of spiky (*Kiki*) vs rounded (*Bouba*) shapes, originally studied in a mapping between speech sounds and the visual shape of objects. This paradigm has been used to study CCs between taste and shape, often using word variants such as "*Takete*" for spiky and "*Maluma*" for rounded shapes. Across studies, it is commonly demonstrated that spiky shapes (*Kiki*) are associated with a sour taste, while rounded shapes (*Bouba*) are associated with a sweet taste (Salgado Montejo et al., 2015; Velasco et al., 2015) in both food and beverages. For example, Gallace et al. (2011) found that crisps are deemed more *Kiki* than a cheddar cheese, and that plain chocolate is deemed more "*Bouba*" than mint chocolate. However, food stimuli are usually represented only as words and the *Kiki* and *Bouba* shapes as words (Spence and Gallace, 2011) or 2D images (Bremner et al., 2013). Consequently, neither actual gustation nor tangible shapes are involved.

There are some studies, however, using tangible *Kiki-Bouba* 3D representations. For example, Fryer et al. (2014) investigated CCs between non-words (*Kiki-Bouba)* and two different types of 3D shapes (irregular and spiky, bulbous and smooth). The results showed a robust association between the non-word *Kiki* and the spiky 3D shape and between the non-word *Bouba* and the smooth 3D shape. Similarly, Graven and Desebrock, 2018 found the *Kiki-Bouba* effect extends to the haptic handling of 3D shapes with and without the participant's visual involvement. Rougher textures have also been associated with non-words formed by sharper sounds (e.g., *Takete*), while smoother textures are associated with non-words formed by rounded sounds (e.g., *Maluma*) as well as hedonic experiences of pleasantness, relief, and comfort (Etzi et al., 2016). Similarly, Riofrio-Riofrio-Grijalva et al., 2020 revealed that sweetness was related to tactile descriptors such as "smooth" and "velvety", while sour was more so associated with "Gritty" and "Sharped".

However, regarding actual food shape and taste perception, far fewer scientific contributions are found. Attempts are commonly related to dish presentation by varying the shape of certain elements in a dish. For example, Fairhurst et al. (2015) presented pieces of beetroot cut either in half-spheres and displayed in a circle (rounded presentation) or into pyramids (angular presentation). They found that changes in the perceived sweetness of the dishes were driven by the interaction between the shape of the plate and the presentation of the food. In another example, Risso and Gallace (2019) found that brown and yellow star-shaped cookies as more *Kiki* than brown and yellow round-shaped cookies. However, while some studies have explored the Kiki-Bouba paradigm using tactile shapes, whether the *Kiki-Bouba* effect extends to the mouthfeel of edible shapes remains unexplored. This was the first aim of the current study.

### 1.2. Ambient effects on taste perception and opportunities of VR environments

The multisensory features perceived from the overall (real world) environment can modulate taste experiences and user behaviour (Spence and Carvalho, 2020; Spence et al., 2014a). These include sounds (Crisinel, 2010; Reinoso Carvalho et al., 2015), light (Lefebvre et al., 2022) and visual locations (Xu et al., 2019). For example, Spence et al. (2014b) explored participants' wine judgements while exposed to different lighting (white, red, green) and music (sour, sweet) conditions. They found that wine was perceived as fresher and less intense under green light and sour music. Similarly, Velasco et al., 2013 explored how people rate different attributes of whisky while being exposed to three different multisensory rooms (grassy, sweet, and woody). They found that the whisky was rated as being grassier in the grassy room, as being sweeter in the sweet room, and as having a woodier aftertaste in the woody room.

There are increasing applications of taste stimulation in Human-Computer Interaction (HCI) that also combines different sensory modalities (e.g., vision and taste) to augment user experiences, often in entertainment contexts (CNET, 2017), interactive media (Ablart, 2017) and storytelling (Jaller et al., 2021; Velasco et al., 2018). Moreover, there are growing efforts towards digitalizing taste experiences (Jaller et al., 2021; Ranasinghe et al., 2012, 2014) and using food as a computational artifact (Deng et al., 2021, 2022). HCI research particularly takes advantage of integrating multisensory cues to augment taste perception. Some examples include adding light (Ranasinghe et al., 2020), changing the virtual scenarios (Chen et al., 2020), and varying the user's locations (Kong et al., 2020).

The augmentation of multi-sensory taste experiences in VR is both a novel area in HCI and an excellent method to efficiently design and modulate environments (i.e., colour); enabling consistent virtual representations of real environments with greater control over different variables to induce emotional responses. For instance, Kong et al. (2020) explored taste perception of three kinds of chocolate (milk, white, and dark) in three different contextual settings; sensory booths (control) and two VR environments (a pleasant sightseeing tour, and a live music concert). The results showed that dark chocolate was associated with more positive emotions when tasted in the "virtual live concert" environment, and with more negative emotions when tasted within the other two environments. Similarly, Chen et al., 2020 explored taste attributes of the same beverage in a sweet-congruent, neutral, and sweet-incongruent environment. The results showed that the sweet-congruent condition (pink-red colours and rounded shapes) enhanced the participant's sweetness perception, as compared to the other two conditions (black and grey colours and sharp shapes).

The effect of environmental lighting has also been explored. For instance, Nygård and Lie (2020) investigated participants' coffee taste expectations under red, green, and white light. The results showed that colour hue influenced coffee flavour, temperature expectation and experience likeability. For example, in a white atmosphere, people perceived coffee as more flavourful relative to the red atmosphere. However, they also found that the various colour hue in a 360-degree environment had no effect on participants' expectations of coffee taste (sweetness and acidity). In another example, Picket and Dando (2019) revealed that participants' willingness to pay for and the overall enjoyment of sparkling wine increased when placed in a virtual winery context relative to a bar, but ratings of beer were unchanged. Moreover, Spence (2020) reported that when exploring the atmospheres of virtual bar environments, participants selected drinks based on perceptual, semantic, and cognitive associations with the presented environment (warm beverages such as coffee, tea or hot chocolate with the warm environment). Building on these novel advances in taste stimulation in virtual/digital environments (e.g., Jaller et al., 2021; Velasco et al.,

2018) we aimed to explore the influence of ambient lighting on taste experience of edible samples within VR.

### 1.3. Summary and aims

While research has largely shown this influence of colour and shape attributes on taste expectations, previous studies are based on non-edible shapes usually shown as 2D images, words, or by modulating aspects secondary to the food itself. Since these previous studies have not focused on the actual mouthfeel of the food itself, it is unclear whether these associations extend beyond taste expectations to edible food. Specifically, how does an edible *Bouba* (rounded) shape affect someone's perception of food sweetness? As a result, we aimed to assess whether CCs of taste and shape extend to edible 3D shapes that vary in mouthfeel. Moreover, we used the benefits of Virtual Reality to assess the multi-sensory influence of ambient lighting. To do so, we produced edible 3D models of *Kiki* and *Bouba* samples to be eaten under different ambient lighting conditions.

We hypothesise that: (1) ratings of sweetness will be significantly greater for Bouba-shaped samples (rounded) relative to Kiki-shaped samples (spiky), and (2) participant ratings of sweetness will be significantly greater when samples are consumed in the red lighting condition relative to the neutral lighting condition. We also aimed to investigate how mouthfeel and ambient lighting these variables may affect taste experiences of pleasantness and familiarity and affective experiences of valence, arousal, and dominance.

## 2. Materials and methods

### 2.1. Taste stimuli

*Kiki* and *Bouba* samples were created with two different sugar contents (sweet and neutral). Both samples were made with 100 ml of water, 4.5g of pork gelatine, and 0.6g of agar (vegan gelatine). The sweet recipe contained 27.5g of cane sugar and the neutral samples contained 2.5g (see Fig. 1a-b). This mixture was chosen because it allowed for samples whose structure was not dependent on the sugar content and its relatively neutral flavour and transparent set. A small quantity of sugar was added to the neutral sample to counteract the taste of water, agar, and gelatine. The sample recipe was systematically developed with user feedback prior to the study to balance taste, structure, and texture.

For production, two food-safe 3D-printed negative moulds were used to create 3D models of *Kiki* and *Bouba* shapes (see Fig. 1c). The process involved clamping the top and bottom moulds together, injecting the mixture through an inlet, chilling the samples for 1–2 h at 4 °C, and then removing the samples from the moulds. The samples were then returned to the fridge for at least 12 h. The final structure was between that of jelly and gummy bears. All participants received samples 24–72 h after preparation and from the same batch to avoid variation. Each participant ate 12 samples (2 cm in size) in each of the three different lighting environments (e.g., red lighting condition: 3 sweet *Bouba*, 3 neutral *Bouba*, 3 sweet *Kiki*, and 3 neutral *Kiki*), resulting in 36 samples in total.

### 2.2. Experimental design

A within-subjects user study following a 2 × 2 × 3 experimental design was conducted – 2 sample sugar contents (neutral, sweet), 2 food shapes (*Kiki*, *Bouba*) and 3 environment lighting conditions (red, blue, neutral). In total, participants ate 36 food samples.

### 2.3. Study setup and technology

The virtual environment was programmed using the Unity Game engine and presented using an Oculus Quest 2 (1832× 1980 pixels per eye at 80hz). The real environment was a small kitchen-style room that included a fridge, sink, cabinets, and seating for participants and the experimenter (see Fig. 2a). Virtual counterparts of this furniture were used for the VR environment including the chair and desk participants were seated at (see Fig. 2b) which matched the location of their real counterparts (see Fig. 2c). This meant that participants could accurately feel the table edges to orientate themselves and accurately take samples from the plate. The Quest's in-built hand tracking was used for interactions in the virtual environment.

### 2.4. Virtual environment

To assess the influence of ambient lighting colour, a realistic and neutral style kitchen-living room environment that was illuminated in either with neutral (*R255, G255, B255*), red (*R255, G0, B0*), or blue lighting (*R0, G0, B255*) was used (see Fig. 2d–f). These lighting conditions were created by changing the virtual lighting of the room and not the colours of the environment itself. Participants were seated at a breakfast bar from which they could see a sofa, TV, rug, bookshelf, coffee table, and other decorations (see Fig. 2c) and behind them was a modern kitchen. To minimise the influence of ambient noise from the testing environment (e.g., nearby people or the experimenter) a neutral background noise was played at low volume (noise cancellation was not used as the researcher needed to talk to participants initially). Virtual models of the *Kiki-Bouba* samples were also created and were presented as opaque white shapes (see Fig. 3a).

### 2.5. Measures

For each combination of shape, light, and sugar content we assessed both participants' taste perceptions and their affective experiences using the following measures.

*Pre-task questionnaire:* Demographic information including sex, gender, age, and nationality were collected. Items regarding taste profiling (e.g., taste preferences) and Virtual Reality experience (e.g., familiarity) were also collected for a separate investigation.

*Taste attributes assessment:* To assess participants' ratings of sample sweetness, pleasantness, and familiarity (relative to other taste experiences) we employed a continuous Visual Analogue Scale (VAS, Crichton, 2001). This scale consisted of a continuum on which participant could rate, for example, the sweetness of a sample on a continuous slider from 0 to 100. Only the labels of "0" and "100" were presented at each extreme of the scale to reduce the amount of visual information while in

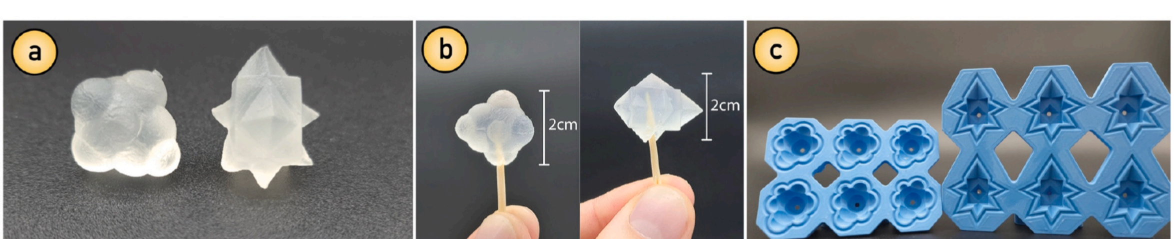


**Fig. 1.** (a–b) Kiki and Bouba jelly samples. (c) Two top portion 3D-printed food grade moulds.

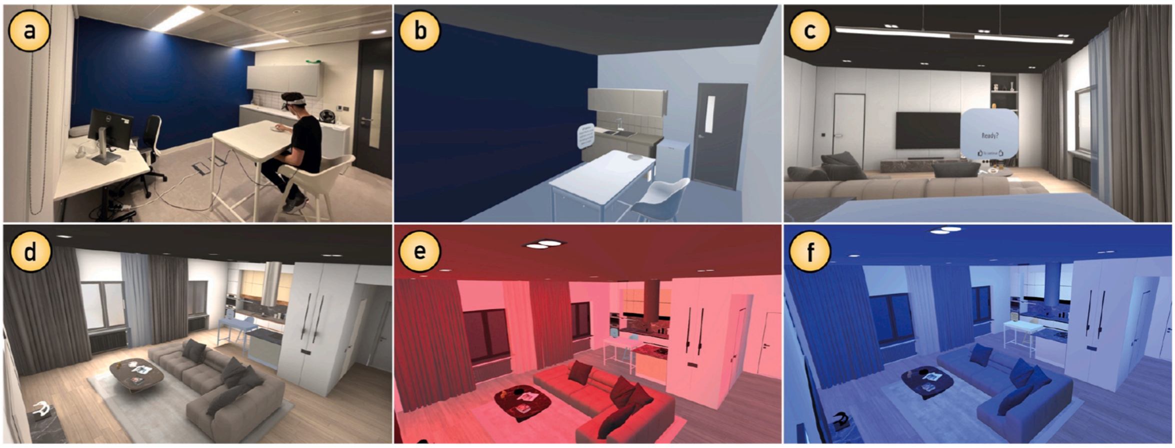


**Fig. 2.** Real environment (a) and its virtual counterpart (b) that participants used to practice. When the experiment started, they saw a realistic kitchen-living room environment (c) which was either illuminated with neutral (d), red (e), or blue lighting (f). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

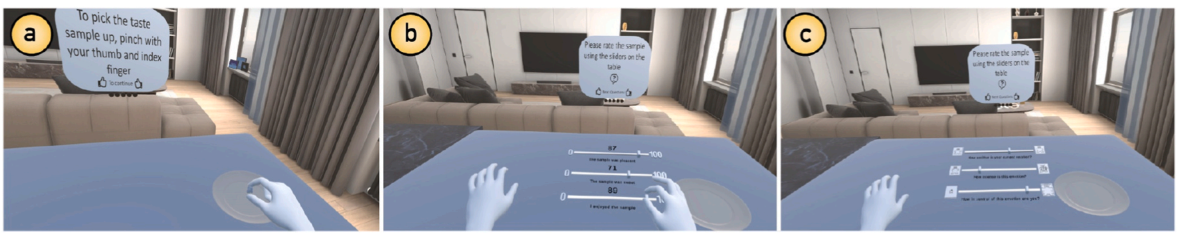


**Fig. 3.** Participants rated the taste sample using Virtual Reality rating scales and hand tracking. Left: three of the four taste attributes items. Right: the three VAS scale.

VR. Participants could view their current numeric rating as they moved the virtual response sliders (Fig. 3b).

*Emotion assessment:* A Self-Assessment Manikin (SAM) scale (Bradley and Lang, 1994) was used to assess participants' experiences of valence, arousal, and dominance. While this scale was also recorded in a scale from 0 to 100, these labels markers were replaced by the respective demonstrative mannequins of each scale (Gatti et al., 2018) (see Appendix I). Unlike the taste attributes assessment, participants could not see their current numeric rating (Fig. 3c).

*Sense of Presence assessment (SOP):* To assess the Sense of Presence (the feeling of 'being there') reported by participants during the study, we used a presence questionnaire proposed by Witmer and Singer (1998). This consisted of 10 questions about the experience immersion and the total score was taken as the outcome variable. The same 0–100 scale of the taste attributes questions was used to be consistent and reduce the complexity of the task. See Appendix I for all the questions.

*Post-task feedback:* Finally, post-task feedback was requested. Firstly, participants were asked "Could you perceive a different in the mouthfeel (shape) of the taste samples you tried?" to support that the manipulation of shape had been successful. Next, open-ended responses were requested on the experience. Participants were also asked to what extent they found eating in VR to be a) comfortable b) pleasant and c) enjoyable on a scale from 0 ("Not at all") to 100 ("Very Much") and whether they thought the taste experience would be perceived differently in real life relative to VR on a scale of 0 ("I disagree") to 100 ("I completely agree").

### *2.6. Procedure*

As illustrated in Fig. 4, after passing the pre-screening criteria and consenting their participation, participants were asked to eat a taste sample (a neutral *Bouba* or *Kiki*) to ensure they did not find the sample unpleasant and to explain the sample rating process to participants outside of VR. After participants confirmed they were happy to continue, they next completed the demographic information. Participants then went through the main VR task (explained in detail in the next section), followed by completing the post-task feedback and thereafter being debriefed. Finally, each participant was rewarded with an £15 Amazon

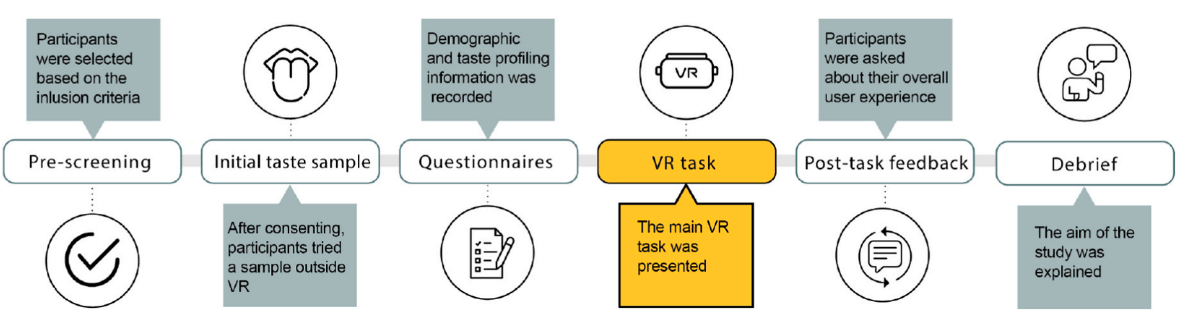


**Fig. 4.** Experiment procedure followed by participants outside of VR activities.

voucher to thank their participation.

### 2.6.1. Virtual reality task

The VR experience consisted of an explanation and practice stage followed by the actual experimental task.

*Explanation and practice:* Participants were seated at the breakfast bar style table and saw a virtual replica of the real kitchen-style room (Fig. 2a–b). The practice began with a notice board presenting the instructions. The first mechanic explained was gesturing. Participants were asked to hold a thumbs up gesture with both hands for 500 ms to signal “OK”, “Next” or “I’m ready” (see Fig. 5a). When a gesture was recognised, the task progressed, and a sound effect (a positive sounding ‘ding’) was played. The next mechanic to practice was grabbing, which consisted of pinching with the right thumb and index finger to either grab taste samples or respond using the sliders. During this practice, the experimenter placed a taste sample on the plate and spawned the respective virtual 3D model in the same location. Participants were then asked to grab this sample and place it onto a second plate in front of them (see Fig. 5b). Finally, participants practiced grabbing the sliders by pinching a centre tick mark and moving it along a slider (see Fig. 5c). Participants practiced each mechanic three times and then verbally confirmed comprehension.

*Virtual Reality task:* As shown in Fig. 6, after the practice, participants were teleported into one of the three rooms at random (i.e., neutral, red, or blue) with the location of the table, chair, and plate being persistent. Participants used the learnt gestures to progress through the instructions. In each room, participants completed a brief visual search task, consisting of finding two objects (a plant and a photo frame) and rating the object’s appealingness using the sliders. This was done to ensure participants looked around the room and did not isolate their attention to the table alone. After participants confirmed their ratings, the primary task instructions were presented.

Within the experimental trial loop (see “Taste” in Fig. 6), each trial began with the experimenter placing a taste sample on the plate and the respective 3D model being spawned in VR. The order of taste samples (e.g., “rounded – sweet”) was randomised for each lighting condition. Participants then grabbed the sample with their right hand and put it in their mouth. The notice board asked participants to explore the shape in their mouth and counted down from five seconds. Next, participants were told to chew and swallow the sample. After three seconds the notice board informed participants that they should rate their experience using the sliders (Fig. 7). The taste attributes and SAM questions were presented in blocks of which the order was randomised. Presentation of the taste attributes items were randomised for each participant whereas the SAM items were not.

After all questions were answered participants confirmed their choices with gesturing, the sliders animated away, and the notice board asked participants to wait for the next sample. This procedure was repeated 12 times in each of the three ambient lighting conditions (neutral, red, blue) resulting in a total of 36 samples being eaten. Between lighting conditions, the SOP questionnaire was completed in VR and there was a 2-minute break in which participants took the headset off and had a sip of water. When participants re-entered the environment, they were in the kitchen-style room again and the process was repeated. When all 36 samples were eaten (45–55 min) participants then rated their experience of the VR environment on Qualtrics. Overall, the whole study lasted approximately 1 h and 15 min including breaks.

## 2.7. Participants

Out of 35 participants recruited, 32 were included in this study (20 biologically male; $M_{age}$ = 28.1 years, SD = 7.6 years, range = 19–59 years, all with normal to normal-corrected vision). Participants varied in their nationalities, 12 being British/dual British citizens, 7 Chinese, 4 American/dual American nationality, and the remainder split between European, Asian, and South African nationalities. Participants were also requested not to consume spicy food 24 h prior, any food or drink (except water) 1 h prior, and alcohol 6 h prior to participating following prior research (Obrist et al., 2014). Ethical approval was obtained from University College London’s internal ethics committee and all participants gave informed consent (approval number: UCLIC_2021_014_ObristPE).

## 2.8. Analysis strategy

From an original sample of 35 participants, 3 were removed from lack of variability in their sweetness ratings between the sweet and neutral sample (assumed to be inattention). From the final sample of 32 participants, two blocks of 12 trials were removed due to unsuccessful data retrieval. Initial data screening suggested bimodal distributions persisted across all six outcome variables stemming from the use of neutral and sweet samples. As a result, the following analyses were conducted separately for each sample type. Each of these six outcome variables were analysed using Linear Mixed-Effects (LME) (Pinheiro and Bates, 2000) models which are similar in interpretation to linear regression. Each model contained the random-effects of trial repetition and participant and the fixed-effects (‘main effect’) of sample shape and ambient lighting colour. The two-way interactions between these variables were also investigated. However, for succinctness, none of these interaction models were a significantly better fit to the data according to $\chi 2$ difference tests and lower AIC values. Model coefficients were individually tested for significance using the *lmerTest* R package (Kuznetsova et al., 2017). All analyses were conducted in R studio (Team R Core, 2020) using several statistical (Lenth et al., 2018) and data visualisation (Wickham, 2016) packages.

# 3. Results

## 3.1. Recipe validation

A LME model confirmed that sweet samples were rated as significantly sweeter (B = 50.8%, $\beta = 0.81$[0.79, 0.84], $p < .001$), pleasant (B = 35.0%, $\beta = 0.64$[0.60, 0.68], $p < .001$), and familiar (B = 24.5%, $\beta = 0.47$[0.44, 0.51], $p < .001$). The median ratings for the neutral samples were as follows: sweetness 13%, pleasantness 25%, enjoyment 22%, and familiarity 24%, respectively; validating both that the recipe was not considered sweet and that the taste experience was relatively neutral. Moreover, 26 of the 32 participants confirmed the mouthfeel of the two


**Fig. 5.** Gesturing mechanics explained during the practice phase: (a) thumbs up gesture to progress during the VR task (b–c) pinching gesture to either grab the taste stimulus or rating using the scales.

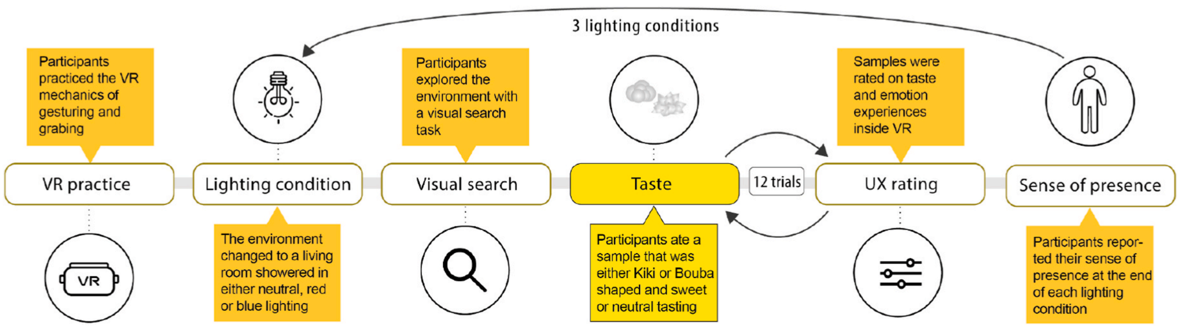


**Fig. 6.** Experimental procedure followed by participants during the VR phase which consisted of 36 trials (samples).

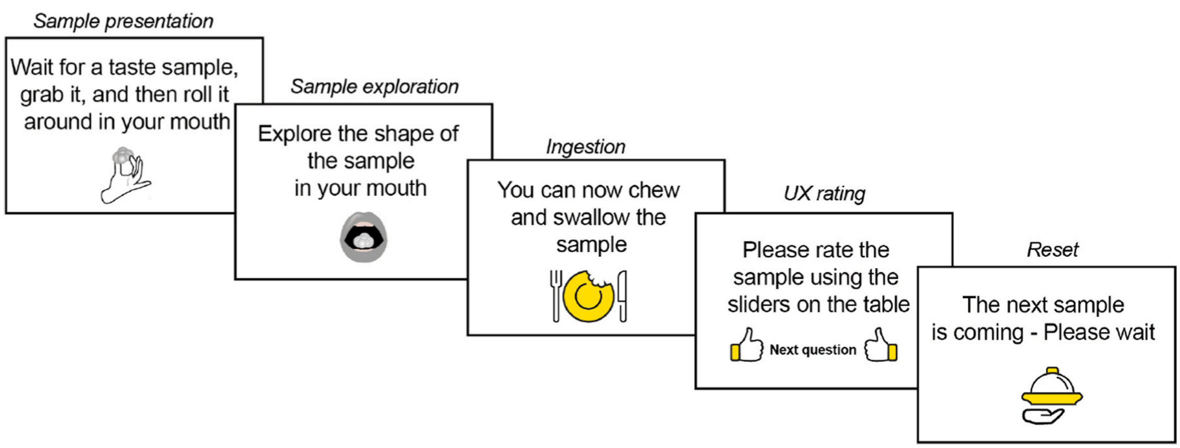


**Fig. 7.** Task flow diagram of each trial. This procedure was repeated 12 times in each of the three ambient lighting conditions (neutral, red, blue) resulting in a total of 36 trials (samples). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

shapes was distinguishable.

### 3.2. *The effect of shape and ambient lighting on taste experience*

#### 3.2.1. *Sweetness*

Neutral samples: There was a significant fixed-effect of the blue lighting to predict reduced sweetness ratings relative to neutral lighting (B = −2.6%, β = −0.07[−0.13, −0.01], $p$ = .02), but neither red lighting (B = −0.7%, β = 0.02[−0.08, 0.04], $p$ = .51) nor sample shape predicted sweetness ratings (B = −0.5%, β = −0.01[−0.07, 0.04], $p$ = .59).

Sweet samples: There was a marginally significant fixed-effect of rounded samples to predict higher sweetness ratings relative to spiky samples (B = 2.1%, β = 0.05[0.00, 0.10], $p$ = .05). The effects of blue lighting (B = −1.7%, β = −0.04[−0.11, 0.01], $p$ = .19) and red lighting (B = −1.9%, β = −0.04[−0.10, 0.02], $p$ = .15) were non-significant relative to neutral lighting (see Fig. 8, Top).

#### 3.2.2. *Pleasantness*

Neutral samples: Neither the fixed-effects of shape ($p$ = .58), blue lighting ($p$ = .13), nor red lighting ($p$ = .57) were significant.

Sweet samples: There was trend level evidence that blue lighting predicted reduced ratings of pleasantness relative to neutral lighting (B = −2.5%, β = −0.07[−0.14, 0.01], $p$ = .090), but the effects of red lighting (B = −2.3%, β = −0.06[−0.14, 0.01], $p$ = .11) and sample shape (B = 0.7%, β = 0.02[−0.04, 0.09], $p$ = .53) were non-significant (Fig. 8, Middle).

#### 3.2.3. *Familiarity*

Neutral samples: There was a significant fixed-effect of rounded samples to predict increased familiarity ratings (B = 1.9%, β = 0.04 [0.00, 0.08], $p$ = .040), but the effects of blue lighting (B = −0.5%, β = −0.01[−0.05, 0.03], $p$ = .666) and red lighting (B = 0.9%, β = 0.02 [−0.03, 0.06], $p$ = .423) were non-significant.

Sweet samples: Neither the fixed-effects of shape ($p$ = .27), blue lighting ($p$ = .49) nor red lighting ($p$ = .64) were significant (see Fig. 8, Bottom).

### 3.3. *The effect of shape and ambient lighting on affective experience*

#### 3.3.1. *Valence*

Neutral samples: There was a significant fixed-effect of the blue lighting to predict lower valence ratings relative to neutral lighting (B = −3.0%, β = −0.07[−0.13, −0.01], $p$ = .02). However, the effect of red lighting (B = −1.7%, β = −0.04[−0.10, 0.02], $p$ = .19) and sample shape (B = −1.12%, β = −0.03[−0.08, 0.02], $p$ = .29) were non-significant.

Sweet samples: There was a significant fixed-effect of the red lighting to predict reduced valance ratings relative to neutral lighting (B = −2.4%, β = −0.08[−0.16, −0.01], $p$ = .03), but the effects of blue lighting (B = −0.1%, β = −0.00[−0.10, 0.02], $p$ = .90) and sample shape (B = 0.6%, β = −0.02[−0.04, 0.08], $p$ = .54) were non-significant (Fig. 9, Top).

#### 3.3.2. *Arousal*

Neutral samples: Neither the fixed-effects shape ($p$ = .81), red lighting ($p$ = .14), nor blue ligthing ($p$ = .11) were significant.

Sweet samples: There was a significant fixed-effect of the blue lighting to predict reduced arousal ratings relative to neutral lighting (B = −3.2%, β = −0.07[−0.13, −0.02], $p$ = .007). However, the effects of red lighting (B = −0.5%, β = −0.01[−0.07, 0.04], $p$ = .64) and sample shape (B = 1.1%, β = 0.03[−0.02, 0.08], $p$ = .23) were non-significant (Fig. 9, Middle).

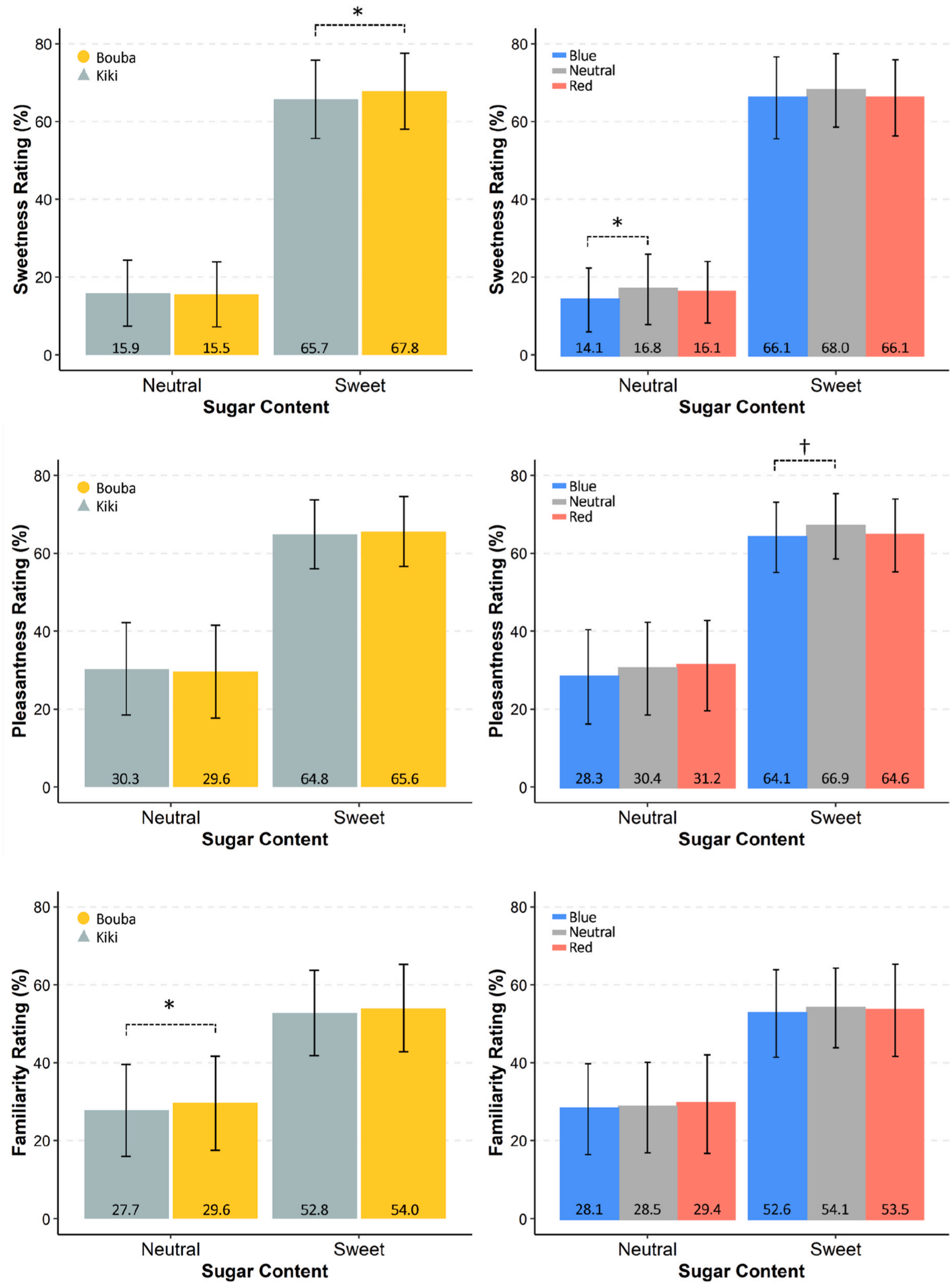


**Fig. 8.** Participant's ratings of sweetness (top), pleasantness (middle) and familiarity (bottom) according to sample sugar content, shape, and ambient lighting colour. Values represent the statistical mean and error bars represent the standard deviation. Note: * = $p < .05$, † = $p < .1$. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

### *3.3.3. Dominance*

Neutral samples: There were significant fixed-effects of both the blue lighting (B = −4.9%, β = −0.09[−0.15, 0.03], $p = .003$) and red lighting (B = −3.8%, β = −0.07[−0.13, −0.01], $p = .02$) to predict reduced ratings of dominance relative to neutral light. Howvever, the effect of sample shape non-significant (B = −0.1%, β = 0.00[−0.05, 0.05], $p = .956$).

Sweet samples: Neither the fixed-effects shape ($p = .98$), red lighting

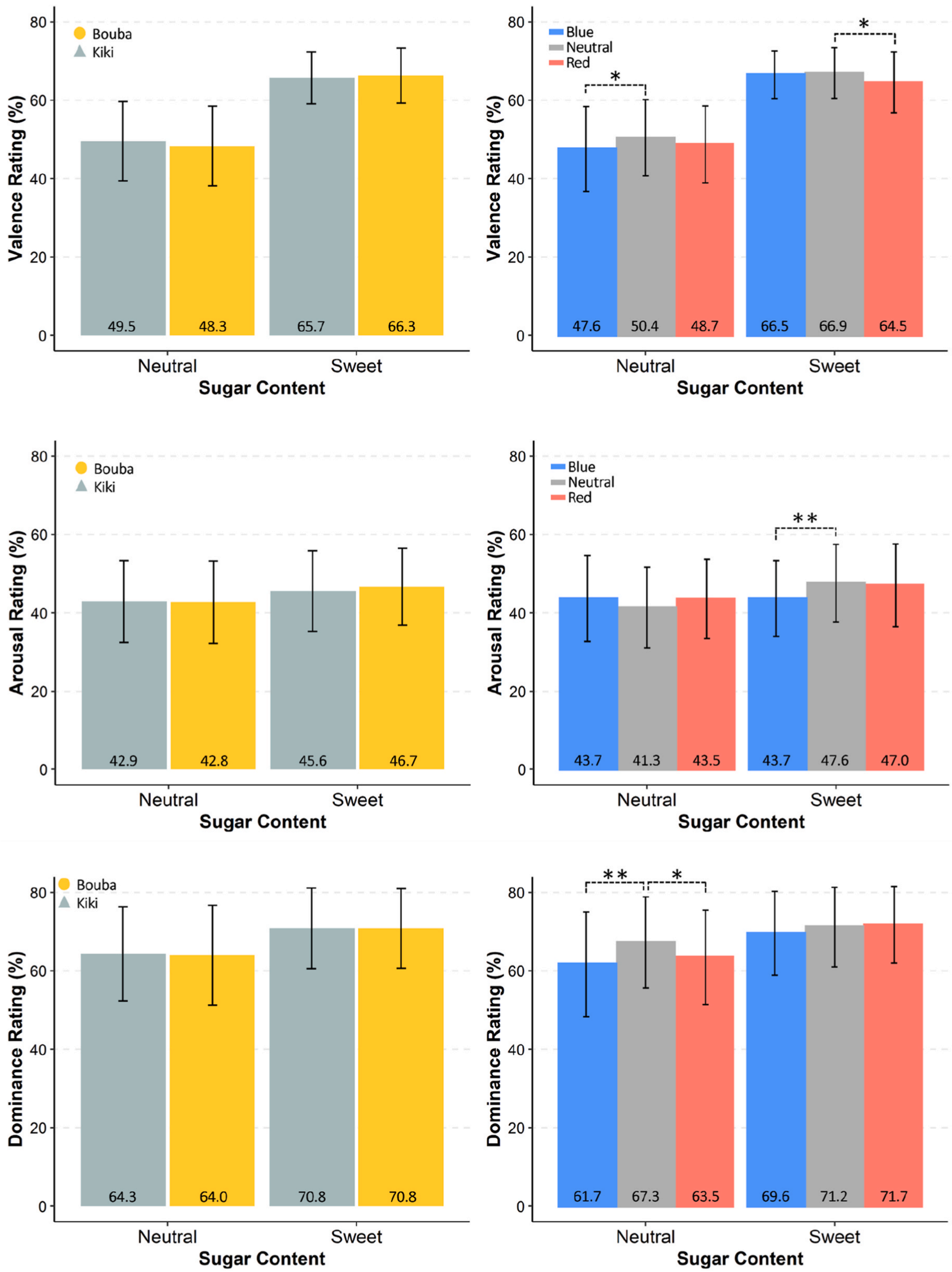


**Fig. 9.** Participant's ratings of valence (top), arousal (middle) and control (bottom) according to sample sugar content, shape, and ambient lighting colour. Values represent the statistical mean and error bars represent the standard deviation. Note: ** = $p < .01$, * = $p < .05$. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

($p = .66$), nor blue ligthing ($p = .35$) were significant (Fig. 9, Bottom).

### 3.3.4. *Sense of Presence*

A further LME model predicting SOP ratings from the fixed-effect of lighting colour revealed that SOP ratings were significantly lower for the blue lighting condition (M = 75.6%, SD = 9.7) relative to neutral lighting (M = 78.9%, SD = 11.9, B = −3.3%, β = −0.15[−0.27, −0.03], $p = .02$). However, the effect of red lighting (M = 77.2%, SD = 9.0) was non-significant (B = - 1.7%, β = −0.08[−0.20, 0.04], $p = .20$).

### 3.3.5. VR feedback

Finally, post-task feedback was summarised. Participants rated the eating experience in VR as comfortable (median = 72.5, MAD = 11.1), relatively enjoyable (median = 62.0, MAD = 30.3) and pleasant (median = 65.5, MAD = 19.3), which open-ended comments suggested this was due to the flavour of the taste samples (rather than VR itself). There was large variation in whether participants felt the experience would have been perceived differently in real life (median = 44.0, MAD = 41.5).

## 4. Discussion

This study investigated the cross-modal correspondences (CCs) between sample taste, shape (mouthfeel), and ambient lighting. Our findings supported that Bouba-shaped samples were significantly sweeter than Kiki-shaped samples (*Hypothesis 1*), but only when the samples themselves were sweet and not neutral tasting. We did not find that samples eaten under red lighting would be rated as sweeter (*Hypothesis 2*), although samples eaten under blue lighting were rated as less sweet, but only when the samples themselves were neutral tasting.

Our results showed that when participants tasted the sweet *Kiki-Bouba* samples (but not the neutral samples), they rated Bouba-shaped samples as sweeter compared with Kiki-shaped samples. This result supports our first hypothesis and is consistent with studies suggesting that rounded shapes are associated with a sweet taste (Fryer et al., 2014; Gallace et al., 2011; Graven and Desebrock, 2018; Salgado Montejo et al., 2015). These results also support that these associations found in non-edible representations of *Kiki-Bouba* extend to the actual mouthfeel of edible samples. This finding highlights the contribution of the tactile receptors located inside the mouth to taste perception and suggests that the salient characteristics of food shape can influence sweetness perception. Indeed, participants noted the difference between *Kiki--Bouba* shapes as reported in the post-task feedback (e.g., "*It was playful to feel the different shapes of the samples*", "*my feeling changes mostly when the shape of jelly shifts*", and "*the spiky jellies made the experience more engaging*"). Moreover, finding this sweetness modulation effect in sweet but not neutral samples may suggest this effect is specific to cases of cross-modal correspondence (Bouba-Sweet, congruent), but not when this is violated (Bouba-Neutral, incongruent).

In terms of ambient lighting, our results showed that sweetness ratings were lower when samples were eaten in a blue lighting environment relative to a neutral lighting environment (Hypothesis 2). This is in line with the work by Spence et al. (2015), which showed that blue colour usually leads to salty taste expectations rather than sweet taste expectations. Moreover, the fact that this finding was only replicated in neutral but not sweet samples, further supports for the above cross-modal correspondence suggestion (i.e., Bouba-Sweetness, Blue--Neutral or Blue- 'not sweet'). Although, this does not explain why red lighting did not increase sweetness ratings for the sweet samples.

While environmental lighting colour has been suggested to increase sweetness perception and expectations in real-life settings (Lefebvre et al., 2022; Spence et al., 2014b; Velasco et al., 2013), these findings may not extend to the present study using immersive virtual environments. This is further supported by the literature, for example, Nygård and Lie (2020) found that various colour hues in a 360-degree environment did not affect participants' expectations of coffee taste. Similarly, Kong et al., 2020 found no significant effects of context type on chocolate tasting experiences in a 360-degree virtual environment. Although, there is evidence that changing virtual locations (rather than showing the same location in a different colour) may elicit taste perception changes. For example, being in a concert, a bar, or a winery (Kong et al., 2020; Picket and Dando, 2019). Previous studies exploring taste perception in VR have also focused on other aspects of user experience (e.g., ratings of intensity, willingness to pay, liking, and enjoyment) rather than sweetness specifically. Additionally, other contextual aspects of the environment, apart from its colour, might help in this influence. For example, Chen et al. (2020) reported that sweetness ratings were influenced when the virtual environment combined colour (red vs grey) and furniture shape (spiky vs rounded). Therefore, our results seem to support that red light alone is not sufficient in immersive virtual environments.

One possible reason for this result could be the realism and intensity of the red and blue lighting environments creating a subjective preference for the neutral environment by some participants (e.g., "*It was a weird experience especially with the changing colours of the environment*", "*I preferred being in the white* [neutral] *room without the colour as it felt most realistic*"). This is consistent with both higher SOP ratings being reported for the neutral environment and the post-task feedback questionnaire (e.g., "[The] *red room and the colour didn't make me feel at ease compared to the blue and white rooms*", "*Last room colour* [neutral] *was the most realistic of the three and made me feel more like I was there*"). This may also explain the reduced ratings of dominance (feelings of being in control of one's own emotions) reported in the blue and red environments, because the reduced SOP of these rooms may have created a sense of dissonance between virtual and real experiences and a reduced sense of control. Finally, these effects on dominance were only found for neutral samples. This may suggest that when the taste experience is low (neutral), other aspects of the experience such as ambient lighting affect taste perception. However, when the taste experience is sufficiently high (sweet) this more relevant information takes precedence. Further studies need to investigate this effect and relationship to dominance.

In summary, our findings provide mixed support for the influence of ambient light colour in a virtual setting. Specifically, while blue lighting may dampen sweetness experiences, red lighting may not enhance sweetness experiences. Other hedonic experiences of taste may be more easily modulated (liking, emotion, preference, etc.) especially when the entire environment rather than only lighting is modulated.

### 4.1. Considerations for eating in virtual reality and opportunities for future work

Our study involved not only an immersive environment (realistic and modern living room), but also a compelling eating experience with natural interaction between the real and virtual worlds (e.g., "*It was interesting to see how the virtual reality is synched with real life sensory experience which is mostly not the case with VR. Maybe it can be used to provide different culinary experience in the future.*"). We carefully tracked both the participants' hands and the real taste samples, with respect their virtual counterparts. However, this level of synchronisation also led participants to report feelings of eating 'virtual food' (e.g., "*it felt like I was just eating the virtual object and when I think back on it, it doesn't really feel like I was eating at the time because it took place in the virtual environment rather than 'in real life'*", "*the shape of the them reminded me of the universe and astronomy, which made me excited*"). Future research should be mindful that immersive VR taste experiences may detract from a real-life tasting experience through perceived artificialness.

A second consideration is around the familiarity of sample shapes within a virtual environment. We based our study in the widely used *Kiki-Bouba* paradigm following insights from the literature, but such shapes are rarely found in daily life and therefore more familiar representation of food could be recommendable for a more realistic taste experiences (e.g., "… *the samples looked kind of 'fake' in the virtual environment* …", "*the shape of them reminded me of the universe and astronomy*").

A primary strength of the current study is that participants consumed real food samples created with a high level of experimental control (i.e., samples varied only in sweetness and environments only in ambient lighting colour), rather than rating their expected taste experiences. This may explain the relatively small (but theoretically consistent) effects of the current study. Specifically, perhaps much of the influence of cross-modal correspondence is in the *expectation* of the experience, rather than the actual experience itself. The relatively small effect sizes here may suggest that the modulation of shape and light is not strong enough to create meaningful differences in taste experiences. Although, the perceived artificialness of food samples due to eating in VR may have played a role in some participants.

In light of future work, we also need to acknowledge some limitations of our current study. One limitation is that the samples were clearly neutral and sweet tasting, this may have made the task itself too easy and produced ceiling effects. A study using varying levels of sweetness may produce greater effects. Another limitation is that the influence of other demographic factors such as age, sex, and culture were not assessed. Future research could replicate the current study in a larger sample to investigate potential moderators of cross-modal correspondence. Finally, while this study achieved a statistical power level of 86% or greater for a medium effect size (Westfall, 2015) the study design was not powerful enough to detect small effects. Consequently, it cannot be concluded that the null associations here support that these variables were *unrelated*.

## 5. Conclusion

In this paper we investigated the effect of food shape (mouthfeel) and environmental lighting colour on taste perception (sweetness ratings) in a realistic virtual environment, through an edible jelly-based *Kiki-Bouba* paradigm. Overall, our result showed increased ratings of sweetness when participants tasted Bouba-shaped samples (rounded) relative to Kiki-shaped samples (spiky) suggesting that tactile receptors located inside the mouth identifying characteristics of food shape can influence sweetness perception. Furthermore, we concluded that light colour in a virtual setting might dampen experiences of sweetness. However, this effect may only be present when there is a cross-modal correspondence with taste. Finally, based on our findings we provided considerations that we consider to be relevant for designing experiences on eating in VR, including the balance of virtual immersion and artificialness in mixed reality.

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## Author statement

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## Implications for gastronomy

This manuscript explores the influence of ambient lighting and food shape on taste perception and experiences. Previous research is limited by assessing the effect of shape on food/taste through using images, manipulating aspects other than the food itself (e.g., container shape), or by using non-edible representations of the food - meaning experiences focus on taste expectations rather than taste experiences. This manuscript tackles these issues by creating edible 3D food samples following the *Kiki* (spiky) *Bouba* (rounded) paradigm. We further consider the influence of ambient lighting by creating three separate coloured virtual reality environments (neutral, red, or blue lighting). The presented results advance our understanding on how to integrate eating experiences within digital worlds as it contributes to the growing efforts of using food as a computational artifact by capitalizing advances in virtual reality and multisensory stimulation. Based on our findings, we conclude by describing considerations for designing eating experiences in virtual reality.

## Declaration of competing interest

The authors declare that this research was conducted as part of a commercial and financial relationship between UCL and Sony. However, neither party benefitted financially from the outcome of this research.

## Data availability

Data will be made available on request.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijgfs.2022.100626.

## References

Ablart, D., 2017. Integration of touch and taste with interactive media. In: Adjunct Publication of the 2017 ACM International Conference on Interactive Experiences for TV and Online Video. https://doi.org/10.1145/3084289.3084294.

Bradley, M.M., Lang, P.J., 1994. Measuring emotion: the self-assessment manikin and the semantic differential. J. Behav. Ther. Exp. Psychiatr. 25 (1), 49–59. https://doi.org/10.1016/0005-7916(94)90063-9.

Bremner, A.J., Caparos, S., Davidoff, J., de Fockert, J., Linnell, K.J., Spence, C., 2013. Bouba" and "Kiki" in Namibia? A remote culture make similar shape–sound matches, but different shape–taste matches to Westerners. Cognition 126 (2), 165–172. https://doi.org/10.1016/j.cognition.2012.09.007.

Chen, Y., Huang, A.X., Faber, I., Makransky, G., Perez-Cueto, F.J., 2020. Assessing the influence of visual-taste congruency on perceived sweetness and product liking in immersive VR. Foods 9 (4), 465. https://doi.org/10.3390/foods9040465.

CNET, 2017. Royal Caribbean's high-tech ship lets you be lazier than ever, 2021, Available from: https://www.cnet.com/news/royal-caribbeans-high-tech-ship-lets-you-be-lazier-than-ever-vr-self-driving-shuttles/.

Crichton, N., 2001. Visual analogue scale (VAS). J. Clin. Nurs. 10 (5), 706, 706.

Crisinel, A.-S., 2010. As bitter as a trombone: synesthetic correspondences in nonsynesthetes between tastes/flavors and musical notes. Atten. Percept. Psychophys. 72 (7), 1994–2002. https://doi.org/10.3758/APP.72.7.1994.

Deng, J., Olivier, P., Andres, J., Ellis, K., Wee, R., Mueller, F.F., 2022. Logic bonbon: exploring food as computational artifact. In: Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems. Association for Computing Machinery, New Orleans, LA, USA. https://doi.org/10.1145/3491102.3501926. Article 47.

Deng, J., Olivier, P., Mueller, F.F., 2021. Design of Cyber Food: Beginning to Understand Food as Computational Artifact. Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems. Japan, Association for Computing Machinery, Yokohama. https://doi.org/10.1145/3411763.3451687. Article 293.

Etzi, R., Spence, C., Zampini, M., Gallace, A., 2016. When sandpaper is 'Kiki'and satin is 'Bouba': an exploration of the associations between words, emotional states, and the tactile attributes of everyday materials. Multisensory Res. 29 (1–3), 133–155. https://doi.org/10.1163/22134808-00002497.

Fairhurst, M.T., Pritchard, D., Ospina, D., Deroy, O., 2015. Bouba-Kiki in the plate: combining crossmodal correspondences to change flavour experience. Flavour 4 (1), 1–5. https://doi.org/10.1186/s13411-015-0032-2.

Fryer, L., Freeman, J., Pring, L., 2014. Touching words is not enough: how visual experience influences haptic–auditory associations in the "Bouba–Kiki" effect. Cognition 132 (2), 164–173. https://doi.org/10.1016/j.cognition.2014.03.015.

Gallace, A., Boschin, E., Spence, C., 2011. On the taste of "Bouba" and "Kiki": an exploration of word–food associations in neurologically normal participants. Cognit. Neurosci. 2 (1), 34–46. https://doi.org/10.1080/17588928.2010.516820.

Gatti, E., Calzolari, E., Maggioni, E., Obrist, M., 2018. Emotional ratings and skin conductance response to visual, auditory and haptic stimuli. Sci. Data 5 (1), 1–12. https://doi.org/10.1038/sdata.2018.120.

Graven, T., Desebrock, C., 2018. Bouba or kiki with and without vision: shape-audio regularities and mental images. Acta Psychol. 188, 200–212. https://doi.org/10.1016/j.actpsy.2018.05.011.

Harrar, V., Spence, C., 2013. The taste of cutlery: how the taste of food is affected by the weight, size, shape, and colour of the cutlery used to eat it. Flavour 2 (1), 1–13. https://doi.org/10.1186/2044-7248-2-21.

Huang, F., Huang, J., Wan, X., 2019. Influence of virtual color on taste: multisensory integration between virtual and real worlds. Comput. Hum. Behav. 95, 168–174. https://doi.org/10.1016/j.chb.2019.01.027.

Jaller, C., Andersen, N.B., Nilsson, N.C., Paisa, R., Damsbo, M., Serafin, S., 2021. MARTYR: exploring ingredients of virtual dining experiences. 2021 IEEE conference on virtual reality and 3D user interfaces abstracts and workshops (VRW). IEEE. https://doi.org/10.1109/VRW52623.2021.00049.

Köhler, W., 1940. Gestalt Psychology, Liveright, New York, 1929. Google Scholar.

Kong, Y., Sharma, C., Kanala, M., Thakur, M., Li, L., Xu, D., Harrison, R., Torrico, D.D., 2020. Virtual reality and immersive environments on sensory perception of chocolate products: a preliminary study. Foods 9 (4), 515. https://doi.org/10.3390/foods9040515.

Kuznetsova, A., Brockhoff, P.B., Christensen, R.H., 2017. lmerTest package: tests in linear mixed effects models. J. Stat. Software 82, 1–26. https://doi.org/10.18637/jss.v082.i13.

Lefebvre, S., Hasford, J., Boman, L., 2022. Less light, better bite: how ambient lighting influences taste perceptions. J. Retailing Consum. Serv. 65, 102732 https://doi.org/10.1016/j.jretconser.2021.102732.

Lenth, R., Singmann, H., Love, J., Buerkner, P., Herve, M., 2018. Emmeans: estimated marginal means, aka least-squares means. R package version 1 (1), 3. https://CRAN.R-project.org/package=emmeans.

Lin, Y.-J., Punpongsanon, P., Wen, X., Iwai, D., Sato, K., Obrist, M., Mueller, S., 2020. FoodFab: creating food perception illusions using food 3D printing. In: Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems. https://doi.org/10.1145/3313831.3376421.

Lundström, J.N., Boesveldt, S., Albrecht, J., 2011. Central processing of the chemical senses: an overview. ACS Chem. Neurosci. 2 (1), 5–16. https://doi.org/10.1021/cn1000843.

Michel, C., Velasco, C., Spence, C., 2015. Cutlery matters: heavy cutlery enhances diners' enjoyment of the food served in a realistic dining environment. Flavour 4 (1), 1–8. https://doi.org/10.1186/s13411-015-0036-y.

Nakata, R, Kawai, N, 2017. The "social" facilitation of eating without the presence of others: Self-reflection on eating makes food taste better and people eat more. Physiol. Behav. 179, 23–29. https://doi.org/10.1016/j.physbeh.2017.05.022.

Nygård, M., Lie, C.L., 2020. How Changes in Environmental Colour Hue Affect Taste Expectations, Perceptions, and Product Preferences at Different Levels of Attention towards Atmospheric Cues: A Mixed Experimental Design. Handelshøyskolen BI. https://hdl.handle.net/11250/2686800.

Obrist, M., Comber, R., Subramanian, S., Piqueras-Fiszman, B., Velasco, C., Spence, C., 2014. Temporal, affective, and embodied characteristics of taste experiences: a framework for design. In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems. https://doi.org/10.1145/2556288.2557007.

Picket, B., Dando, R., 2019. Environmental immersion's influence on hedonics, perceived appropriateness, and willingness to pay in alcoholic beverages. Foods 8 (2), 42. https://doi.org/10.3390/foods8020042.

Pinheiro, J.C., Bates, D.M., 2000. Linear mixed-effects models: basic concepts and examples. Mixed-effects models in S and S-Plus 3–56. https://doi.org/10.1007/0-387-22747-4_1.

Piqueras-Fiszman, B., Alcaide, J., Roura, E., Spence, C., 2012a. Is it the plate or is it the food? Assessing the influence of the color (black or white) and shape of the plate on the perception of the food placed on it. Food Qual. Prefer. 24 (1), 205–208. https://doi.org/10.1016/j.foodqual.2011.08.011.

Piqueras-Fiszman, B., Laughlin, Z., Miodownik, M., Spence, C., 2012b. Tasting spoons: assessing how the material of a spoon affects the taste of the food. Food Qual. Prefer. 24 (1), 24–29. https://doi.org/10.1016/j.foodqual.2011.08.005.

Piqueras-Fiszman, B., Spence, C., 2011. Do the material properties of cutlery affect the perception of the food you eat? An exploratory study. J. Sensory Stud. 26 (5), 358–362.

Ranasinghe, N., Cheok, A.D., Nakatsu, R., 2012. Taste/IP: the sensation of taste for digital communication. In: Proceedings of the 14th ACM International Conference on Multimodal Interaction. https://doi.org/10.1145/2388676.2388768.

Ranasinghe, N., James, M.N., Gecawicz, M., Bland, J., Smith, D., 2020. Influence of electric taste, smell, color, and thermal sensory modalities on the liking and mediated emotions of virtual flavor perception. In: Proceedings of the 2020 International Conference on Multimodal Interaction. https://doi.org/10.1145/3382507.3418862.

Ranasinghe, N., Lee, K.-Y., Suthokumar, G., Do, E.Y.-L., 2014. Taste+ digitally enhancing taste sensations of food and beverages. In: Proceedings of the 22nd ACM International Conference on Multimedia. https://doi.org/10.1145/2647868.2654878.

Reinoso Carvalho, F., Van Ee, R., Rychtarikova, M., Touhafi, A., Steenhaut, K., Persoone, D., Spence, C., Leman, M., 2015. Does music influence the multisensory tasting experience? J. Sensory Stud. 30 (5), 404–412. https://doi.org/10.1111/joss.12168.

Riofrio-Grijalva, R., Lago, M., Fabregat-Amich, P., Guerrero, J., Cuesta, A., Vázquez-Araújo, L., 2020. Relationship between tactile stimuli and basic tastes: CATA with consumers with visual disability. J. Sensory Stud. 35 (1), e12549 https://doi.org/10.1111/joss.12549.

Risso, P., Gallace, A., 2019. Cognitive and Multisensory Integration Effects in Functional Food Perception: A Preliminary Report.

Rolls, E.T., 2012. Mechanisms for sensing fat in food in the mouth* presented at the symposium "the taste for fat: new discoveries on the role of fat in sensory perception, metabolism, sensory pleasure and beyond" held at the institute of food technologists 2011 annual meeting, new orleans, La., USA, june 12, 2011. J. Food Sci. 77 (3), S140–S142. https://doi.org/10.1111/j.1750-3841.2011.02584.x.

Salgado Montejo, A., Alvarado, J.A., Velasco, C., Salgado, C.J., Hasse, K., Spence, C., 2015. The sweetest thing: the influence of angularity, symmetry, and the number of elements on shape-valence and shape-taste matches. Front. Psychol. 6, 1382. https://doi.org/10.3389/fpsyg.2015.01382.

Spence, C., 2013. Multisensory flavour perception. Curr. Biol. 23 (9), R365–R369.

Spence, C., 2020. Temperature-based crossmodal correspondences: causes and consequences. Multisensory Res. 33 (6), 645–682. https://doi.org/10.1163/22134808-20191494.

Spence, C., Carvalho, F.M., 2020. The coffee drinking experience: product extrinsic (atmospheric) influences on taste and choice. Food Qual. Prefer. 80, 103802 https://doi.org/10.1016/j.foodqual.2019.103802.

Spence, C., Deroy, O., 2013. On the shapes of flavours: a review of four hypotheses. Theoria et Historia Scientiarum 10, 207–238. https://doi.org/10.12775/ths-2013-0011.

Spence, C., Gallace, A., 2011. Tasting shapes and words. Food Qual. Prefer. 22 (3), 290–295. https://doi.org/10.1016/j.foodqual.2010.11.005.

Spence, C., Puccinelli, N.M., Grewal, D., Roggeveen, A.L., 2014a. Store atmospherics: a multisensory perspective. Psychol. Market. 31 (7), 472–488. https://doi.org/10.1002/mar.20709.

Spence, C., Van Doorn, G., 2017. Does the shape of the drinking receptacle influence taste/flavour perception? A review. Beverages 3 (3), 33. https://doi.org/10.3390/beverages3030033.

Spence, C., Velasco, C., Knoeferle, K., 2014b. A large sample study on the influence of the multisensory environment on the wine drinking experience. Flavour 3 (1), 1–12. https://doi.org/10.1186/2044-7248-3-8.

Spence, C., Wan, X., 2015. Beverage perception and consumption: the influence of the container on the perception of the contents. Food Qual. Prefer. 39, 131–140. https://doi.org/10.1016/j.foodqual.2014.07.007.

Spence, C., Wan, X., Woods, A., Velasco, C., Deng, J., Youssef, J., Deroy, O., 2015. On tasty colours and colourful tastes? Assessing, explaining, and utilizing crossmodal correspondences between colours and basic tastes. Flavour 4 (1), 1–17. https://doi.org/10.1186/s13411-015-0033-1.

Stewart, P.C., Goss, E., 2013. Plate shape and colour interact to influence taste and quality judgments. Flavour 2 (1), 1–9. https://doi.org/10.1186/2044-7248-2-27.

Stoeckel, L.E., Kim, J., Weller, R.E., Cox, J.E., Cook III, E.W., Horwitz, B., 2009. Effective connectivity of a reward network in obese women. Brain Res. Bull. 79 (6), 388–395. https://doi.org/10.1016/j.brainresbull.2009.05.016.

Stribitcaia, E., Evans, C.E., Gibbons, C., Blundell, J., Sarkar, A., 2020. Food texture influences on satiety: systematic review and meta-analysis. Sci. Rep. 10 (1), 1–18. https://doi.org/10.1038/s41598-020-69504-y.

Team R Core, 2020. R Core Team R: a Language and Environment for Statistical Computing. Foundation for Statistical Computing.

Tournier, C., Sulmont-Rossé, C., Guichard, E., 2007. Flavour Perception: Aroma, Taste and Texture Interactions. Global Science Books.

Trivedi, B.P., 2012. Gustatory system: the finer points of taste. Nature 486 (7403), S2–S3. https://doi.org/10.1038/486S2a.

Van Doorn, G., Woods, A., Levitan, C.A., Wan, X., Velasco, C., Bernal-Torres, C., Spence, C., 2017. Does the shape of a cup influence coffee taste expectations? A cross-cultural, online study. Food Qual. Prefer. 56, 201–211. https://doi.org/10.1016/j.foodqual.2016.10.013.

Velasco, C., Jones, R., King, S., Spence, C., 2013. Assessing the influence of the multisensory environment on the whisky drinking experience. Flavour 2 (1), 1–11. https://doi.org/10.1186/2044-7248-2-23.

Velasco, C., Tu, Y., Obrist, M., 2018. Towards multisensory storytelling with taste and flavor. In: Proceedings of the 3rd International Workshop on Multisensory Approaches to Human-Food Interaction. https://doi.org/10.1145/3279954.3279956.

Velasco, C., Woods, A.T., Deroy, O., Spence, C., 2015. Hedonic mediation of the crossmodal correspondence between taste and shape. Food Qual. Prefer. 41, 151–158. https://doi.org/10.1016/j.foodqual.2014.11.010.

Velasco, C., Woods, A.T., Petit, O., Cheok, A.D., Spence, C., 2016. Crossmodal correspondences between taste and shape, and their implications for product packaging: a review. Food Qual. Prefer. 52, 17–26. https://doi.org/10.1016/j.foodqual.2016.03.005.

Wickham, H., 2016. ggplot2: Elegant Graphics for Data Analysis. springer.

Witmer, B.G., Singer, M.J., 1998. Measuring presence in virtual environments: a presence questionnaire. Presence 7 (3), 225–240. https://doi.org/10.1162/105474698565686.

Xu, Y., Hamid, N., Shepherd, D., Kantono, K., Spence, C., 2019. Changes in flavour, emotion, and electrophysiological measurements when consuming chocolate ice cream in different eating environments. Food Qual. Prefer. 77, 191–205. https://doi.org/10.1016/j.foodqual.2019.05.002.