Original research

Virtual Flavor: High-fidelity simulation of real flavor experiences

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Abstract— Food and drink are a key part of our lives. While Virtual Reality has the potential to provide high-fidelity simulation of real experiences in virtual worlds, the incorporation of flavor appreciation within these virtual experiences has largely been ignored. In this paper we introduce a virtual flavor device to simulate real flavor experiences. The goal is to provide virtual flavor experiences, using food safe chemicals for the three components of a flavor (taste, aroma, mouthfeel), which are perceived as "indistinguishable" from the equivalent real experience. Furthermore, because we are delivering a simulation, the same device can be used to take a user on a "flavor discovery journey" from a start flavor to a new, preferred flavor by adding or removing any amount of the components. In the first experiment, participants (N=28) were exposed to real and virtual samples of orange juice, and the health product, rooibos tea, and asked to rate their similarity. The second experiment investigated how participants (N=6) could move within "flavor space" from one flavor to another. The results show that it is possible to simulate, with a high degree of precision, a real flavor experience, and precisely controlled "flavor discovery journeys" can be undertaken using virtual flavors.

How often have you seen an interesting food or drink on television, in a game, in a virtual world, or on the shelf of a real shop, and thought: "*I wonder what that tastes like?*" Without knowing the flavor of some food or drink, customers are hesitant to purchase it in case they do not like it. Indeed, producers face a real challenge when planning to introduce a new product: "*Will our existing and new customers like it?*". Prior to launch, tens of thousands of dollars are spent trying to understand consumer preferences to mitigate the likelihood of a potential new product failing. While tasting sessions and devices, such as e-tongues and e-noses, can help, the former is subjective, and the latter does not provide knowledge of overall human flavor perception. Both require access to a wide range of samples of the product, which, in the case of a new product, may not be fully ready yet.

This paper describes the emerging field of virtual flavor, to enable people to experience a flavor of a food or drink, quickly, accurately, and without having to have access to real samples. Users of the virtual flavor device proposed in this paper, which we term *FlavoSim*, can have an authentic experience of a real flavor in the real or virtual world, or share the same flavor experience with others remotely, for example, players in an online game sharing a tea. Because it is a simulation, users can also add and remove precise amounts of the individual flavor components (taste, mouthfeel, aroma) of the food or beverage, e.g. adding more sugar or less lemon to the tea,

with instant feedback on their new choice. Users can either experiment with flavors or be guided rapidly in this journey from an initial "base flavor" to a preferred flavor using optimization software which directs them as to which components should be manipulated and by how much.

It is important to note that that virtual flavor is a superset of artificial flavor which is a single (unmodifiable) sample of a virtual flavor.

BACKGROUND

The molecules of food are chemicals detected by taste receptors in the mouth, and the olfactory receptors in the nose. There are five primary tastes: salty, sour, bitter, sweet and umami (from the Japanese for "tasty" - which corresponds roughly to the taste of glutamate)[1]. How we perceive food is also influenced by its texture, smell (both orthonasal ("sniffed in") and retronasal ("from the food in the mouth")), temperature, looks, cost, and environmental and cultural factors, such as who we are, where we are eating, and with whom, etc,[1-4].

In 2003, Iwata et al [5] presented their three-sense food simulator: a haptic interface to mimic the taste, sound and feeling of chewing real food. A mouth device simulated the force of the food type, a bone vibration microphone provided the sound of biting, while chemical simulation of taste was achieved via a micro injector which squirted the chemicals into the mouth. Recently, Miyashita demonstrated the "Norimaki taste display" [6] using 5 gels to recreate basic tastes and a "lickable TV" was announced [7]. Although highly novel, these devices do not include mouthfeel, temperature or aroma, key components of flavor [1].

Work from Ranasinghe et al. [8] has shown that it is possible to simulate the sensation of some of the primary tastes by direct electrical and thermal stimulation of the tongue. This work led to the development of virtual cocktail device [9]. However, this device can only simulate a few flavors. Electrical stimulation of the inner nose has also been used to attempt the simulation of smell, with limited success so far [10]. In 2010, Narumi et al. [11] showed how cross-sensory perception can influence enjoyment of food by superimposing virtual color onto a real drink, while the MetaCookie+ project [12] changed the perceived taste of a cookie using visual and auditory stimuli. Virtual Reality has also been used to see how an environment can affect the perception of flavor[13,14], however the tastes used in these studies (berry-flavored beverage, blue cheese) were real and not simulated.

How multisensory stimuli, in particular visuals, audio, smell and motion, may affect a real experience (singularly or in combination) has been studied extensively, e.g.[15], including their impact on flavor perception, e.g.[1,4]. Traditionally people try the flavor of a product by consuming a small sample of it, e.g. in a supermarket. If such a sample is not available, then the consumer has no way of knowing what it tastes like before purchase. Companies use tasting panels to better understand how people might react to the flavor of their products. Tasting panels can be expensive ($20,000 a time) and generate a lot data that needs to be properly analyzed[16]. Furthermore, human struggle to precisely describe flavor and their results are very subjective[3]. Scientific instruments, such as electronic-noses (e-noses) and e-tongues can be used to obtain scientific representations of smell or taste, but they do not provide a holistic perception of how a human may appreciate a flavor. More recently Artificial Intelligence and Big Data has been used to analyze data collected from large numbers of flavor choices in order to better predict whether a new flavor may be liked or not, e.g. FlavorWiki. The accuracy of such predictions, however, depends on subjective flavor-preferences that have previously been captured.

THE DEVICE

Two versions of the *FlavoSim* device have been created: a 6-cartridge prototype, Figure 1, which has informed the design of an 18-cartridge system for delivering high-fidelity virtual flavors in a paper cup. A smaller 6 cartridge system for use with a head mounted display (HMD) is under development. The HMD version will include a soft "mouth-guard-like" device in the mouth for delivering taste and retronasal smell, and a small tube just in front of the user's nose for delivering orthonasal smell. The mouth device can be washed and reused.

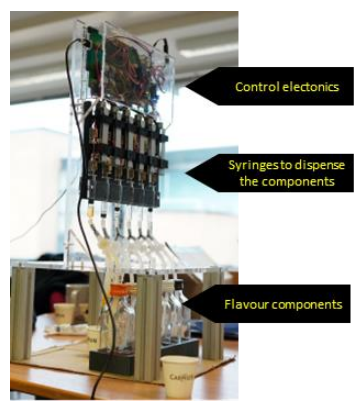

FIGURE 1. FlavoSim 6-cartridge prototype

The 18-cartridge high-fidelity system comprises:

- Nine cartridges containing UK Food Standards Agency approved food-safe chemicals: basic tastes (sweet, sour, bitter1 & bitter2 (the human tongue is particularly sensitive to bitter), salty, umami), and mouthfeel (oiliness, astringency, capsaicin). The food-safe ingredients are mixed at the right precision together with distilled water before being delivered to the paper cup.
- A collection of six aroma cartridges capable of delivering appropriate food-safe aromas for the type of flavor being considered. Note: Although the human nose can identify many thousands of smells, because of the presence of other modalities (taste, mouthfeel, temperature) in *FlavoSim*, it is only necessary to deliver a limited number of accurate key odorant markers (typically 6 or 9 depending on the aroma) for any flavor, in order for the user to perceive the "right smell"[17].
- Three cartridges for providing an appropriate color for the virtual samples.
- A device for heating or cooling the virtual flavor to warm or slightly chilled.

The device is controlled digitally via USB or Bluetooth with a computer or mobile device. Users can increase or decrease the strength of individual virtual flavor components in a controlled manner, e.g. to make the flavor sweeter, or smell more of vanila, less astringent, etc. When combined with a HMD, visuals (e.g. color of sample, environment where product is being enjoyed, etc.) and audio (e.g. sound of environment, crunch of the bite (as heard inside your head), etc.) are delivered via the HMD's screen and headphones.

METHOD

This section presents the methodological aspects of the two experiments that were undertaken. The experiments involve participants trying real and virtual flavor samples. The objectives are two-fold: (a) to determine how accurately real flavors could be simulated and (b) because the virtual flavor is a simulation, to study whether it could be used to take a participant on a "journey" through flavor-space from a "starting flavor" to a new "preferred flavor".

Experiment 1

Experiment 1 investigates three hypotheses:

- Hypothesis 1: Individuals are able to differentiate between similar flavors
- Hypothesis 2: Individuals are able to identify two exactly the same flavors
- Hypothesis 3: Individuals will not be able to differentiate between real and virtual samples

Design

The overarching objective of the experiment was to ascertain how well a real flavor experience could be simulated with a limited number of flavor components. An orange juice (fresh - not from concentrate) and three different blends of rooibos tea (Original, Focus, Creamy-Vanilla) were analyzed. Rooibos tea is made from the drying and fermenting the branches of the Aspalathus Linearis plant which only grows in the arid north west of South Africa. This tea has been drunk for thousands of years by the indigenous people of Southern Africa. It is a rich source of dietary antioxidants and has been medically proven to help prevent a range of diseases including type-2 diabetes[18]. Focus is a blend of rooibos which includes Masala Chai spices (cinnamon, ginger, cardamom, cloves, black pepper) and Turmeric, while the Creamy-Vanilla blend includes vanilla.

In this within-participants experiment, participants were given two samples at a time in a biodegradable paper cup. The participants were asked to rank on a 1-5 Likert scale how similar the two samples were (where 1 is not at all similar, and 5 is extremely similar). Two versions of the virtual orange juice were prepared, one with 6 flavor components (V6F) and one with 10 flavor components (V10F). Table 1 shows the IV combinations of the different types of orange juice and rooibos tea.

TABLE 1. Combinations used in Experiment 1

Orange Juice		Rooibos Tea	
Real & Real	R-R	Real Focus – Real Focus	RF-RF
Real & 6-component Virtual	R-V6F	Real Focus – Virtual Focus	RF-VF
Real & 10-component Virtual	R-V10F	Virtual Focus-Virtual Focus	VF-VF
6-component & 10-component Virtual	V6F-V10F	Real Original – Virtual Original	RO-VO
6-component & 6-component Virtual	V6F-V6F	Real Vanilla – Virtual Vanilla	RV-VV
10-component & 10-component Virtual	V10F-V10F		

A within-subjects experimental design was employed. The experiment was completed in two parts. In the first part, the IV was a combination of different types of orange juice with 6 levels (R-R, R-V6F, R-V10F, V6F-V10F, V6F-V6F and V10F-V10F), as described in Table

1. Participants in each trial were asked to report similarity ratings using a Likert scale. The second part utilized the same approach but used different combinations of rooibos tea with an IV with 5 levels (RF-RF, RF-VF, VF-VF, RO-VO and RV-VV). The order of the samples was counterbalanced to avoid any order effect.

Participants

Twenty-eight participants were recruited using the opportunity sampling technique from University of Warwick staff and students. 51.7% participants were between 18 and 25 years old, 10.7% were in the 26-30, 17.8% in the 31-40, 21.5% were 41 and older. None had previous experience of virtual flavors.

Materials

Real samples of the orange juice and the 3 blends of rooibos tea were analyzed to extract the quantities of the individual flavor components. These were then simulated with UK Food Standards Agency approved food-safe chemicals.

Table 2 shows the 6 components for V6F and the extra for V10F of virtual orange juice in a 20ml sample. The common base comprised: Gum Arabic (12%), salt (0.9%), mouthfeel (malic acid 1.0%, citric acid 0.8%, tannic acid 0.01%), orange coloring. The orange juice was served slightly chilled at 16°C. A cooking thermometer was used to control the temperature of the samples.

TABLE 2. Components in ml for virtual orange juice in 20ml sample

Virtual orange juice	V6F	V10F
Base	2	1.75
Sucrose	2.1	1.83
MSG	1	0.87
Limolene	1.2	1.05
ethylbutyrate	1.4	1.22
hexanal and ethyloctanoate	0.8	0.70
alpha pinene		0.87
Beta myrcene		1.05
Beta phellandrene		0.11
Octanol		0.52
Water	11.5	10.03

Table 3 shows the differences between the virtual rooibos tea samples for the Original, Focus and Vanilla blends. The common rooibos base comprised: Hexanal (5.5ml/l), Linalool (1ml/l), beta-Damascenone (17.25 ml/l), Guaiacol (7.25ml/l). The rooibos samples were heated with a microwave to 30°C. As with the orange juice, a cooking thermometer was used to control the temperature. Note: The temperatures were used to "match participant expectations"; an orange juice is expected to be cool, while a tea is expected to be warm.

TABLE 3. Components in ml for virtual rooibos teas in 20ml sample

Rooibos tea	Original	Focus	Creamy Vanilla
Rooibos base	0.36	0.36	0.36
Salt	0.62	0.62	0.5
Iso alpha acid	0.24	0.24	0.23
Tannic acid	0.48	0.42	0.42
Black food color	0.07	0.04	0.07
Red allura	0.73	0.43	0.73
Yellow Quinoline	0.16	0.09	0.16
Vanillin	0	0	2
Eugenol	0	0.05	0
Cinnamaldehyde	0	0.8	0
Water	17.34	16.95	15.53

Procedure

Ethical approval was obtained from the University of Warwick Biomedical and Scientific Research Committee for both experiments. Participation in the study was voluntary, anonymous, and participants were informed that they could withdraw at any time with no explanation required. Before participation, individuals were provided with an informed consent form to read through and were given a chance to ask questions prior to the study. The informed consent form included background information to the study, procedure instructions, the approximate duration of the study, and consent statements. Then, after they agree to take part in the study, participants were asked to complete a short demographic questionnaire. They were also asked about any allergies before conducting the experiment. Anyone with any history of any allergy or atopic disease (food or medicine allergy, eczema, hay fever, etc.) or any family history of severe atopic disease were excluded. The list of UK Food Standards Agency approved food-safe chemical for each flavor component was presented to participants. In accordance with Health & Safety regulations, the research team also notified first aiders located at the University of Warwick that the experiment was being undertaken and that human participants would be consuming samples.

During the experiment, participants were asked to wait in the experiment area, whilst samples were prepared in a separate room. Samples were prepared in 4oz paper cups and were filled around ¼ of the cup. A microwave and cooking thermometer was used to maintain the same temperature of pairs of rooibos tea samples around 30ºC, whilst the orange juice samples were served at 16ºC. After participants received the first pair of samples, they were asked to sip it without looking directly at the sample and focus on the provided picture of orange juice or rooibos tea instead to avoid any bias. After that, they were instructed to score the similarity between the two samples on a scale from 1 to 5 (1 is not at all similar and 5 is extremely similar). They were also asked to provide any additional comments on the perceived difference between the two samples by referring to samples as A and B, which were written on the bottom of each cup. Between every trial, participants were asked to drink some water and eat a cracker to clear their palette to possibly avoid any carry-over effect. One member of the research team was always present with participants in case of an unexpected allergic reaction. After successful experiment completion, participants were given a debriefing form with the lead researcher's contact details.

Results

A total of 28 (23 male, 5 female) individuals participated. The mean self-rated ability to differentiate flavors was 3.46 (SD=.64), where 1 was described as very poor and 5 is very strong. Regarding food tasting abilities, the majority (78.6%) indicated having no previous food tasting experience.

Similarity ratings were measured using a Likert scale described in the methods section. It is worth noting that although similarity rating was an ordinary variable, the repeated-measures analysis of variance was identified as a suitable statistical analysis in this case. According to Norman [19], it is an appropriate approach to use this type of analysis using a Likert scale with "symmetrical" answers with the justification that in practice the distance between the points is arguably equivalent, thus could be treated as interval data.

Figure 2 shows the results for the orange juice samples differentiation. The orange juice samples combination types (R-R, R-V6F, R-V10F, V6F-V10F, V6F-V6F and V10F-V10F) data was analyzed using repeated-measured analysis of variance. Since the assumption of sphericity was violated due to the Mauchly's Test being significant, χ 2 (14)= 41.64, p<.001 degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity (ε=.64). There was a statistical difference between the samples, F(3.21, 83.55)=16.94, p<.001. The pairwise comparison further showed that the difference was specifically between both real-virtual samples combinations and control combinations (R-R and V6F-V6F, but not V10F-V10F for R-V6F). Moreover, there was also a significant difference between R-V10F and V6F-V10F. The difference between V6F-V10F and control combinations (R-R, V6F-V6F) was significant as well. These findings are interpreted further in the discussion section.

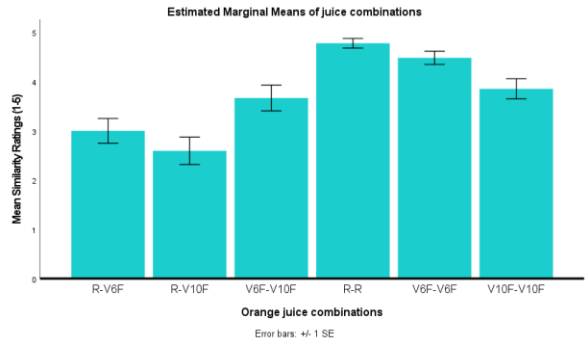

FIGURE 2. Mean similarity ratings for different orange juice combinations

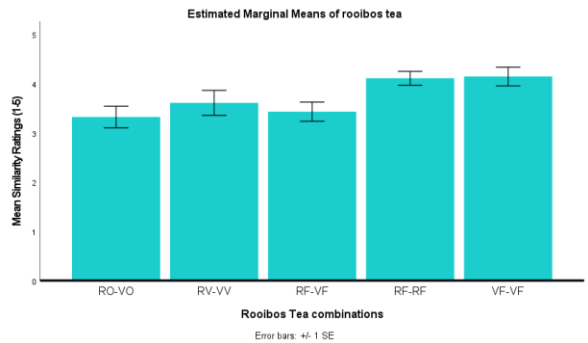

FIGURE 3. Mean similarity ratings for different rooibos tea combinations

Figure 3 shows the results for the different rooibos tea samples considered. Similarly to the orange juice, repeated-measured ANOVA was used to analyze the results for rooibos tea. As the sphericity assumption was not violated, the findings reported a significant difference between the means F(4, 108)=4.75, p=.001. Further posthoc analysis showed that a significant difference occurred between RF-VF and RF-RF as well as RF-VF and VF-VF. According to the outcome, RF-RF similarity scores were also significantly different from RO-VO but not RV-VV.

EXPERIMENT 2

Experiment 2 was a pilot study which investigated one hypothesis:

- ➔ Hypothesis 4: Individuals can be taken on a flavor journey from one flavor to a preferred new flavor

Design

The goal of Experiment 2 was to take participants on a guided journey from a start flavor to a new flavor which they preferred. This preference was subsequently confirmed in a "blind test" with the start flavor.

Participants

A total of 6 (3 male, 3 female) participants took part in the study. 66.7% of the participants were between the ages of 18 and 25, one person was between 31-35 and one between 41-45 years old. The mean self-rated ability to differentiate flavors on the scale from 1 to 5 was 3.67 (SD=.816). In addition, the majority (83.3%) reported having food tasting experience.

Materials

The study was conducted using the UK Food Standards Agency approved food-safe chemicals and the virtual flavor device, Figure 1, to create samples. Table 4 shows the composition of the virtual flavor.

TABLE 4. Composition in ml of start flavor and first three samples when manipulating sweetness

Virtual orange juice	Start	Sample A	Sample B	Sample C
Base	2	2	2	2
Sucrose	2	1	2	3
MSG	2	2	2	2
Limolene	2	2	2	2
Water	12	13	12	11

Procedure

Three components, namely, sucrose, MSG and limonene were manipulated to take participants on the flavor journey. Participants were first presented with the start flavor, Table 4, and then three identical-looking samples. The first set of these contained the same composition as the start flavor, but with the component being manipulated with -1ml (Sample A), 0 (Sample B), +1ml (Sample C) of that component, shown for sucrose in Table 4.

During each step, participants were asked to taste all three samples and arrange them in the order from the least liked to the most liked and provide a pleasantness and confidence rating. The labels were on the bottom of the cup and thus not known to the participants.

If a participant's preferred sample was either A or C they then moved to the second step of the journey. The participant was again presented with three samples with the component further changed by -1ml, 0, +1ml from the amount in their previous chosen top preference. The amount of the manipulated component would thus be:

If Sample A chosen: 0ml, 1ml, 2ml

If Sample C chosen: 2ml, 3ml, 4ml

The participants were again asked to taste all three samples and arrange them in the order from the least liked to the most liked and provide a pleasantness and confidence rating.

Finally, each participant was randomly presented with the start sample and their final choice of preferred sample and asked to choose which one they preferred the most. Step 2 choices were selected for participants who completed step 2, and step 1 choices for those who only completed a single step.

The same procedure was undertaken for all three components being considered.

Results

Sucrose: During the first step for the sucrose component, 83.3% of participants identified sample C (3ml of sucrose) as their most preferred option, and 16.7% selected sample B (2ml of sucrose). Therefore, 83.3% of participants progressed to step 2 of the experiment. Results showed that 80% of participants chose sample C2 as the most preferred option with a 4ml of sucrose and 20% identifies a 3ml of sucrose as an ideal amount (sample B2). Overall, during step one of the experiment, 66.7% selected source as their preference over the outcome with a mean confidence rating of 4.0 (SD=1.6); in step 2, 80% preferred outcome over source with a confidence rating of 4.4 (SD=0.6).

MSG: During the first step for the MSG component, 66.7% of participants selected sample B (2ml of MSG) as their most preferred option, 16.7% selected sample A (1ml of MSG) and 16.7% selected sample C (3ml of MSG). Only two participants (33.3%) progressed to step 2. Both of these participants identified sample A as the most preferred option with 0ml of MSG. Regarding the preference for either source or outcome sample, 50% preferred outcome in step 1 and in step 2 both of the participants identified the source as having a more pleasant flavor. Confidence ratings for step 1 and step 2 were 3.7 (SD=1.4) and 4.5 (SD=.7), respectively.

Limonene: During the first step for the limonene component, 66.7% of participants identified sample B (2ml of limonene) and 33.3% identified sample A (1ml of limonene) as their preference. In step 2 of the

experiment, only 33% participated. One recognized sample A (0ml limonene) and another chose sample B (1ml limonene) as their preferred flavor. In step 1, 66.7% selected the outcome and 33.3% selected source based on flavor pleasantness with a mean confidence rating of 3.8 (SD=1.0). In step 2, both participants selected the outcome with confidence rating of 4.0 (SD=0).

In the final part of the experiment, 83.3% of participants identified the outcome sample with all three components manipulated, as the most pleasant one. The overall mean confidence rating was 4.1 (SD=.5).

DISCUSSION

Experiment 1 showed that participants could sometimes distinguish between real and virtual samples, but not all the time. This ability to tell the difference was more apparent with orange juice than rooibos tea. It is interesting to note that people also struggled to distinguish between two identical flavors, for example, for two samples of real Focus rooibos, the mean was 3.61 and SD=1.34 and between the two identical samples of virtual Focus rooibos, the mean was 4.14 and SD=1.01.

We had hypothesized that creating a virtual flavor with more components would bring the resultant virtual flavor closer to the real flavor. This has proved not to be the case as the difference between R-R and R-VF10 was statistically significantly different, whereas there was no statistically significant difference between R-R and R-VF6. Interestingly there was also a statistically significant difference between V6F-V10F and V6F-V6F. In this case the additional components (alpha pinene, Beta myrcene, Beta phellandrene, Octanol) were all linked to the aroma of the flavor, however, as can be seen in Table 2, the amounts of some of the taste components were altered when these additional components were included. This suggests that just including a limited number of additional aroma components is not enough to bring the virtual flavor closer to the real one. Aroma and taste components of a flavor are closely linked, and thus care should be taken when adding additional components to ensure this balance is not altered. Future work will investigate this threshold for the appropriate number of aroma components to include in a virtual flavor. We will also investigate how the addition of other senses, such as visuals and audio in the HMD version of *FlavoSim* might affect this perception.

The closest match in perceived flavor was vanilla rooibos tea (RV-VV), mean of 3.61 SD=1.34. This compares well with RV-RV mean 4.11 SD=.74.

The flavor discovery experiment, experiment 2, showed that it is possible to move from one flavor to another in flavor space with the device. Because it is a simulation, it is possible to both add and remove flavor components, e.g. you can make the sample less sweet or less savory by removing some sucrose or MSG. This is not possible with a real flavor; the best you can do is to try "mask" one taste by adding another. Once the preferred flavor has been identified it will be up to the flavor scientist and producers of the products to alter their manufacturing or blending process to produce the real flavor that matches the preferred virtual flavor. Confirming the match can simply be done by analyzing the new real flavor and comparing the results with the component values for the preferred virtual flavor.

Limitations

A pilot study showed that participants expected orange juice to be slightly chilled and a tea to be at least warm. This was behind the decision to serve the orange juice at 16ºC and the rooibos tea at 30ºC. Although a thermometer was used to try and ensure the temperature of any two samples were the same, this thermometer was not accurate and any difference in temperature could have influenced participants when comparing the similarity between samples.

Furthermore, care was taken to get the color of the real and virtual samples to match. The match was not perfect though, especially for the orange juice, which again may have influenced participants.

Finally, the low number of female participants in Experiment 1 is an issue we will address in the future.

CONCLUSION

Enjoying a meal or drink together is an important part of human interaction. Virtual flavor can add such an ability to a virtual world. This paper has shown that it is possible to analyze real flavors, extract their flavor components (taste, aroma, mouth feel) and then recreate, with good precision using a virtual flavor device, these real flavor experiences with simulations using food-safe chemicals for the different flavor components. This should enable people in remote locations, if they each have a device, to all experience the same flavor of a food or beverage in the virtual world at the same time.

Furthermore, the device enables the virtual flavor to be manipulated in real-time, taking the users on a "flavor journey" through flavor space. In a virtual world, this could even allow one user to recommend changes to another's food or drink, e.g. to add a "dash" of lemon to the sauce. We are currently working on a virtual world application where a clinician can get a remote patient to try different flavors. The clinician is able to manipulate

the intensities of the components on his/her computer and then the new flavor is delivered immediately to the remote patient via *FlavoSim.* This is an important healthcare application, as failure to distinguish between certain intensities of flavors could be a sign of a neurodegenerative condition, such as or long-COVID[21].

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