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Development and Testing of a Small-Size Olfactometer for the Perception of Food and Beverages in Humans

Paola Risso [1]*, *Mario Covarrubias Rodriguez* [2], *Monica Bordegoni* [2] *and Alberto Gallace* [1]

[1] *Department of Psychology, Milan Center for Neuroscience, University of Milano-Bicocca, Milan, Italy,* [2] *Department of Mechanical Engineering, Politecnico di Milano, Milan, Italy*

Studies of olfactory perception and about the way humans interact with, and perceive food and beverages require appropriate olfactory devices. Moreover, small size, and portable interfaces are needed within the context of Human Computer Interaction (HCI), to enrich and complete the design of different mediated experiences. In this paper, the authors tested a new portable olfactory device for the orthonasal administration of smells. The main aim was to verify if the experience generated by the odors delivered through such device can affect people's taste perception. Once established that people could perceive odors using the olfactory device, a group of participants was asked to taste two different types of food (Experiment 1) and three types of beverages (Experiment 2) and to evaluate them on a number of perceptual-dimensions (such as pleasantness, freshness, sweetness, saltiness, and bitterness). The participants could taste the food and the beverage without the presence of additional olfactory stimuli, or under conditions where olfactory stimuli (the smell of chocolate or citrus) were also presented using the device. The results showed that the participants' evaluation of food and beverages was significantly modulated by the concurrently presented odors. The experimental results suggest that: (1) the device is effective in controlling the delivery of odors to human participants without the complexity of management that often affect larger odors delivery systems; (2) odors administered by means of such device can have an effects on food and beverage perception, without the need to change their chemical properties.

Keywords: olfaction, taste, human machine interfaces, multisensory interaction, cognitive neuroscience, gustatory perception

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***Correspondence:**
Paola Risso
p.risso@campus.unimib.it

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INTRODUCTION

In Human-Computer Interaction (HCI), olfaction is rarely included as interaction modality. This is, at least in part, because: (1) most of the available devices for odor presentation are extremely costly, cumbersome and not easily manageable by non-expert technicians; (2) scientific knowledge of olfactory perception is less developed as compared to other sensory modalities. The implementation of devices able to simulate a real flavor experience by means of trigeminal and tactile taste stimulation has proven to be a difficult task. Technical difficulties associated with the digitization of flavors and odors have likely contributed to the reduced commercial success of the devices that have been developed so far for this purpose (see Spence et al., 2017, for a detailed review). As consequence, it is still hard nowadays to effectively use smell by means of an olfactometer device, especially under conditions of multisensory stimulus presentation (Sanders and McCormick, 1993; see Barfield and Danas, 1995; Nakaizumi et al., 2006; Nakamoto, 2012). In this work, we propose and test a new and innovative olfactory display able to present multiple odors to human participants.

A brief review follows on the state of the art of olfactory devices. In particular, the focus of the review will be on the description of the most recent miniaturized and portable olfactory devices.

State of the Art of Portable Olfactory Devices

Generally, the term "olfactometer" is used to describe complex devices, mainly used in a laboratory setting in a standardized computer-controlled manner with determined air flow, odor concentration, odor duration, onset, and offset (Al Aïn and Frasnelli, 2017). Such devices are often custom-built prototypes, although a few commercial versions do exist. Usually, these devices are very expensive and exceed the financial budget available for the largest part of research laboratories. Moreover, because of their technical characteristics, the majority of these olfactometers are cumbersome, not practical to handle and often not easily transportable or wearable.

Recently, a series of olfactory devices designed for administering odors in less controlled and more ecological situations have been developed (see **Table 1**). For example, jewelry or parts of clothing controlled by smartphones and pc accessories can now be used for odor delivery purposes. However, all these different approaches to olfactory stimulation have to face the challenge of using invisible, extremely volatile, and persistent stimuli. Moreover, they require a sophisticated miniaturization system to adequately spread the smells in the environment.

In those cases where the olfactory devices have been miniaturized, their potential use has been rather limited. For example, Nakaizumi et al. (2006) developed a device that makes use of two air cannons to project rings of odors directly to the nose of the participants. The authors implemented four prototypes of the device and the last, presented at the SIGGRAPH'2005, is capable of launching four different odorants. However, the size of the two cannons was not specified in the original reports. Nevertheless, despite of its high level of technological implementation, such device is certainly not easily transportable, at least in its current form (also note that precise distances and positions from the cannons are needed for the device to deliver the smell correctly). By contrast, an example of a small wearable and transportable device is the Essence necklace, designed to control odor intensity, and frequency of release through a smartphone (Amores and Maes, 2017). The scent delivery is controlled by an encapsulated piezoelectric transducer, which vibrates by emitting ultrasounds. Such transducer is immersed in the odorant liquid contained in a 3D printed cover, hang on the participant's neck. The ultrasonic sounds transform the scented liquid into vapor-like particles, which immediately are distributed around the necklace. The 3D print cover can contain 7 ml of an essence, sufficient to provide 27–28 h of continuous odor volatilization. Despite of its small size, it is important to note that this prototype allows delivering only one essence at a time, limiting its field of use to a very few situations (and without considering the problem of perceptual and neural adaptation to the same odor by humans).

A portable device that allows the delivery up to six scents through the digital integration of odors is Aroma Shooter (Aromajoin Corporation, Kyoto). Such a device delivers essences up to a distance of 600 mm by using a gas ejection method that allows the control of the directional air flow. The system uses a series of scented cartridges, which can be automatically changed at intervals of 1 s and can be remotely controlled by computers and mobile devices. Also, a wearable version of the same device, with the approximate size of a small pendant (the Aroma Shooter Mini), has been developed to deliver only one essence at a time.

A small olfactory device designed, once again, in the form of a piece of jewelery is the Mist Shine, produced by Indiegogo (Indiegogo). Mist Shine is a perfume spray bottle, which can be worn by the user. Such a device allows the liquid odorant to be transformed into a micron mist using an ultrasonic unit and be delivered by simply pressing a bottom. A version of this apparatus can be connected to the mobile devices through Bluetooth technology.

The largest part of the above mentioned olfactory devices are conceived as a part of a new trend in clothing, smartphone, and pc accessories and targeted to a wide range of fashion consumers. In the same vein, the Scentsory Design® & Technology Ltd., (Scentsory Design) designed the 'Aroma Rainbow Sensitive Dress'. The idea of this conceptual dress was born from a multi-disciplinary research project, with the aim of exploring the *emotional fashion* through the release of odorous molecules. In practice, several colored tubes corresponding to different scents are embedded in the dress. The odors are delivered to the user and to the environment using nanotechnology-based release systems. The tubes are activated by touch screen monitors according to their different color labels.

An extreme application of the odor delivery devices is the Swallowable Parfum® by Lucy McRae (Swallowable Parfum). In this case, the olfactory device is a digestible scented capsule that after the ingestion allows the body skin to emanate a unique fragrance. The odor is excreted by the skin in the form of droplets, which emanate a fragrance determined by the enzymes that metabolize fat in the human body. In this case, no change of the delivered odors would seem to be possible after the ingestion of the capsule. However, this new technology is based on chemical rather than electromechanical mechanisms.

Some years ago, another interesting transportable/wearable olfactory device was developed by Yamada et al. (2006). The aim of the authors was at enabling a person to identify the placement of an odor source in a virtual environment by changing its strength. Their device includes: (1) an Odor Presenting Unit worn by the user; (2) a backpack containing the odor generator unit that is used to modulate the strength of the essences

TABLE 1 | Key features of the reviewed devices.

Device name	Year	Producer/Researchers that implemented the device	Method of odors delivery	Number of odors administered	Webpage
Multiple Scent Projectors	2006	Nakaizumi and colleagues	two air cannons that project odors rings	4	—
Essence Necklace	2017	Amores and Maes	encapsulated piezoelectric transducer which vibrates by emitting ultrasounds	1	—
Aroma Shooter	—	Japan's National Institute of Information and Communications Technology (NICT).	gas ejection method that allows the control of the directional air flow	6	https://aromajoin.com/en/hardware/shooters/aroma-shooter-mini-1
Mist Shine	—	Indiegogo	micro mist delivered by means of an ultrasonic unit	1	https://www.indiegogo.com/projects/mist-shine-wearable-smart-scent#/
Aroma Rainbow Sensitive Dress	2006	Scentsory Design®	nanotechnology-based release systems	unknown	http://www.escent.ai/smartsecondskin https://link.springer.com/content/pdf/10.1007/978-3-540-79486-8_32.pdf
Swallowable Parfum®	—	Lucy McRae	digestible scented capsule that after the ingestion allows the body skin to emanate a unique fragrance	1	https://www.lucymcrae.net/swallowable-parfum/
Wearable Olfactory Display	2006	Yamada and colleagues	piezotype inkjet head device	3	—

according to the position of the carrier, (3) a neckband connected with a tube to the odor generator unit that conveys the essence to the user's nose, (4) a little bag attached to the waist containing the system to detect the position of the carrier by means a tag reader, (5) a breath detecting sensor to ensure that odors are administered to the user during the breath inhalation phase. All the wearable components have been miniaturized to give the minimum clutter and annoyance to the wearer. In particular, the Odor Presenting Unit carries smells to the nose using a piezo-type inkjet head device. The piezo element component applies a pressure pulse to the tubule filled with the odorant liquid that directly reaches the nose in the form of droplets. The response time of the inkjet head device is 300 μs. Moreover, the wearable device is monitored by an Odor-Controlling Unit composed by a microcomputer that controls the air pump and a notebook PC that calculates the strength of odor presentation according to the data sent by the user's positioning system. Besides its very high technological level and the miniaturizations of its components, this olfactory device allows only a limited series of odors to be presented and still produces some degree of clutter for the wearer.

As recently pointed out by a number of authors (Obrist et al., 2016; Spence et al., 2017), in order to obtain good results in chemosensory digitization, it is necessary to take into account both technical and psychological limitations of an olfactory display. Moreover, the effectiveness of these devices should depend on the similarity of the human responses to the stimuli elicited by the device, concerning those occurring under natural emissions of odors (e.g., see the Smell Synthesizer of the Museum of Food and Drink's MOFAD Lab; Berenstein, 2015). That would seem to suggest that novel olfactory devices will need to be tested also using perceptual and neuroscientific experiments and paradigms.

Olfactory Crossmodal Integration

In the last decades, psychological and neuroscientific research has shown that the different features of a product, such as its color, shape, odor, taste, tactile feel, sound and so on, are rarely processed in isolation by our neural system. Some interactions occur among them, and human's final perception is much more than a mere sum of these characteristics (see Spence, 2011, 2017). This consideration also applies to food evaluation. In this context, the perception of taste should be considered a multisensory experience, rather than a unisensory experience (e.g., Spence et al., 2013). In fact, psychological and neuroscientific research has shown that visual, auditory, olfactory and tactile aspects of food (see Spence and Piqueras-Fiszman, 2014, for a recent review) can all modulate our gustatory perception. For example, Michel et al. (2014) reported that the participants in their experiment provided higher tastiness ratings when asked to taste a salad dish visually arranged in an artistic way (similar to a Kandinsky's paint), than when the same dish was presented without any artistic arrangement. As far as beverages are concerned, Zampini and Spence (2005) reported that participants' perception of carbonation intensity of sparkling mineral water is affected by an alteration of the frequency of the auditory feedback emitted by the liquid just before consumption. In particular, amplification of the higher frequencies emitted by the beverage when served, results in the participants reporting a higher intensity of carbonation while tasting the water.

Interestingly, several studies have also demonstrated that food perception is not only affected by the different sensory qualities of the food itself, but also by those of the context where food is presented. For example, the color of a container can affect the taste of food and beverage presented in it (e.g., Zampini and Spence, 2005; Krishna and Morrin, 2008; Piqueras-Fiszman et al., 2012; Spence and Wan, 2015; Biggs et al., 2016). In particular, Risso et al. (2015) recently reported that people perceive mineral water as more carbonated when contained in a red or blue plastic cup, than when contained in a white cup. Similarly, Stewart and Goss (2013) showed that different combinations of colors and shapes in a plate could significantly modify the sweetness, flavor intensity, quality, and enjoyment perception of the dessert served in them (see also Bruno et al., 2013). Even the weight of the container would seem to affect the perception of the beverage presented in it, where heavier cups make the participant perceive the mineral water less pleasant than when served in lighter cups (Maggioni et al., 2015).

As far as the crossmodal interaction between odors and food is concerned, it was demonstrated that an odor could also elicit a taste response in a tasteless solution, besides the expected olfactory response (Burdach et al., 1984). In a series of pioneering experiments, it was observed that strawberry odor enhanced the sweetness of a sucrose whipped cream, while peanut butter odor did not enhance such perception. Moreover, strawberry odor did not enhance the saltiness of sodium chloride. Interestingly, it was also shown that the color red, differently from the strawberry odor, did not modulate the perception of sweetness (Frank and Biram, 1988; Frank et al., 1989). It was also demonstrated that "cut grass smell" defined as a "green odor," enhanced bitterness perception (Caporale et al., 2004). Similarly, it was shown that the sardine aroma enhanced salt intensity in tasteless solutions or in low-salt content solutions (Nasri et al., 2012). That is, under natural conditions of stimulus presentations, certain odors can affect the perception of food and beverages. An effective olfactometer device should then lead to similar interactive effects.

Olfaction is certainly one of the most important sensory system used by humans to evaluate gustatory stimuli. In fact, it has been shown that our taste perception decreases when olfaction is not available (e.g., Murphy and Cain, 1980). By these observations, if one's aim is at modulating people's experience of food also under ecologically valid conditions of stimulus presentation, olfactory stimuli need to be presented effectively and in a highly controlled way. In particular, small-size transportable olfactory interfaces would allow us to present in a timely precise context specific odors, which might modulate people's food experiences and choices.

The Multi-Fragrance Olfactory Display (MFOD)

In this paper, a novel Multi-Fragrance Olfactory Display (MFOD), which is light, small and able to release multiple fragrances, was used for the presentation of odor stimuli in two behavioral experiments. The MFOD is a multi-odor dispenser consisting of small cases that release up to eight fragrances in a precisely controlled manner.

The MFOD is based on the SFR (Solid Fragrance Release) method for the generation and the release of fragrances. The SFR consists of delivering scents through the modulation of an airflow striking a tablet of solid fragrance. This method differs from that adopted in those devices where liquid or vaporous fragrances are delivered (which in turn are more "invasive" and permeating into the environment). Also, the use of solid particles delivered through airflow allows a more precise control of the flow.

The same principle can be used for the implementation of a wearable configuration and of a desktop configuration (Covarrubias et al., 2016). In this specific research, a desktop version of the MFOD was used (see **Figure 1**). It consists of an actuated dispenser able to store up to eight fragrances and to control timing, intensity, and duration of the fragrance release. The MFOD (see **Figure 1**) includes a centrifugal fan (1), which provides and controls the airflow, a servo-motor (2), a cylindrical repository (3), and eight small tubes including compact powder fragrances (4). The servo-assisted cylindrical repository is controlled through an Arduino board (arduino.cc), which is connected to the E-Prime tool (E-Prime). E-Prime is a software environment used for design, implementation, data collection, and analysis of computer-based behavioral experiments. In this work, it was used for the selection and delivery of the fragrances. Finally, a pipe (5) releases the selected odor to the user's nostrils.

The MFOD performs three main functions.

1. Airflow Generation– A 12 Volt Direct Current (DC) powered fan generates an airflow that is directed toward the fragrance repository.
2. Odor Selection– Small PVC tubes contain the fragrance compact powders. Each tube contains a specific fragrance, except one that is left empty and is used for cleaning functions. The tubes are connected to a rotating cylinder at 30° of angular steps (**Figure 1**). A servo motor, produced by Hitec RCD USA, is used to rotate the cylinder to the desired position and select the specific smell to deliver.

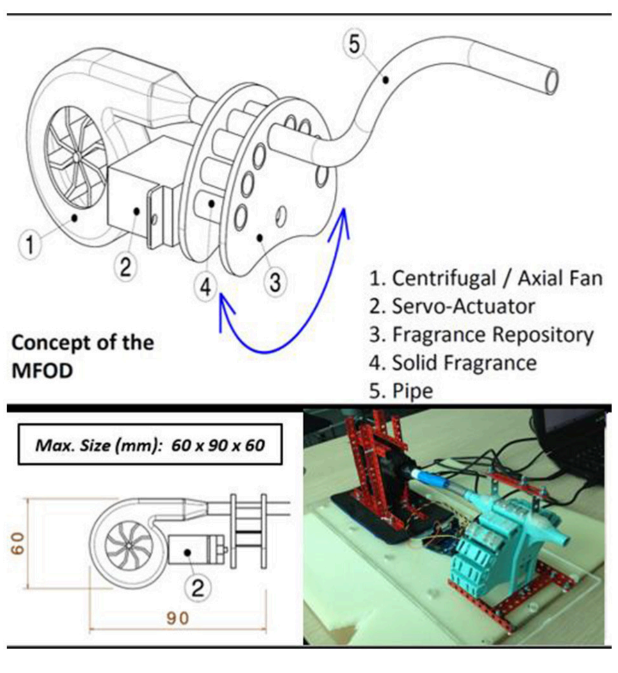

FIGURE 1 | The multi-fragrance olfactory display.

3. Odor Delivery– The airflow generated by the fan passes through the selected tube in the fragrance repository, and the odorous airflow, generated by an erosion process, goes through the flexible plastic pipe (600 mm length and 10 mm internal diameter) and is delivered close to the user's nose (about 3 cm from the pipe).

The fragrance intensity can be adjusted by modifying the airflow generated by the centrifugal fan. The latency from generation to the perception of a selected odor is <0.5 s. This time interval was calculated on the basis of a series of pre-tests performed by setting two characteristics of the device, i.e., the fan speed and the servo motor speed.

By using a small anemometer, which is a device for measuring the air speed with a fan, some measurements were taken at several points of the prototype when varying the input voltage of the DC fan from 5 to 20 Volt, as shown in **Figures 2**, **3**.

A further test was carried out to measure the time that the servo-motor takes to rotate the cylinder at specific angles. In particular, a rotation of 60° is performed in 0.16∼0.13 s. The configuration with 12 Volts was adopted to produce a perception of synchrony between the delivery of the fragrance and the presentation of the stimuli.

The device used in this study extends the functionalities of previous devices and reduces their limitations (i.e., technical complexity, use complexity, and size). In particular, the device can be used to deliver up to eight fragrances. Note, however, that its current design allows up to twenty odors to be easily delivered. Moreover, the olfactometer was designed to be easily interconnected with the software for behavioral research EPrime 2.0. Therefore, the device can be integrated into complex psychological and neurocognitive studies where a high level of

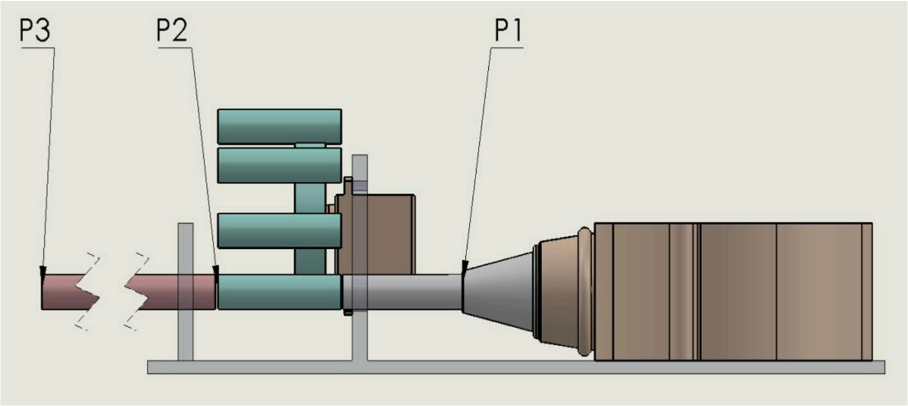

FIGURE 2 | Olfactory display with the reference points for fluid dynamic testing: P1, at the exit of the DC fan; P2, at the exit of the selector; and P3, at the exit of a delivery tube 600 mm long.

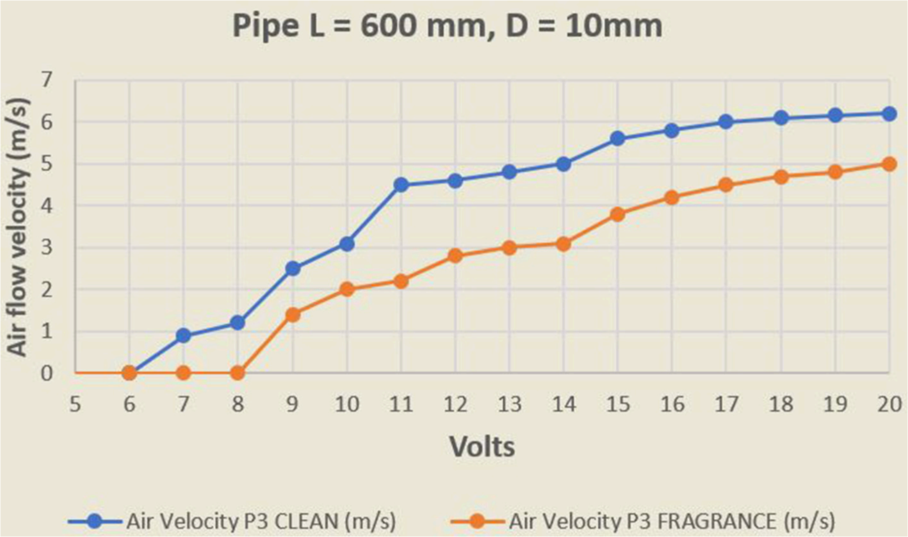

FIGURE 3 | Measurements taken at P3 with a tube 600 mm long and 10 mm diameter.

control on timing, randomization of conditions, reaction times of participants is required. Additionally, by means EPrime 2 the olfactometer can be interconnected to other scientific devices (i.e., eye tracker, skin conductance response recorders, etc.).

The device might be used in a large number of applied contexts. In fact, the prototype used in the present study has been designed to be adapted both in experimental contexts, and in less controlled and more ecological contexts. For example, it might be used to deliver odors in virtual reality environments, where it would help to enhance the sense of presence (Bordegoni and Carulli, 2016; Carulli et al., 2016). The device might also be adopted to improve the effect of exposure therapies in posttraumatic stress disorders patients (see a detailed review of Aiken and Berry, 2015 on this topic), to alleviate the effect of pain in a number of clinical conditions (Marchand and Arsenault, 2002) or to provide alerting cues to drivers (Ho and Spence, 2017). Given the large numbers of odors which can be presented with this new device, one additional application of our system is also to provide a valid alternative to the odor kits (manually administered), that are used at the moment for testing olfactory capability in different populations of participants (e.g., see the small bottles of the kit for sommelier's training 'Le Nez du vin®, Sniffin' Sticks, University Pennsylvania Smell Identification Test).

In this paper, the authors used the olfactory display in order to determine if the sensory experience generated by the device affects people's evaluation of some food and beverage characteristics (just as it occurs for odors naturally present in the environment). In particular, in the experiments presented here, the olfactory device was used to modulate people's perception of four different qualities of food (Experiment 1; pleasantness, sweetness, saltiness, and bitterness) and of beverages (Experiment 2; pleasantness, sweetness, saltiness, bitterness, and carbonation intensity).

The main aim of the present research was to investigate whether the device might be used to deliver odors under conditions of multisensory stimulus presentation and to generate perceptual multisensory interactions between the concurrently presented stimuli (food and odors). It is important to highlight that in the present experimental design, the crossmodal interaction among foods, beverages, and odors was tested by only using two odors (despite the possibility of administering up to eight odors). Adding more odor-food combinations could have affected negatively the participants' evaluations due to the multiple interactive effects likely occurring during the presentation of a large number of foods and odors in a reduced amount of time.

EXPERIMENT 1

The aim of the experiment is to test the effect on food perception of the orthonasal presentation of odors administered by means the new small-size olfactory device. In particular, Experiment 1 aims at verifying if the experience generated by the odors delivered through such device can affect people's taste perception of two different types of food on a number of hedonic and perceptual-dimensions (such as pleasantness, freshness, sweetness, saltiness and bitterness).

Materials and Methods

Participants

Twenty-two participants with a mean age of 24.5 years (*SD* = 6.84, 12 female), took part in the experiment. All the participants gave written informed consent before their participation. The experiments described here were all performed in accordance with the ethical standards laid down in the 2008 Declaration of Helsinki and approved by the local ethical committee. The experiment lasted for approximately 20–30 min. People who claimed to be affected by any permanent or temporary olfactory or taste dysfunction, were excluded from taking part in the study.

Stimuli

Two different types of food were used: salty crackers (Carrefour) and lemon sugar candies (Perugina). The stimuli have been selected in order to have opposite taste characteristics (salt and sweet), without changing their organoleptic quality during the experiment (such as fresh food). Common white plastic dishes (produced by Bibo Italy S.p.A. for Carrefour) were used to serve the food. The *two* odors administered were chocolate and a mixture of citrus fruit (Oikos Fragrances®). The odor selection was focused on finding *two* completely different and easily classifiable smells. A very important characteristic of the fragrances used is to be made up of scented powder. This important innovation adopted in our device does not require the dilution of fragrances, thus making the delivery of odors much easier under experimental procedures.

Procedures

Before starting the experiment, a short pre-test was performed in order to evaluate people's ability to perceive the odors by means of the experimental device. The study was conducted in an experimental booth with the participants sitting comfortably on a chair in front of a desk. The participants were instructed to grasp and eat the food presented on the desk at a signal of the experimenter, while at the same time they smelled an odor or clear air administered to both nostrils for about 15 s. The odor was administered by means of a small pipe connected to the olfactometer and held attached to the participants' nose, just between their nostrils (at about 3 cm). The method for releasing the odorant molecules, based on SFR-Solid Fragrance Release, ensured that the flow of odorant molecules effectively reached the participant's nostrils. This method, as compared to the volatilization of liquid compounds, results to be more effective in preventing the dispersion of part of the odor molecules in the surrounding environment. Given that the process that leads to olfactory perception of the airflows dynamics and allows peripheral processing of the signal, is extremely complex and delicate, the experimenter avoided inserting the pipe directly into the participant's nostrils. In fact, the insertion of the tube into the participants' nostrils could have prevented an effective perception of the odor presented. As a consequence of this presentation modality, some odorant molecules administered through the MFOD in our experiment may likely have reached people's mouth as well as the nostrils, and thus be also processed by retronasal route. However, it should be considered that this is the natural condition in which human perceive orthonasal olfactory stimulation in everyday situations.

The administration modality and timing of the stimuli in Experiment 1 were defined using some pre-tests. This procedure assured that all participants started to smell the odor before grasping the food and bring it to their mouth. Such a precaution was introduced to be sure that people chewed and swallowed the foods, while they were smelling the odor. The device was contained in a box that was hidden from the participant's view.

The participants were informed that after tasting the food they had to rate it along four dimensions (pleasantness, sweetness, saltiness, and bitterness) by means of a 150 mm long visual analog scale (VAS), anchored with the terms "not at all" and "very much." The VAS was presented at the center of a 17″ PC screen. The participants used the mouse to select the point on the scale that best represented their evaluation. Each food was presented three times for each olfactory condition, for a total of 18 (2 foods × 3 odors × 3 repetitions) samples of food to be evaluated by each participant. The presentation of the food and the odors were completely randomized.

Results

The mean participants' judgments along the VASs were submitted to a series of repeated measures ANOVAs for the hedonic dimension of Pleasantness, as well as for the dimensions of Sweetness, Saltiness and Bitterness (belonging to the so-called "basic tastes" of the flavor network; see Spence et al., 2014; Spence, 2016) with the within-subjects factors of Odor (chocolate vs. citrus), Repetition (evaluation 1, evaluation 2, evaluation 3) and Food (sugar candy vs. cracker).

On the dimension of Pleasantness, the analysis revealed significant main effect of Food [$F_{(1, 21)} = 7.26$; $p = 0.014$; $d = 0.26$]. The factor of Repetition [$F_{(2, 42)} = 0.70$; $p = 0.50$] and Odor [$F_{(2, 42)} = 0.35$; $p = 0.70$], as well as the interaction between Repetition and Odor [$F_{(4, 84)} = 0.22$; $p = 0.93$], Repetition and Food [$F_{(2, 42)} = 0.07$; $p = 0.94$], and Odor and Food [$F_{(2, 42)} = 0.76$; $p = 0.47$], and the interaction between Repetition, Odor and Food [$F_{(4, 84)} = 2.10$; $p = 0.089$] did not revealed any significant effect. A *post-hoc* test (Newman–Keuls corrected) on the main effect of Food showed that participants perceived crackers as more pleasant than candies ($p = 0.01$).

The data analysis on the dimension of Sweetness showed a significant main effect of Odor [$F_{(2, 42)} = 5.27$; $p = 0.01$; $d = 0.20$] and Food [$F_{(1, 21)} = 163.28$; $p < 0.0001$; $d = 0.87$], the interaction between Repetition and Odor [$F_{(4, 84)} = 3.10$; $p = 0.02$; $d = 0.13$] effect size and Repetition and Food [$F_{(2, 42)} = 4.27$; $p = 0.21$; $d = 0.17$]. The main effect of Repetition [$F_{(2,42)} = 0.58$; $p = 0.56$], as well as the interaction between Odor and Food [$F_{(2, 42)} = 0.93$; $p = 0.40$] and Repetition, Odor and Food [$F_{(4, 84)} = 0.23$; $p = 0.92$] did not revealed any significant effect. A Newman-Keuls *post-hoc* test on the dimension of Odor revealed that partecipants perceived both foods as sweeter when tasted together with chocolate odor, as compared to citrus odor ($p = 0.21$) and air ($p = 0.01$; **Figure 4**). A Newman-Keuls *post-hoc* test on the dimension of Food showed that participants, as expected evaluated candies as sweeter than crackers ($p = 0.0001$).

A Newman-Keuls *post-hoc* test on the interaction between Repetition and Odor showed that people perceived both foods as sweeter when tasted together with chocolate odor as compared to air ($p = 0.001$) and citrus odor ($p = 0.05$) during the third evaluation but not during the previous two (**Figure 5**). The comparison of the first and second evaluations did not show any significant effect. A Newman-Keuls *post-hoc* test on the interaction between Repetition and Food showed that participants perceived candies as sweeter during the third evaluation, as compared to the first evaluation ($p = 0.2$). No other significant differences were found.

On the dimension of Saltiness, the analysis revealed a significant main effect of the Food dimension [$F_{(1, 21)} = 237.37$; $p < 0.0001$; $d = 0.92$]. The effect of Repetition [$F_{(2, 42)} = 3.13$; $p = 0.13$], Odor [$F_{(2, 42)} = 0.92$; $p = 0.41$], as well as the interaction between Repetition and Odor [$F_{(4, 84)} = 0.16$; $p = 0.96$], Repetition and Food [$F_{(2, 42)} = 1.83$; $p = 0.17$], odor and Food [$F_{(2, 42)} = 0.37$; $p = 0.69$] and Repetition, Odor and Food [$F_{(4, 84)} = 0.13$; $p = 0.97$] did not show any significant effect. A Newman-Keuls *post-hoc* test on the Food dimension showed, as expected, that crackers were evaluated as more salty than candies ($p < 0.0001$).

The data analysis on the dimension of Bitterness, revealed a significant main effect of Food [$F_{(1, 21)} = 4.84$; $p = 0.04$; $d = 0.19$]. The dimension of Repetition [$F_{(2, 42)} = 1.44$; $p = 0.25$], Odor [$F_{(2, 42)} = 0.60$; $p = 0.55$], as well as the interaction between Repetition and Odor [$F_{(4, 84)} = 0.39$; $p = 0.82$], Repetition and Food [$F_{(2, 42)} = 1.85$; $p = 0.83$], Odor and Food [$F_{(2, 42)} = 1.33$; $p = 0.27$], and Repetition, Odor and Food [$F_{(4, 84)} = 0.54$; $p = 0.70$] did not showed any significant effect. A Newman-Keuls *post-hoc* test on the dimension of Food demonstrated, as expected that crackers were evaluated as more bitter than candies ($p < 0.04$).

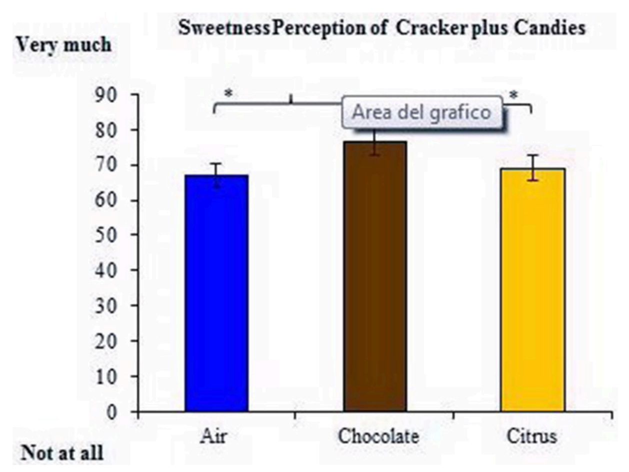

FIGURE 4 | The participants' mean judgments of sweetness for both foods tasted regardless of the evaluation sequence, as a function of the different odor conditions. Error bars represent the standard errors of the means. Asterisks represent Newman-Keuls significant differences at *$p < 0.01$.

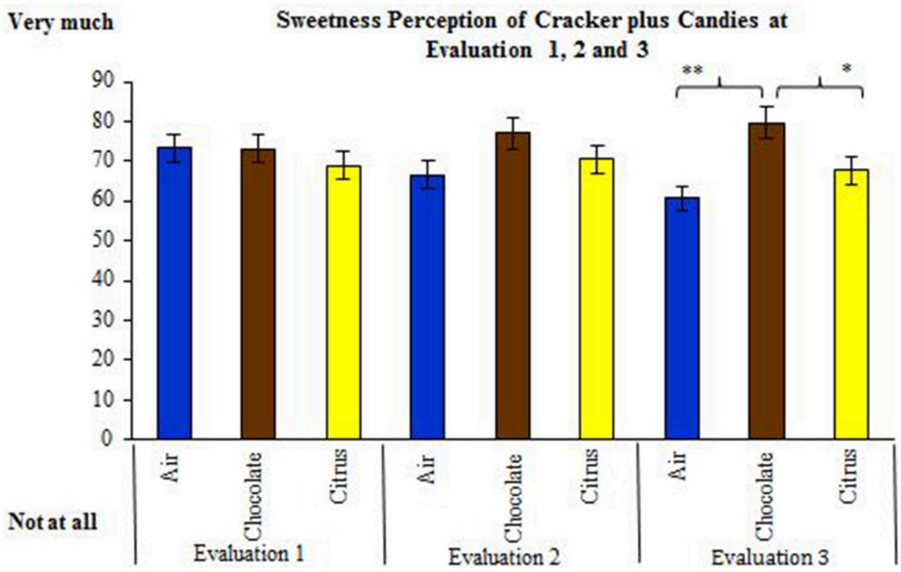

FIGURE 5 | The participants' mean judgments of sweetness for both foods tasted as a function of the different odor conditions and of the evaluation sequence. Error bars represent the standard errors of the means. Asterisks represent Newman-Keuls significant differences at *$p < 0.01$ and **$p < 0.001$.

EXPERIMENT 2

In summary, Experiment 1 revealed that that participants perceived both foods (crackers and candies), as sweeter when presented together with the chocolate odor, as compared to when presented with air or citrus odors. Based on that result, we proceeded with the second experiment to extend our investigation to liquid taste perception.

The aim of Experiment 2 was to test if the experience generated by the odors delivered through our olfactory device could affect people's taste perception of three different types of beverages on a number of hedonic and perceptual-dimensions (such as pleasantness, freshness, sweetness, saltiness, bitterness and carbonation intensity).

Materials and Methods

Participants

Twenty-seven participants with a mean age of 24.19 years ($SD = 3.53$, 21 female), took part in the Experiment. All the participants gave informed written consent prior to their participation. The Experiment described here were all performed in accordance with the ethical standards laid down in the 2008 Declaration of Helsinki and approved by the local ethical committee. The Experiment lasted for approximately 20–30 min. People who claimed to be affected by any permanent or temporary olfactory or taste dysfunction were excluded from taking part in the Experiment.

Stimuli

Three different types of beverages were used: sparkling mineral water, tonic water and Sprite®. Common transparent plastic cups were used to serve the liquids. The beverages were selected on the basis of the same rationale of Experiment 1 with the additional characteristic to be all three transparent (to avoid the color-related effect on taste perception). The two odors administered were the same of Experiment 1 (chocolate and a mixture of citrus fruit, manufactured by Oikos Fragrances®).

Procedures

Before the beginning of the experiment, a short pre-test was performed to evaluate people's ability to perceive the odors by means the experimental device. The study was conducted in an experimental booth. The participants sat comfortably on a chair in front of a desk. The participants were instructed to grasp the plastic cup and taste the beverage served in it at a signal of the experimenter, while at the same time they smelled an odor or clear air administered to both nostrils for about 6 s. The timing of Experiment 2 differed from that adopted in Experiment 1 (<9 s) given that the act of drinking a sip of a beverage is very fast, as compared to the act of taste a solid food. Therefore, if the experimenter had asked to the participants to hold the liquid in their mouth for a time that exceeded the normal act of tasting a beverage, the results could have been distorted. Specifically, following a number of pre-tests a time of 6 s was given to the participants to keep the liquid in their mouth. Longer intervals were in fact considered excessive (and lead to boredom) for the participants. The procedure of odor delivery was completely identical to that of Experiment 1, as well as the fact that the olfactometer was not visible to the participants. The participants were also informed that after tasting the liquid they had to rate it along five dimensions (pleasantness, sweetness, saltiness, bitterness and carbonation intensity) by means of a 150 mm long visual analog scale (VAS), anchored with the terms "not at all" and "very much." The VAS was presented at the center of a 17″ PC screen. The participants used the mouse to select the point on the scale that best represented their evaluation. Each liquid was presented three times for each olfactory condition, for a total of 27 (3 beverages × 3 odors × 3 repetitions) samples of liquid to be evaluated by each participant. The presentation of the beverages and the odors was completely randomized.

Results

The mean participants' judgments along the VASs were submitted to a series of repeated measures ANOVA with the within-subjects factors of Odor (chocolate vs. citrus), Repetition (evaluation 1, evaluation 2, evaluation 3) and Beverage (Sparkling Water, Tonic Water, Sprite®) for the hedonic dimension of Pleasantness, as well as for the dimensions of Sweetness, Saltiness, Bitterness and Carbonation Intensity. The results of the analysis on the dimension of Pleasantness revealed a significant effect of Beverage [$F_{(2, 52)} = 16{,}06$; $p < 0.0001$; $d = 0.38$] and Repetition [$F_{(2, 52)} = 6.16$; $p = 0.00$; $d = 0.19$]. The main effect of Odor [$F_{(2, 52)} = 0.32$; $p = 0.73$], as well as the interaction between Odor and Beverage [$F_{(4, 104)} = 0.91$, $p = 0.46$] the interaction between Odor and Repetition [$F_{(4, 104)} = 0.65$; $p = 0.63$], the interaction between Beverage and Repetition [$F_{(4, 104)} = 0.58$, $p = 0.68$] and the interaction between Repetition, Odor and Beverage [$F_{(8,208)} = 1.58$, $p = 0.13$] did not result to be significant. That is, the odors presented did not modulate the participants' perception of pleasantness. A Newman–Keuls corrected *post-hoc* test on the main effect of Beverage revealed that participants evaluated Sprite® as more pleasant, as compared to Tonic Water ($p < 0.000$) and sparkling mineral water ($p < 0.000$). A Newman–Keuls *post-hoc* test on the main effect of Repetition showed that people regardless of the odors administered found all beverages as more pleasant during the first evaluation, as compared to the second evaluation.

The analysis on the dimension of Sweetness revealed a significant main effect of Odor [$F_{(2, 52)} = 3.99$; $P = 0.24$; $d = 0.13$], Beverage [$F_{(2, 52)} = 51.82$; $p < 0.000$; $d = 0.67$], and Repetition [$F_{(2, 52)} = 6.27$; $p < 0.01$; $d = 0.19$]. A *post-hoc* test (Newman–Keuls) on the main effect of the Odor showed that participants found all the beverages as sweeter when tasted simultaneously with the chocolate odor than when tasted together with the citrus odor ($p = 0.03$; **Figure 6**). A Newman–Keuls *post-hoc* test on the main effect of Beverage revealed, as expected, that people perceived Sprite® as sweeter with respect Tonic Water ($p < 0.000$) and sparkling water ($p < 0.000$). A Newman–Keuls *post-hoc* test on the main effect of Repetition showed that participants found all the beverages as sweeter during first evaluation, as compared to the second ($p = 0.00$) and third ($p = 0.01$) evaluation.

The results of the analysis of Saltiness showed a significant main effect of Beverage [$F_{(2, 52)} = 6.34$; $p = 0.00$; $d = 0.20$] and of Repetition [$F_{(2, 52)} = 3.11$; $p = 0.05$; $d = 0.11$]. The main effect of odor [$F_{(2, 52)} = 2.37$; $p = 0.10$], the interaction between Odor and Beverage [$F_{(4, 104)} = 1.42$; $p = 0.23$], the interaction between Odor and Repetition [$F_{(4, 104)} = 0.77$; $p = 0.54$], the interaction between Beverage and repetition [$F_{(4, 104)} = 0.21$; $p = 0.93$] and the interaction between Odor, Beverage and Repetition [$F_{(8, 208)} = 1.92$; $p = 0.25$] did not showed any significant effect. A *post-hoc* test (Newman–Keuls) on the main effect of the Beverage revealed that as expected, people perceived Sprite® as less salty than Tonic Water ($p = 0.01$) and sparkling water ($p = 0.01$). A *post-hoc* test (Newman–Keuls) on the main effect of the repetition showed that all the beverages were perceived as more salty during the first evaluation, as compared to the third evaluation ($p = 0.04$).

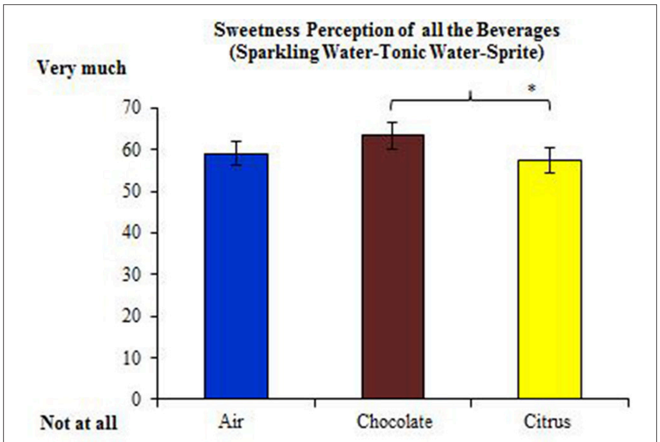

FIGURE 6 | The participants' mean judgments of sweetness for all the beverages tasted regardless of the evaluation sequence, as a function of the different odor conditions and. Error bars represent the standard errors of the means. Asterisks represent Newman-Keuls significant differences at *$p < 0.01$.

The analysis performed on the Bitterness dimension revealed a significant main effect of Beverage [$F_{(2, 52)} = 38.60$; $p < 0.0001$; $d = 0.60$]. The dimension of Odor [$F_{(2, 52)} = 0.82$; $p = 0.44$], Repetition [$F_{(2, 52)} = 1.25$; $p = 0.30$], as well as, the interaction between Odor and Beverage [$F_{(4, 104)} = 0.86$; $p = 0.49$], Odor and Repetition [$F_{(4, 104)} = 0.50$; $p = 0.74$], Beverage and Repetition [$F_{(4, 104)} = 1.02$; p 0.40] and the interaction between Odor, Beverage and Repetition [$F_{(8,208)} = 1.37$; $p = 0.21$] did not show any significant effect. A newman-Keuls *post-hoc* test on the main effect of Beverage revealed that as expected, participants perceived Tonic Water as more bitter than sparkling water ($p < 0.001$) and Sprite® ($p < 0.001$).

The results regarding the Carbonation Intensity dimension revealed a significant main effect of Beverage [$F_{(2, 52)} = 8.30$; $p = 0.00$; $d = 0.24$]. The main effect of Odor [$F_{(2, 52)} = 0.27$; $p = 0.77$], Repetition [$F_{(2, 52)} = 0.74$; $p = 0.48$], as well as, the interaction between Odor and Beverage [$F_{(4, 104)} = 0.83$; $p = 0.51$], Odor and Repetition [$F_{(4, 104)} = 0.46$; $p = 0.71$], Beverage and Repetition [$F_{(4, 104)} = 0.41$; $p = 0.80$ and the interaction between Odor, Beverage and Repetition [$F_{(8,208)} = 0.83$; $p = 0.57$] did not revealed any significant effect. A newman-Keuls *post-hoc* test on the main effect of Beverage revealed that people perceived sparkling water as less carbonated than Tonic Water ($p = 0.16$) and *Sprite®* ($p = 0.001$).

DISCUSSION

The results of the present study suggest that odors administered by means our olfactory device can alter people's experience of food, just as it occurs in natural multisensory environments.

Moreover, the present study also suggests that the device used to deliver the essences is highly manageable in a laboratory setting. In fact, the possibility to interconnect the olfactometer with the behavioral research software EPrime 2 and to interact with other devices connected to it, allows the implementation of sophisticated experiments in the field of psychology and cognitive neuroscience. With the aid of such device we were able to show multisensory interactions on food perception that are similar to those occurring without the mediation of a HCI device (e.g., when an odor perceived orthonasally affect the taste of the food in the mouth; Borowsky, 1987).

In particular, the results of Experiment 1 showed that participants perceived both foods (crackers and candies), as sweetest when presented together with the chocolate odor, as compared to when presented with air or citrus odors. In Experiment 2, the participants perceived all the beverages (Sparkling Water, Tonic Water, and Sprite), as sweetest when presented together with the chocolate odor, as compared to when presented with citrus odor regardless of the evaluation sequence. That is, the olfactory stimuli delivered by means of the new olfactory display showed to be effective in modulating people's evaluation of food and beverages.

The experimental results demonstrated for the first time that the orthonasal integration of an odor by means our device could affect people's food taste evaluations without adding any additional ingredient to the food. Intriguingly, this is an unusual result concerning a number of claims regarding orthonasal crossmodal integration between food and odors. In fact, it has been previously suggested that, while retronasal integration (e.g., when the odorant contained in food molecules reaches the back of the nose through eating or drinking) should modulate food flavor perception (i.e., sweetness or saltiness), orthonasal integration (e.g., when odor is smelled directly by the nostrils) should only modulate the hedonic dimension (i.e., pleasantness) of food evaluation (see Spence, 2016, for a detailed review). It is, however, worth noting that, despite the fact that during the experiments the olfactory stimulation was orthonasal, some chemical molecules may have somehow reached the oral cavity, and may have been processed also via the retronasal route. Such a possibility, raise the question of how to obtain a pure measure of orthonasal integration between odors and foods under experimental conditions. Future research should be directed to shed light on this issue.

The experimental results reported here are fully consistent with those by Stevenson et al. (2011). These authors demonstrated that the taste intensity ratings of a sweet solution could be significantly enhanced by the concurrent orthonasal presentation of an odor. Interestingly, Stevenson et al.'s results were found while participants tasted a solution, while we showed similar results both for foods and beverages. It is possible that the high precision of the computerized control of the odors administration timing of the MFOD (the latency from generation to perception of a selected odor is <0.5 s, with a length of the delivery pipe of 600 mm) is at the basis of the result found (the presence of orthonasal crossmodal integration). That is, the device used in this paper might have allowed better management of the technical procedures and precision of stimulus delivery, necessary for this kind of studies (although our previous considerations about a retronasal interaction may also be applied here; see the previous paragraph).

Intriguingly, our results have shown that people perceived both foods as sweetest when tasted together with the simultaneous administration of chocolate odor, as compared to air or citrus odors only during the third evaluation and not during the first or the second one. One possible interpretation of this result is that after the first two tasting sessions, food habituation may have occurred. That is, a reduced activation of taste receptors due to habituation (Poellinger et al., 2000) could have amplified the modulatory effect exert by the olfactory stimuli presented by means of the device (i.e., the weaker the taste, the stronger the effect produced by olfaction). This hypothesis should certainly be verified by means of further studies.

As far as the modulation of beverage perception by the device is concerned, it is worth noting that the majority of previous works failed to create the sensation of tasting "virtual beverages" (via the internet) by means of electrical and thermal stimulation (Lant and Norman, 2017; Ranasinghe et al., 2017). One of the reasons for these failures might be due to the lack of a simultaneous chemical stimulation by means odors (using olfactory devices). Since odors represent a pivotal component of taste perception, it would be then interesting to try to use our device also under similar conditions of stimulus presentation (i.e., virtual tasting).

Importantly, no modulatory effects were found on the dimensions of Pleasantness, Bitterness, Saltiness, and Carbonation Intensity. As far as this negative result is concerned, it should be considered that the more or less explicit perception by the participants that the context of stimulus presentation was artificially manipulated (e.g., that the odor did not arise from the beverage itself), could have made more difficult the integration between the olfactory and gustative qualities of the drinks (cf. Dietrich, 2006). Alternatively, it is possible that during Experiment 2 participants experienced a greater difficulty to achieve the temporal and spatial coincidence (Spence, 2011) needed to integrate taste and olfactory stimulation. In fact, also because of the risk of choke, people cannot swallow and sniff from the nostrils at the same time. Interestingly, in Stevenson et al. (2011) experiments, participants held the solution to be tasted in their mouth while smelling the odors through the nostrils, perhaps with the specific aim to achieve this important condition of sensory integration. Note, however, that this procedure likely reduces the ecological validity of the study, given that it is not a natural procedure adopted by people when they are drinking liquids.

In Experiment 2, differently from Experiment 1, no interactive effects were found among repetitions and odors. This result suggests that the tastings sequence did not modulate people's beverages evaluations. This result would seem to suggest that orthonasal crossmodal integration of odors and taste at the basis of people evaluation, might somehow differ, as a function of the gustatory experience involved (foods or beverages). Future research should be addressed to better comprehend the mechanisms at the basis of this difference.

Importantly, the small size and weight of the device presented in this paper (size Height 40 cm, Width 40 cm, Length 50 cm, and Weight <2 kilos) makes it easily adaptable in laboratory and even in more ecological contexts than other olfactory systems. The olfactometers used so far in research laboratories are difficult to be handled, extremely complex during the experimental managing, rather cumbersome and extremely expensive.

The results of Experiment 1 and 2 are in line with previous scientific evidence showing that people's perception of food and beverages can be altered by the multisensory context where the stimuli are presented (Zampini and Spence, 2005; Stevenson et al., 2011; Piqueras-Fiszman et al., 2012; Maggioni et al., 2015; Risso et al., 2015). In fact, despite of the fact that the participants knew that the odor did not originate from the food itself, their evaluation was still significantly affected by it. As far as this point is concerned, our results are the first to show an orthonasal interaction between taste and odor in people's evaluation of food and beverages sweetness by using a small size olfactory interface.

Our results may also be interpreted in terms of a "halo dumping" enhancement effect caused by the sweet quality of chocolate odors. That is, the sweetness of the odors "drove" people's judgments of taste. However, such an evaluative bias was previously found by retronasal perception only and in an unaware condition of stimulus presentation (Green et al., 2012). By contrast, in the present study, odors presentation was orthonasal, and people were perfectly aware of the nature of odor presentation. Finally, halo dumping is generally a homogeneous effect that involves all the characteristics to be evaluated (Thorndike, 1920). By contrast, our results showed a significant modulation only on the scale of sweetness.

Another possible interpretation concerning to the effect found in our experiments could be referred to the fact that participants could have rated the chocolate odor sweetness, instead of food sweetness. However, it is important to highlight that the presentation of the olfactory stimuli here was orthonasal. For this very reason, people were well aware that beverage and food taste perceptions were separated from odor perception. That is, it is unluckily that the olfactory stimuli delivered by our device were confused with the retronasal perception of the odor molecules contained in the stimuli to be evaluated. That said, it is still possible that the sweet quality of chocolate odor was unconsciously transferred and integrated to food perception, thus influencing the participants in their evaluation. Indeed, often people use verbal expressions that are generally used in taste perception to describe an odor. For example, *smells sweet* is often used concerning vanilla odor (Auvray and Spence, 2007). It is possible that the confusion generated by the use of this kind of semantic metaphor is at the base of the effects found in the present study. Future studies are needed to further clarify this point (see Gallace et al., 2010, for the semantic associations between words and food).

Further studies should also be addressed at investigating the effects of delivering olfactory stimuli by means of devices, such as that presented here, on the perception of different food and beverages, also under ecologically valid condition of stimulus presentation (e.g., in restaurants). Finally, a series of studies will need to be performed in order to study the effects of delivering odors by means olfactory devices within virtual reality simulations. In particular, it will be interesting to observe how olfactory information contribute to our sense of presence, and what aspects of the stimulation are more relevant to improve this perception (e.g., temporal visuo-olfactory synchrony, spatial position, etc.).

It is important to highlight here that the olfactory stimuli delivered by means of the MFOD consisted of compressed powders. Differently from the solution adopted by the majority of olfactory device commercialized nowadays, such a technical arrangement avoids the use of liquid odorants that requires complex systems in order to balance their dilutions.

It should be mentioned that the device adopted in the present study is a prototype and that further devices (which will allow to deliver up to 20 odors and with a higher degree of miniaturization) are now under development. These new generation of portable olfactometers, will certainly allow a large number of applications, comprising those related to enhancing the sense of presence in virtual reality environments. These devices will also contribute to investigating perceptual, emotional, and retention-related (memory) aspects of olfaction in humans, as well as be part of multisensory rehabilitations techniques for a number of neuropsychological disorders (Atanasova et al., 2008; Baba et al., 2012).

WEB LINKS

Aroma Shooter, https://aromajoin.com/en/hardware/shooters/aroma-shooter-mini-1

Scentsory Design https://link.springer.com/content/pdf/10.1007/978-3-540-79486-8_32.pdf

Aroma Rainbow Sensitive Dress http://www.escent.ai/smartsecondskin

Mist Shine Indiegogo, https://www.indiegogo.com/projects/mist-shine-wearable-smart-scent#/

Swallable Parfum, https://www.lucymcrae.net/swallowable-parfum/

E-Prime, www.pstnet.com/eprime.cfm

AUTHOR CONTRIBUTIONS

PR: Experiment design, Experiment implementation, olfactometer interface with ePrime2, data collection, data analysis, manuscript writing; MC: Olfactometer design, Olfactometer implementation, Olfactometer interface with ePrime2, manuscript writing; MB: Olfactometer design, Olfactometer implementation, Olfactometer interface with ePrime2, manuscript writing, manuscript supervision; AG: Experiment design, Experiment implementation, data analysis, data analysis supervision, manuscript writing, manuscript writing supervision.

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