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Congruency of multisensory olfactory stimuli

Gözde Filiz[1], Johannes Frasnelli[1,2,3,*]

[1]Department of Anatomy, Université du Québec à Trois-Rivières, Trois-Rivières, QC, Canada
[2]Research Center, Sacré-Cœur Hospital, CIUSSS-NIM, Montréal, QC, Canada
[3]Research Center, Institut Universitaire de Gériatrie de Montréal, CIUSSS-CSM, Montréal, QC, Canada

[*]Corresponding author: Department of Anatomy, Université du Québec à Trois-Rivières, 3351 Boulevard des Forges, Trois-Rivières, QC G9A 5H7, Canada. Email: johannes.frasnelli@uqtr.ca

We perceive our environment via different sensory channels in a multisensory fashion. During multisensory integration, these channels can enhance or hinder each other depending on congruency. Here, we aimed to investigate how the congruency of gustatory and visual costimulation alter the perception of olfactory stimuli. We hypothesized that congruent costimulation enhances the perception of likeness, i.e. how well stimuli match a label, compared with no and to incongruent costimulation. We also aimed to quantify the effect of gustatory and visual costimulation. We tested 48 healthy young participants. We used retronasal olfactory stimuli (strawberry, cheese, lemon, and coffee) (i) alone or with congruent/incongruent costimulation ((ii) with congruent gustatory (sweet, salty, sour, and bitter), (iii) with congruent visual (images of strawberry, cheese, lemon, and coffee), (iv) with congruent visual and gustatory, (v) with congruent visual and incongruent gustatory, (vi) with congruent gustatory and incongruent visual, (vii) with incongruent visual and gustatory costimulations). Olfactory and gustatory stimuli were presented by means of droplets on the tongue, i.e. olfactory stimuli were delivered retronasally, while visual stimuli were presented on a computer screen. We asked participants to evaluate the solutions' likeness to the respective olfactory label on visual analog scales. We observed a significant effect of congruency on likeness ($P < 0.001$). Gustatory costimulation had a significantly stronger effect than visual costimulation ($P = 0.02$). Congruent costimulation enhances the evaluation of likeness while incongruent costimulation reduces it, with gustatory costimulation having significantly stronger effects than visual costimulation. This could be useful in multisensory olfactory training paradigms for olfactory loss.

Key words: olfaction, gustation, vision, perception, likeness, taste.

1. Introduction

We perceive our surroundings as multisensory percepts, based on mental models, preconceived knowledge about the complex scenes, objects, events from the world (Klasen et al. 2012; Duncan 2025). Multisensory perception is the combination of sensory modalities into one percept (Driver and Spence 2000). Congruent sensory input corresponds to previous experiences and semantic knowledge (Gau and Noppeney 2016). For example, we expect strawberries to be red, strawberry-shaped, sweet, etc., in line with our pre-existing knowledge of this fruit. However, if we are presented with a blue colored or bitter tasting strawberry, the incongruent costimulation interferes resulting in the perception of an object that corresponds less to stored features of the object. Therefore, incongruent costimulation in other modalities leads olfactory stimuli to be perceived as less familiar (Prescott 1999; Labbe et al. 2006), less intense (Zampini et al. 2008), and to be detected only at higher concentrations (Dalton et al. 2000) and more slowly (Wongtrakun et al. 2024) while congruent costimulation in other modalities leads olfactory stimuli to be perceived as more intense, faster, and more accurately (Ernst and Bulthoff 2004; Laurienti et al. 2004; Kim et al. 2008; Roberts et al. 2024). As a consequence, when white wine is colored red, even experienced participants describe its sensory properties with labels that are normally attributed to red wine (Morrot et al. 2001). In other words, incongruently colored drinks (e.g. green colored, orange flavored drinks) are identified less accurately (Zampini et al. 2007). In turn, when combined with congruent tastants (e.g. sweet saccharin), odorants (e.g. almond smelling benzaldehyde) are more intense and can be perceived even at levels below perception threshold of monomodal olfactory stimuli (Dalton et al. 2000). Consequently, sensory training with congruent olfactory-visual stimuli leads to lower detection thresholds as well as better performance in discrimination (Li et al. 2023) and memory tasks (Olofsson et al. 2020).

Olfactory training, i.e. self-administration of a limited number (e.g. 4) of odorants regularly (e.g. twice a day) and repeatedly (e.g. for 12 wk) (Hummel et al. 2009) is the most promising intervention in olfactory dysfunction following viral infection (Hummel et al. 2009; Vance et al. 2024). In its present form, olfactory training is typically carried out with a unimodal olfactory design. Nevertheless, since congruent multisensory stimuli are perceived as more intense, olfactory training with multimodal stimuli may be more efficient than with monomodal stimuli (Filiz et al. 2024).

Therefore, we aimed to investigate how congruency of multisensory stimuli influences perception in individuals with a

Table 1. Characteristics of olfactory and gustatory stimuli.

Modality	Stimulus	Manufacturer; #	Volume (olfaction)/ amount (gustation)
Olfaction	Strawberry flavor	Foodarom; MET0003559	3 mL
	Cheese flavor	Foodarom; MET0017403	3 mL
	Lemon flavor	Foodarom; MET0000055	3 mL
	Coffee flavor	Foodarom; MET0017403	1.5 mL
Gustation	Sucrose	Acros; 424500010	0.9 g
	Sodium chloride	BDH; 127038.119541	0.3 g
	Citric acid	Milliard; X000HT86Q5	0.3 g
	Sucrose octa-acetate	Sigma-Aldrich; W303801	0.0015 g

Manufacturers: Foodarom: Foodarom Glanbia Nutritionals, St. Hubert, QC, Canada; Acros: Acros Organics, Thermo Fischer Scientific, New Jersey, USA; BDH: Inc. LOT, Toronto, Ontario, Canada; Milliard: Milliard Brands, New Jersey, USA; Sigma-Aldrich: Sigma-Aldrich, Oakville, Ontario, Canada. Olfactory/gustatory stimuli were diluted in 30 mL of demineralized water.

normal sense of smell. More specifically, we aimed to determine how congruent and incongruent gustatory and visual stimuli affect likeness i.e. how well an olfactory stimulus matches its label. We hypothesized congruent gustatory and/or visual stimuli to increase likeness, while incongruent gustatory and/or visual stimuli decrease likeness. This also allows for estimating the magnitude of the impact of congruency in the different sensory channels.

2. Materials and methods

2.1 Participants

This research was approved by UQTR's ethics board. Participants provided written consent before the experiment. We recruited 50 healthy participants between 18 and 35. Due to technical issues, we had to exclude the data of two participants; the final sample therefore consisted of 23 women and 25 men (average age: 26 years; standard deviation: 4.1). We assessed demographics of our participants (age, gender, health conditions including allergies, COVID history, history of olfactory dysfunction, and history of nasal surgery).

2.2 Stimuli

We used four odorants (strawberry, cheese, lemon, and coffee flavors) and four tastants (sucrose (sweet), sodium chloride (salty), citric acid (sour), and sucrose octa-acetate (bitter)). We opted not to include umami as a taste quality because of its relative unfamiliarity (See Table 1 for an overview over manufacturers; see Table 2 for an overview of the congruency matching of stimuli).

Chemosensory (olfactory and gustatory) stimuli were premixed in amber opaque glass vials (30 mL, Fisherbrand Inc, USA). We further presented participants with images of strawberry, cheese, lemon, coffee (Pixabay) on a computer screen by using Psychopy, GNU (GPL v3+, 2023).

2.3 Conditions

We presented stimuli in seven conditions. Specifically, olfactory stimuli were delivered either without costimulation or with congruent/incongruent, gustatory and/or visual costimulation. The conditions consisted of mixing and matching of four olfactory stimuli (aromas of strawberry, cheese, lemon, and coffee), with five gustatory stimuli (sweet, salty, acid, bitter, and tasteless baseline) and five images as visual stimuli (strawberry, cheese, lemon, coffee, and blank image baseline). Chemosensory stimuli were presented as droplets on the tongue with dropper lids (Filiz et al. 2024). Olfactory stimuli were therefore delivered retronasally. In parallel, participants looked at a computer screen for the presentation of the visual stimuli.

Table 2. Congruency or incongruency of each costimulation.

Olfactory stimulus	Gustatory costimulation			
	Sweet	Salty	Sour	Bitter
Strawberry	Congruent	Incongruent	Incongruent	Incongruent
Cheese	Incongruent	Congruent	Incongruent	Incongruent
Lemon	Incongruent	Incongruent	Congruent	Incongruent
Coffee	Incongruent	Incongruent	Incongruent	Congruent

In the following, *G* indicates the gustatory costimulation; *V* indicates to visual costimulation; *0* indicates the baseline condition, *c* indicates a congruent costimulation; *i* indicates an incongruent costimulation; *c* and *i* always refer to the olfactory stimulus. For example, for a congruent stimulation in all three modalities (*GcVc*) we presented, e.g. strawberry aroma with sweet taste and a strawberry image, while for an incongruent stimulation in all 3 modalities (*GiVi*), we presented, e.g. cheese flavor with acid taste and a coffee image. For partly incongruent/congruent stimulations we presented, e.g. coffee flavor with bitter taste (congruent) and a cheese image (incongruent), which was coded as *GcVi*. *G0V0* in turn represents the baseline condition without costimulation.

2.4 Procedure

We presented stimuli in a randomized order. Upon stimulation, we asked participants to evaluate the likeness of the stimulus to the four labels by the question: "How much like *label* (label: strawberry/cheese/lemon/coffee) is this mixture?" via four separate visual analog scales (VAS; ranging from 0: "not at all *label*" to 100: "completely *label*") presented on the computer screen. We did not control when participants swallowed or spit out the droplets on their tongue. The visual stimuli stayed on the screen until the participants finished rating the VAS.

Stimuli were separated by a 40s interstimulus interval during which participants rinsed their mouth. Participants received a total amount of 25 different costimulations of stimuli in a total of 97 trials. For a given odorant (e.g. strawberry), we used five gustatory costimulations (one congruent one (Gc), here sweet (sucrose), 3 incongruent ones (Gi), here salty (sodium chloride), sour (citric acid), bitter (sucrose octa-acetate), and as well as a blank (tasteless water; G0)). Analogously, a given odorant was presented with five visual costimulations (one congruent one (Vc), here strawberry image; 3 incongruent ones (Vi), here cheese image, lemon image, coffee image, and 1 blank (gray screen; V0)). We did the analogous with the other odorants. This resulted in 4 (4 odorants) * 5 (5 gustatory costimulations) * 5 (5 visual costimulations) = 100 permutations. However, of these permutations only four are GcVc, the condition of interest, giving too much potential weight to outliers. We therefore repeated each of the four GcVc stimuli three times (12 stimuli), leaving us with 108 stimuli. In turn, since we deemed that the experiment would have taken too long, we took out the 12 stimuli that consisted of congruent gustatory-visual combinations (e.g. sweet/strawberry image) that were incongruent to the olfactory stimulus (e.g. cheese). We did the same with the 24 stimuli for which the costimulation of 1 modality was incongruent while the costimulation of the other modality was a blank (e.g. strawberry flavor with a cheese image and no gustatory costimulation). This resulted in a total of 72 stimuli that were presented to each participant. After each trial, participants rated the likeness to the categories (strawberry, lemon, coffee, and cheese) with four different VAS. However, for further analysis we only regarded the category that corresponded to the odor that had been presented.

The number of trials per condition is presented in Table 3.

The experiment took 2 h to complete, and it was divided into 2 sessions with a 15-min break between. The experiment flow is presented in Fig. 1.

Table 3. Overview of items in different conditions.

	GcVc	GcV0	G0Vc	G0V0	GiVc	GcVi	GiVi
Trials	12	4	4	4	12	12	24

2.5 Statistical analysis

We used SPSS 29 (IBM, Armonk, NY) for data analysis.

For the analysis we calculated average scores for the seven conditions across odors. We examined the effects of congruency of the modality of costimulation on *likeness* by computing 3 repeated measures (rm) ANOVA. In the rmANOVA, we investigated the effect of congruency by including congruent costimulations (4 levels: baseline *G0V0* and *GcVc*, *GcV0*, and *G0Vc*). In the second analysis, we investigated the effect of incongruency by including incongruent costimulations (4 levels: baseline *G0V0* and *GiVc*, *GcVi*, and *GiVi*). In the third analysis, we compared the effects of congruency and incongruency (3 levels: baseline *G0V0* and *GcVc*, *GiVi*). In all ANOVA, we used *gender* as a between subject factor.

For post hoc tests we used Bonferroni corrections for multiple comparisons. We set the alpha value at 0.05.

3. Results

Average likeness scores are presented in Table 4.

The first rmANOVA with congruent stimuli revealed a significant effect of *condition* (F (1, 2.4) = 15.3, $P < 0.001$) but no significant effect of *gender* (F (1, 48) = 1, $P = 0.3$), and no interaction *condition* and *gender* (F (1, 2.4) = 0.8, $P = 0.5$).

Next, the rmANOVA with incongruent stimuli revealed a significant effect of *condition* (F (1, 2.4) = 31, $P < 0.001$), but no significant effect of *gender* (F (1, 48) = 1.3, $P = 0.3$) nor an interaction *condition* and *gender* (F (1, 2.4) = 2.6, $P = 0.07$). Finally, the rmANOVA with the incongruent and congruent costimulations, revealed a significant effect of *condition* (F (1, 1.8) = 63.6, $P < 0.001$) but no significant effect of *gender* (F (1, 48) = 1.5, $P = 0.2$) nor an interaction *condition* and *gender* (F (1, 1.8) = 0.5, $P = 0.6$).

Pairwise post hoc comparisons are presented in Fig. 2.

On average, baseline olfactory stimuli without costimulation had a likeness of 56.3 (3.6) points. Congruent gustatory costimulation increased likeness by 11.1 (3.2) points, while

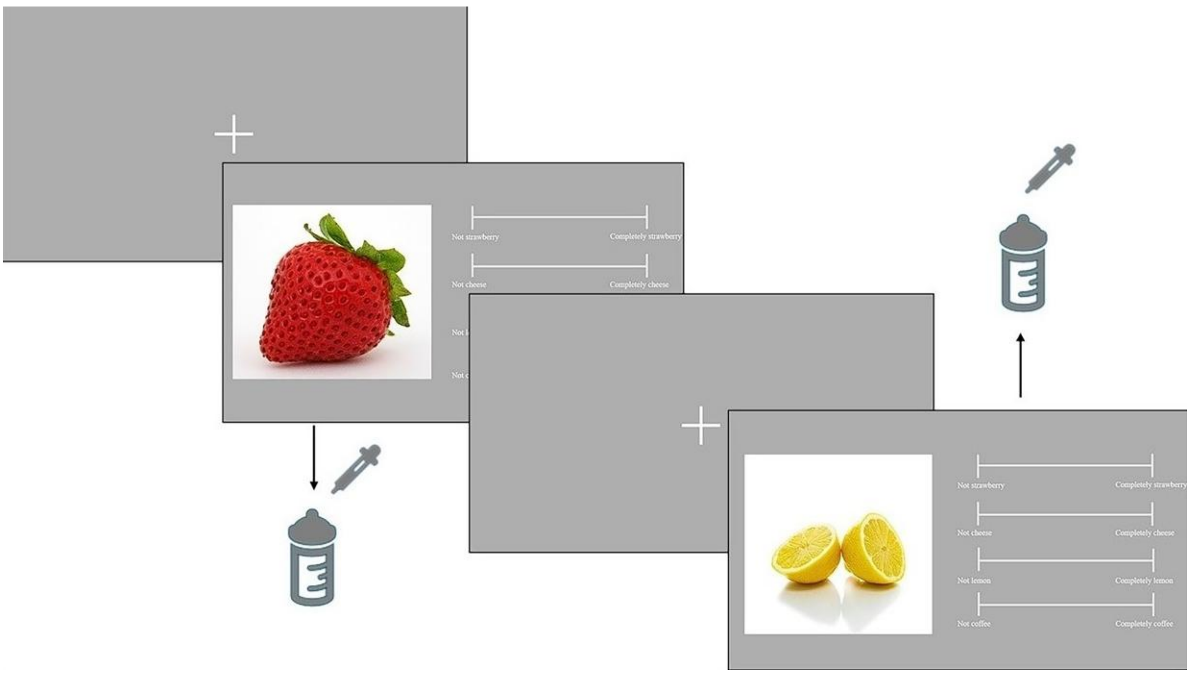

Fig. 1. Flow chart of the experiment.

congruent visual costimulation increased likeness by 4.3 (3.4) points. In turn, incongruent gustatory costimulation decreased likeness by 2.65 (2.8) points, while incongruent visual costimulation still increased likeness by 11.5 (2.8) points. As a result, combined congruent gustatory and visual costimulation increased likeness by 14.1 (2.8) points, while combined incongruent gustatory and visual costimulation decreased likeness by 8.1 (2.8) points. Mixed congruency, e.g. congruent gustatory and incongruent visual costimulation resulted in an increase of likeness by 9.5 (2.8) points, while incongruent gustatory and congruent visual costimulation decreased likeness by 2.6 (2.8) points.

4. Discussion

Here, we report the results of our study on the effects of congruency of gustatory and visual costimulation on retronasal olfactory stimuli. Our main results are (i) congruency increases the perceived likeness of olfactory stimuli; (ii) congruency (incongruency) of gustatory costimulation is more effective in increasing (decreasing) likeness of olfactory stimuli compared with visual costimulation.

We observed that gustatory costimulation affects the likeness of an olfactory stimulus to a label. This is in line with the literature. For example, sweetness is a great enhancer of odor intensity (Fujimaru and Lim 2013). When combined with a sweet taste, retronasally presented cherry flavor were rated as more cherry flavored when compared with a sour taste (Green et al. 2012), and peach flavors more peach flavored (Porto Cardoso and André Bolini 2008); a sweet taste renders a tomato puree to be perceived as more ripe, tropical and fruity (Baldwin et al. 2008). Similar effects have been reported for strawberries (Schwieterman et al. 2014) and citrus (King et al. 2007; Veldhuizen et al. 2017). These effects are not limited to intensity or likeness as participants also respond faster to congruent gustatory-olfactory mixtures compared with monomodal stimuli (Veldhuizen et al. 2010). Participants also report more pleasantness and odor referral to their mouth with the more familiar and congruent stimuli they receive (Fondberg et al. 2018). These results can also be observed when participants were not exposed to the stimuli in training sessions before the experiment, suggesting the effect of congruency in learning associations during experiments (Stevenson et al. 1998). Furthermore, when presented with a congruent gustatory costimulation, olfactory stimuli can be detected at concentrations that are below their monomodal perception thresholds (Dalton et al. 2000; Delwiche and Heffelfinger 2005).

We observed a weaker yet significant effect for visual costimulation. This is again in line with the literature. Red colored tangerine–guava–pineapple mixtures are rated as more fruity in both orthonasal and retronasal odor quality assessments (Koza et al. 2005). Similarly, odorant solutions with matching colors, e.g. red-strawberry or green-mint odorant (Zellner and Whitten 1999), are rated as more intense (Zellner and Kautz 1990). The effect of color congruency of visual congruency extends to higher order olfactory tasks such as odor identification: congruently colored odorants are more easily identified than incongruent ones (Zellner et al. 1991). Similar results are observed when images are presented rather than colors alongside odors. Congruent images lead to increased likeness perception and easier odor detection (Gottfried and Dolan 2003). Congruent visual costimulations with images (e.g. flowers and fruits) led to smaller N400 components in event-related potentials in response to olfactory stimulation (e.g. rose and citrus). This component is thought to reflect

Table 4. Average likeness scores of different conditions.

	Likeness (points)	Standard deviation
GcVc	70.3	2.8
GcV0	67.3	3.1
G0Vc	60.5	3.4
G0V0	56.2	3.6
GiVc	53.6	2.8
GcVi	65.7	2.8
GiVi	48.1	2.8

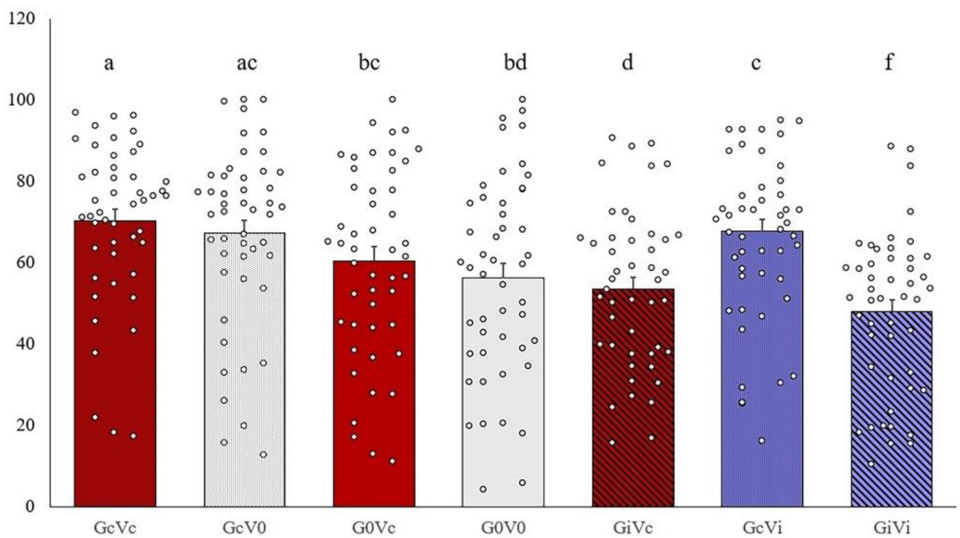

Fig. 2. Average likeness scores (error bars: standard deviation) of different conditions. Significant differences in the pairwise comparisons are indicated by different letters. If 2 bars contain the same letter, they do not have a significant difference. Bars that do not share the same letter are significantly different.

the relatedness of stimuli (Grigor et al. 1999; Sarfarazi et al. 1999). In a similar fashion, visualization of our current results in EEG would be interesting to investigate in the future studies.

Gustatory costimulation had a significantly stronger effect than visual costimulation. This further supports the notion of a strong connection between olfaction and gustation (Czarnecki and Fontanini 2019). The neurobiological underpinning of this may be in the overlap in brain areas responsible for processing of olfaction and gustation such as orbitofrontal cortex (Small et al. 1997), insula and operculum (Small et al. 1999; Cerf-Ducastel and Murphy 2001; Mastinu et al. 2025), anterior cingulate cortex (Small et al. 2003). Similar results can be observed in animal studies, the piriform cortex of rats responds to both olfactory and gustatory stimulation (Maier et al. 2012); in turn, their gustatory cortex also processes particularly retronasal (Blankenship et al. 2019) olfactory stimuli (Maier et al. 2015).

The observations in this study are potentially interesting for olfactory training in a clinical context. Here, olfactory training is a self-administered intervention that consists of sniffing selected odors for 12 wk (Hummel et al. 2009). Previously, we investigated whether a multisensory version of this training with olfactory, gustatory and visual allows for recovery of olfactory function following COVID-induced olfactory dysfunction. We found multisensory olfactory training to be equally effective as a classical olfactory training (Filiz et al. 2024). This is in line with previous findings with multisensory olfactory trainings in which researchers found significant improvement with olfactory-visual multisensory trainings (Khan et al. 2023 ; Li et al. 2023) and gustatory-olfactory multisensory trainings (Fjaeldstad 2025). Our current study suggests that the stimuli used in the present study may be better suited for multisensory training because of higher volumes and amounts of olfactory/gustatory stimuli. We had noticed that patients in our previous study struggled to detect odors.

This is an innovative study because most previous research investigated the effect of one additional modality on olfactory perception such as vision on olfaction, e.g. (Morrot et al. 2001; Sakai et al. 2005; Stevenson and Oaten 2008; Dematte et al. 2009) or gustation on olfaction (Green et al. 2012; Lim et al. 2014; Amsellem and Ohla 2016). Here, we investigated both gustation and vision, and this independently and combined, which allows us to compare their individual effects, but also their synergistic abilities, on flavor perception. Further, while previous research was mostly concerned with the effects of multisensory integration during consumption of food or drinks, e.g. (Fujimaru and Lim 2013; Sukkhown et al. 2019; Wang et al. 2020; Stager et al. 2021) our study was designed with having olfactory training protocols in mind (Hummel et al. 2009; Filiz et al. 2024). Our study's stimuli can directly be used in olfactory training protocols. This is particularly interesting given the raised awareness in the public on olfactory dysfunction after viral infections in the aftermath of the pandemic (Asseo et al. 2020; Cheng et al. 2021; Saegner and Austys 2022; Ziakas and Mylonakis 2024). Finally, we feel that our approach that used the same costimulations as congruent or incongruent, depending on the olfactory stimulation, allowing them to serve as controls for themselves rather elegant.

This study has some limitations. First, to limit testing time we did not include certain conditions (e.g. incongruent gustatory stimuli without visual stimulation) rendering the generalizability of findings on incongruent costimulation are relatively limited. Second, we predefined congruent and incongruent costimulations without verifying in participants if this was the case with everyone. This is particularly true since there may be important effects of cultural background on congruency. For example, bitter taste may not be perceived as congruent with coffee aroma if a participant is used to drink their coffee strongly sweetened. This is why we included the same stimuli in the different conditions. By doing so, we considered a stimulus (e.g. sweet) congruent when presented with one odor (e.g. strawberry), but when presented with another condition (e.g. lemon), the same stimulus was considered as incongruent. In other words, the same stimuli served as congruent intervention and as incongruent control. The fact that we observe significant differences between the conditions, actually shows that the stimuli we considered congruent were perceived, on average, as congruent by the participants. This does however not rule out that other stimuli might have had even stronger effects. Future studies should evaluate congruency on a participant-by-participant basis. Third, we did not assess if the stimuli also stimulated the trigeminal system as this was outside the scope of our experiment. The presence of a minor trigeminal costimulation, however, would not change the main message of the paper. Fourth, it is important to point out that we used food-related odors. In the classical olfactory training protocol rose, eucalyptus, clove, and lemon odors are used, which are not typical food odors. One would not expect non-food odors to be congruent with gustatory costimulations, thereby limiting the applicability of our observations. Previous studies suggest that the choice of odors does not have a predominant importance for the outcome of olfactory training (Altundag et al. 2015; Poletti et al. 2017). Therefore, opting for food odors may be appropriate when including gustatory costimulation. Finally, we excluded umami as a gustatory stimulus since pilot testing suggested that the studied population has difficulties in recognizing it correctly, in line with the literature (Singh et al. 2010; Cecchini et al. 2019).

5. Conclusion

In conclusion, we show that congruent matching of vision and gustation increases perceived likeness and potentially recognition of multisensory solutions. Gustation especially plays a significant role and matching when presented alongside olfactory stimuli. The results from this study might potentially be useful in multisensory training paradigms such as multisensory olfactory trainings.

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Conflict of interest statement. None declared.

Data availability

Data cannot be shared for ethical/privacy reasons.

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