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Auditory–Olfactory Integration: Congruent or Pleasant Sounds Amplify Odor Pleasantness

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Abstract

Even though we often perceive odors while hearing auditory stimuli, surprisingly little is known about auditory–olfactory integration. This study aimed to investigate the influence of auditory cues on ratings of odor intensity and/or pleasantness, with a focus on 2 factors: "congruency" (Experiment 1) and the "halo/horns effect" of auditory pleasantness (Experiment 2). First, in Experiment 1, participants were presented with congruent, incongruent, or neutral sounds before and during the presentation of odor. Participants rated the odors as being more pleasant while listening to a congruent sound than while listening to an incongruent sound. In Experiment 2, participants received pleasant or unpleasant sounds before and during the presentation of either a pleasant or unpleasant odor. The hedonic valence of the sounds transferred to the odors, irrespective of the hedonic tone of the odor itself. The more the participants liked the preceding sound, the more pleasant the subsequent odor became. In contrast, the ratings of odor intensity appeared to be little or not at all influenced by the congruency or hedonic valence of the auditory cue. In conclusion, the present study for the first time provides an empirical demonstration that auditory cues can modulate odor pleasantness.

Key words: auditory cue, auditory–olfactory integration, congruency, the halo/horns effect, odor pleasantness, odor intensity

Introduction

In many cases, odor perception is derived from multimodal integration. For example, it is well known that visual cues such as colors or pictorial images modulate olfactory perception and performance (Zellner and Kautz 1990; Zellner et al. 1991; Zellner and Whitten 1999; Gottfried and Dolan 2003; de Araujo et al. 2005; Sakai et al. 2005; Stevenson and Oaten 2008; Demattè et al. 2009; Seo et al. 2010). In addition, many studies have addressed odor–taste integrations (Frank and Byram 1988; Schifferstein and Verlegh 1996; Dalton et al. 2000; Small et al. 2004; Welge-Lüssen et al. 2009).

We often perceive odors together with auditory cues in everyday life. For instance, while eating or drinking, people experience not only odors through the orthonasal or retronasal route but also sounds elicited by mastication or the drinking process, for example, sipping or swallowing. Another example is the experience of walking along a metropolitan street, where people smell exhaust fumes from automobiles while hearing traffic sounds, for example, car engines or the sound of horns. Nevertheless, surprisingly little is known about cross-modal interactions between olfactory and auditory cues. Even though a series of studies have demonstrated that auditory cues can modulate participants' judgments of food quality, such as crispness, freshness, or carbonation (Vickers and Wasserman 1980; Christensen and Vickers 1981; Zampini and Spence 2004, 2005), taste perception (Crisinel and Spence 2009), and eating/shopping behaviors (for a review, see Spence and Shankar 2010), only a few studies have addressed auditory–olfactory integration (Belkin et al. 1997; Spangenberg et al. 2005; Wesson and Wilson 2010). Specifically, Belkin et al. (1997) demonstrated that participants can match certain auditory pitches with specific odorants, and the authors mentioned that this association seems to be mediated by odor quality but not by odor intensity or hedonic tone. More recently, using a mouse model, Wesson and Wilson (2010) reported novel findings where single units of the olfactory tubercle not only responded to odors but also showed tone-evoked activity. Indeed, 29% of single units in the olfactory tubercle demonstrated either enhanced or suppressed responses to the simultaneous presentation of odors and tones.

In order to build on these findings, the current study aimed to investigate the effects of auditory cues on odor perception and/or pleasantness. In particular, among many potential effects influencing auditory–olfactory integration, we highlighted 2 main factors: "congruency" and the "halo/horns effect". Within the present study, congruency can be understood to refer to "the extent to which auditory and olfactory stimuli are appropriate for combination while eating or drinking a food product" based on the earlier definition by Schifferstein and Verlegh (1996). The congruency factor appears to play a major role in modulating cross-modal associations between olfactory and visual stimuli (Zellner et al. 1991; Gottfried and Dolan 2003; Sakai et al. 2005; Stevenson and Oaten 2008; Demattè et al. 2009; Seo et al. 2010) and between olfactory and gustatory stimuli (Frank and Byram 1988; Schifferstein and Verlegh 1996; Dalton et al. 2000; Small et al. 2004; Welge-Lüssen et al. 2009). Specifically, it appears that congruent visual stimuli not only facilitate odor detection (Gottfried and Dolan 2003), identification (Zellner et al. 1991), and discrimination (Stevenson and Oaten 2008; Demattè et al. 2009) but also magnify odor intensity (Sakai et al. 2005; Seo et al. 2010) and pleasantness (Zellner et al. 1991; Sakai et al. 2005; Seo et al. 2010). The modulating effect of congruency has also been observed in odor–taste interactions (Frank and Byram 1988; Schifferstein and Verlegh 1996; Dalton et al. 2000; Small et al. 2004; Welge-Lüssen et al. 2009). For example, Dalton et al. (2000) demonstrated that orthonasal detection thresholds for the odor of benzaldehyde (cherry/almond odor) were significantly decreased (i.e., participants became more sensitive) in the presence of a subthreshold concentration of congruent taste (saccharin) in the mouth; but a lowering of orthonasal detection thresholds did not result from the presence of an incongruent taste (monosodium glutamate) or of deionized water. Therefore, on the basis of this "congruency paradigm," in Experiment 1, we sought to determine whether auditory cues can modulate odor intensity and/or pleasantness.

In addition to congruency, the "halo effect," coined by Thorndike (1920), could be one of the many factors influencing cross-modal interactions. From the perspective of sensory evaluation, Lawless and Heymann (1997) defined the halo effect as "the tendency of a product to be viewed more positively than normal due to one or more overriding or influential sensory attributes or other positive influences" and/or "the tendency of a sensory attribute to be rated as more intense or more hedonically positive due to other logically unrelated sensory attributes in a product" (p. 809). The opposite negative effect is called the "horns effect" (Lawless and Heymann 1997). The halo/horns effects have been demonstrated in previous cross-modal studies (Chen and Dalton 2005; de Araujo et al. 2005; Kappes et al. 2006; Demattè et al. 2007; Logeswaran and Bhattacharya 2009). For example, Demattè et al. (2007) demonstrated that female participants estimated a male face as being significantly less attractive in the presence of an unpleasant odor than in the presence of a pleasant odor or odorless air. Thus, in Experiment 2, we wanted to determine whether the hedonic valence of auditory cues could modify odor intensity and/or pleasantness. Specifically, we examined whether the hedonic valence of auditory stimuli can be transferred to the pleasantness ratings of subsequently presented odors.

Experiment 1

Materials and methods

Participants

Twenty-two healthy right-handed volunteers (13 females) with an age range from 19 to 39 years (mean ± standard deviation [SD] = 25.1 ± 4.5 years) took part in Experiment 1. Handedness was determined using a translated version of the Edinburgh inventory (Oldfield 1971). Participants were recruited via leaflets. All participants confirmed that they had no clinical history of major diseases, that they had a normal sense of smell and that they had no trouble hearing. In order to exclude participants with impairments in olfactory, auditory, or cognitive function, the following tests were used: the "Sniffin' Sticks" screening test (Burghart Instruments; for details, see Hummel et al. 2001), the tuning fork test (Doyle et al. 1984), and the "Mini-Mental-State Examination" (Folstein et al. 1975). The experiment was explained to all participants in great detail, and informed written consent was obtained.

Olfactory and auditory stimuli

As olfactory stimuli, we used 2 odors: 50% dilution of potato chip odor (#RC721, Fragrance Resources GmbH) and 10% dilution of Coffee odor (#P0613905, Frey + LAU GmbH) in 1,2-propanediol (Sigma-Aldrich Inc.). All odors were delivered using a computer-controlled air-dilution olfactometer (OM6b, Burghart). The olfactory stimuli (25%, v/v) diluted by humidified air were embedded in a constantly flowing airstream (7.0 L/min) with controlled temperature (36 °C) and humidity (80% relative humidity [RH]). Odors were presented for 250 ms via a tube placed in the right-nostril of the participants, a method based on previous studies determining that olfactory performance is better (e.g., improved odor sensitivity, discrimination, and familiarity) when the odors are delivered to the right rather than to the left nostril (Zatorre and Jones-Gotman 1990; Kobal et al. 2000; Broman et al. 2001). In addition, participants were asked to perform the velopharyngeal closure breathing technique (Kobal 1981) to avoid respiratory flow of air inside the nose during olfactory stimulation.

Three auditory stimuli were used: the sound of eating potato chips, the sound of drinking coffee, and white noise (subsequently to be called "no-sound" indicating no additional auditory cue). One of 2 commercial sound clips, the sound of eating potato chips (#295199, Navarr Enterprises, Inc.) or the sound of drinking coffee (#261783, Navarr Enterprises, Inc.), was employed as an auditory cue either congruent or incongruent with the presented odors. In the no-sound condition, no additional sound was presented; instead, white noise was used as a control. Using a sound editor program (Power Sound Editor Free, ver. 6.9.6., PowerSE Co., Ltd.), the sound of eating potato chips and the sound of drinking coffee were edited to last for 5 s and were provided via a headphone at a loudness of 70 dB.

Procedure

Six different combinations of olfactory and auditory cues (2 odors by 3 sounds) were presented 72 times (6 combinations by 12 repetitions) in an irregular order across participants.

Participants received 1 of 3 auditory cues for 5 s. Subsequently, 4 s after the onset of auditory presentation, one of 2 odors was presented for 250 ms. Following stimulus presentation, participants were asked to immediately rate odor intensity and pleasantness on visual analog scales (VAS) ranging between 0 (extremely weak; extremely unpleasant) and 10 (extremely strong; extremely pleasant). Instructions and scales were presented on the monitor. To minimize olfactory desensitization, 25–29 s were allowed to elapse between odor presentations. In addition, to eliminate the residual effects of prior odor and sound, an odorless humidified airstream (7.0 L/min, 36 °C, 80% RH) and white noise (60 dB) were presented between the odor presentations. The white noise also dampened unexpected environmental sounds (e.g., the valve switching sound of the olfactometer).

After the experimental session, all participants were required to answer 3 questions: degree of congruency, auditory pleasantness, and odor identification. First, participants were presented with either potato chip odor or coffee odor, together with its congruent or incongruent sound. These combinations were presented in an irregular order across participants. After receiving each combination of odor and sound, participants were instructed to estimate the degree of congruency between the presented odor and sound via a 9-point scale ranging between 1 (extremely weak) and 9 (extremely strong). Next, after listening to each of the sounds of eating potato chips or drinking coffee, participants were asked to judge the sound's pleasantness on a 9-point scale ranging between 1 (extremely unpleasant) and 9 (extremely pleasant). Finally, after smelling each odor, participants were instructed to judge odor identification (similarity), that is, "How similar is the presented odor to the potato chip (or coffee) odor that you expected/experienced before?," on a 9-point scale ranging between 1 (extremely different) to 9 (extremely similar).

Statistical analyses

Statistical software, SPSS 12.0 (SPSS Inc.) for Windows, was used to analyze the results. Descriptive analyses and paired *t*-tests were used wherever appropriate. To determine whether auditory cues influence ratings of odor intensity or pleasantness, data were analyzed by using repeated measures analyses of variance (RM-ANOVAs). If the Sphericity assumption was violated via the Mauchly Sphericity test, the degrees of freedom were adjusted by using "Huynh–Feldt" correction. If a significant difference of means was indicated by RM-ANOVAs, post hoc comparisons between independent variables were performed using Bonferroni *t*-tests. Moreover, to examine correlations of individual ratings between the degree of congruency and odor intensity or pleasantness, Pearson correlation analyses were conducted. Finally, to predict the pleasantness rating of odors and to identify the factors influencing the odor pleasantness, a stepwise linear regression model using 3 independent rating variables was applied, namely the degree of congruency, auditory pleasantness, and odor identification. The alpha level was 0.05.

Results

Effect of auditory cue on odor intensity and/or pleasantness

As expected, paired *t*-tests revealed that participants judged potato chip odor paired with the sound of eating potato chips (mean ± SD = 6.82 ± 1.50) as significantly more congruent than when paired with the sound of drinking coffee (2.41 ± 1.59), $t_{21} = 8.75$, $P < 0.001$. Also, the combination of coffee odor with the sound of drinking coffee (mean ± SD = 6.32 ± 1.59) was estimated as being significantly more congruent than the combination of coffee odor with the sound of eating potato chips (3.18 ± 1.71), $t_{21} = 6.35$, $P < 0.001$. There was no difference between the congruency ratings of the 2 congruent combinations, $P = 0.25$.

RM-ANOVAs revealed that auditory cues altered the intensity of both potato chip odor, $F_{2,42} = 4.56$, $P = 0.02$, and coffee odor, $F_{2,42} = 8.01$, $P < 0.01$. Specifically, post hoc Bonferroni *t*-tests showed that participants rated the potato chip odor as significantly more intense in the presence of a congruent sound (mean ± SD = 4.63 ± 1.58) than in the no-sound (white noise) condition (4.01 ± 1.63), $P = 0.02$. In addition, coffee odor was evaluated as less intense during the no-sound (white noise) condition (5.01 ± 1.76) than during the conditions of congruent sound (5.43 ± 1.79), $P = 0.02$, or incongruent sound (5.49 ± 2.04), $P < 0.01$.

Furthermore, as shown in Figure 1, congruent sounds influenced the pleasantness ratings of both potato chip odor, $F_{2,42} = 5.58$, $P < 0.01$, and coffee odor, $F_{1.59,33.40} = 5.36$, $P = 0.01$. Post hoc Bonferroni *t*-tests revealed that participants rated the potato chip odor as being more pleasant while listening to a congruent sound (mean ± SD = 5.40 ± 1.59) than while listening to either an incongruent sound (4.37 ± 1.67), $P = 0.04$ or no-sound (white noise) (4.71 ± 1.53), $P = 0.03$. Additionally, participants judged the coffee odor as more pleasant while listening to a congruent sound (6.10 ± 1.66) than while listening to an incongruent sound (4.99 ± 2.03) at $P < 0.05$.

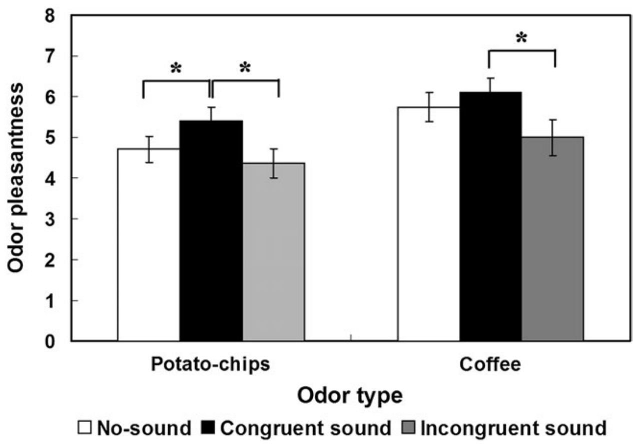

Figure 1 Mean ratings of odor pleasantness in relation to 3 different auditory cues: neutral (i.e., white noise), congruent, or incongruent sound. The pleasantness ratings of either potato chip odor or coffee odor were significantly higher when presented with congruent sound than when presented with incongruent sound. Asterisk indicates significant difference at $P < 0.05$. The error bars represent the standard errors of the means.

Correlations between individual degree of congruency and ratings of odor intensity or pleasantness

We wanted to determine whether a higher congruency of olfactory and auditory stimuli can produce higher ratings of odor intensity or pleasantness. Correlation analyses revealed that as participants judged the combined stimuli of odor and sound to be more congruent, they rated the odor as more pleasant, $r_{88} = 0.41$, $P < 0.001$. A significant correlation was present for both odors, with slightly higher coefficients of correlations in coffee odor, $r_{44} = 0.46$, $P < 0.01$, than in potato chip odor, $r_{44} = 0.38$, $P = 0.01$.

With regard to odor intensity, no significant correlation of individual ratings between degree of congruency and odor intensity occurred either for potato chip odor, $r_{44} = 0.09$, $P = 0.59$ or for coffee odor, $r_{44} = 0.07$, $P = 0.65$.

Next, we attempted to explore whether odor pleasantness can also be influenced by either auditory pleasantness or odor identification. Paired *t*-tests revealed that the sound of eating potato chips (mean ± SD = 6.55 ± 1.47) was preferred to the sound of drinking coffee (5.18 ± 2.06), $t_{21} = 2.86$, $P < 0.01$. However, there was no significant difference in the ratings of odor identification between potato chip odor (mean ± SD = 5.41 ± 1.89) and coffee odor (6.55 ± 1.68), $P = 0.07$. Individual ratings of odor pleasantness significantly correlated to individual ratings of odor identification, $r_{88} = 0.33$, $P < 0.01$. Moreover, this significant correlation of ratings between odor pleasantness and odor identification occurred for the potato chip odor, $r_{44} = 0.32$, $P = 0.03$ but not for the coffee odor, $r_{44} = 0.26$, $P = 0.09$. That is, as participants gaged the presented potato chip odor as more similar to what they had expected/experienced before, they liked the odor more. However, no significant correlation between individual ratings of odor pleasantness and auditory pleasantness was obtained, $r_{88} = 0.06$, $P = 0.58$.

To predict the pleasantness ratings of odors and to identify the factors influencing odor pleasantness, the following stepwise linear regression models using 3 independent variables were used: degree of congruency, auditory pleasantness, and odor identification. The pleasantness ratings of potato chip odor were predicted by 2 factors: degree of congruency and odor identification. This stepwise regression model was significant $F_{2,41} = 6.15$, $P < 0.01$, with an adjusted $R^2 = 0.19$ (Y [odor pleasantness] = 2.393 + 0.223 [degree of congruency] + 0.271 [odor identification]: LRM_PO [linear regression model for the potato chip odor]).

The pleasantness ratings of coffee odor were predicted by only one factor: degree of congruency. The stepwise regression model was also significant $F_{1,42} = 11.35$, $P < 0.01$, with an adjusted $R^2 = 0.19$ (Y [odor pleasantness] = 3.701 + 0.388 [degree of congruency]: LRM_CO [linear regression model for the coffee odor]).

Discussion

Our findings demonstrate for the first time that congruent sounds can enhance odor pleasantness to a higher degree than can incongruent sounds. This result is in line with the previous cross-modal studies reporting that congruent visual or gustatory cues increase odor pleasantness more than incongruent cues (Schifferstein and Verlegh 1996; Sakai et al. 2005; Seo et al. 2010). For example, Sakai et al. (2005) demonstrated that participants judged an odor to be significantly more pleasant when looking at a congruent picture than when looking at an incongruent picture.

It is worth noting that the congruency effect of auditory cues on odor pleasantness varies depending on the participants' judgments of the degree of congruency between auditory and olfactory stimuli. That is, participants who gaged the combined stimuli of odor and sound to be more congruent rated the odor as more pleasant. In addition, participants who judged the presented odor to be more similar to what they had expected/experienced before rated the odor as more pleasant. In other words, as participants identify the odor more easily, they like the odor more. These results herein suggest 2 points. First, the congruency effect of auditory cues on odor pleasantness appears to take place at the semantic or cognitive level. Second, odor identification plays an important role in mediating the congruency effect of sounds on odor pleasantness. Those points are in accordance with earlier cross-modal studies using olfactory and visual stimuli (Zellner et al. 1991; Gottfried and Dolan 2003; Stevenson and Oaten 2008). Specifically, Zellner et al. (1991) argued that an appropriate color facilitates an ability to identify an odor, which in turn enhances the pleasantness of the odor. Similarly, Stevenson and Oaten (2008) demonstrated that inappropriate color–odor matches produced significantly more errors during an odor discrimination task than appropriate matches or an uncolored odor condition; and they suggested that this result is mediated by the odor misidentification elicited by inappropriate colors at the conceptual level. Moreover, a neuroimaging study by Gottfried and Dolan (2003) demonstrated that participants detected odors more quickly and accurately in the presence of semantically congruent odor-picture combinations than when presented with semantically incongruent combinations. This behavioral result elicited by the congruency effect was related to neural activations in the secondary olfactory cortex of the anterior hippocampus and rostromedial orbitofrontal cortex (OFC). That is, by mediating retrieval of semantic information or association, those activated areas of the brain appear to contribute to resolving ambiguity in odor perception during a task using either congruent or incongruent combinations.

It is interesting to note that factors predicting the pleasantness ratings of either potato chip or coffee odor were to some extent different. Specifically, although only one among 3 potential factors, degree of congruency, predicted the pleasantness ratings of coffee odor, the additional factor of odor identification predicted the pleasantness ratings of potato chip odor. This result suggests that odor identification is an important factor in mediating a congruency effect of sound on odor pleasantness, especially in the presence of a less common odor. That is, compared with coffee odor, the potato chip odor appears to be harder to identify and to be less intense (i.e., significantly lower ratings of odor intensity in the presence of no-sound condition, $t_{21} = -3.33$, $P < 0.01$). This ambiguity of potato chip odor might lead participants to rely on the cue of sound to clarify the blurred odor (Alais and Burr 2004; see also Shankar et al. 2010). Indeed, it is assumed that cross-modal enhancement is more pronounced when unimodal stimulus is only weakly effective (Calvert 2001). Additionally, Zampini et al. (2008) demonstrated that the influence of color on flavor identification can differ depending on participants' "taste status." Specifically, super-tasters appeared not to be influenced by the color of flavor solution when identifying their flavors. However, medium-tasters or nontasters identified the flavors more correctly in the presence of appropriately colored solution, and this color effect was more pronounced in nontasters than medium-tasters.

Moreover, our findings demonstrate that congruent sounds can increase the intensity of odors compared with a no-sound (white noise) condition but not in comparison with an incongruent sound condition. Additionally, there was no significant correlation between ratings of the degree of congruency and odor intensity. Indeed, the congruency effect on odor intensity still remains unclear. Specifically, it has been documented that congruent visual or gustatory stimuli can magnify odor intensity or sensitivity in comparison with incongruent stimuli (Dalton et al. 2000; Sakai et al. 2005). Using olfactory event-related potentials, Seo et al. (2010) showed that a congruent symbol produced significantly higher amplitudes of the N1 peak associated with stimulus quality or intensity as compared with an incongruent symbol, but this significant effect was not seen for all odors. Moreover, contrasting results have also been reported, indicating no significant difference in odor intensity between congruent and incongruent combinations (Zellner and Kautz 1990; Zellner and Whitten 1999; Seo et al. 2010). For example, Zellner and Kautz (1990) demonstrated that participants rated the odor of a flavor solution to be stronger in a congruent-colored solution, for example, strawberry-red, than in a colorless solution but not stronger than in an incongruent-colored solution. Zellner and Whitten (1999) argued that regardless of whether the color is congruent or not, the presence or absence of color in a flavor solution appears to be the most important factor in generating a color-induced odor enhancement. Additionally, Schifferstein and Verlegh (1996) suggested that congruency seems to be necessary to mediate odor-induced taste enhancement, but the degree of congruency is not related to the degree of taste enhancement. Thus, further study is needed to determine how congruency can modulate odor intensity.

Finally, the hedonic valence of sounds did not affect the pleasantness ratings of subsequently administered odors in the conditions of Experiment 1. A plausible explanation for the lack of significance is that the hedonic valence of the 2 sounds used in this study appears to be neutral (see above), even though the sound of eating potato chips was significantly preferred to the sound of drinking coffee. In addition, because both sounds were associated with the congruency effect, it is hard to selectively extract influences of auditory pleasantness on the odors in Experiment 1. Thus, in Experiment 2, we attempted to investigate relationships between auditory and olfactory pleasantness using sounds semantically irrelevant to the presented odors.

Experiment 2

In Experiment 2, we set out to determine whether the hedonic valence of auditory cues can modulate intensity and/or pleasantness ratings of subsequently presented odors. To exclude the potential congruency effect of auditory cues, we used sound stimuli irrelevant to the presented odors.

Materials and methods

Participants

Twenty-six healthy right-handed volunteers (20 females) with an age range from 20 to 40 years (mean ± SD = 25.2 ± 4.2 years) participated in Experiment 2. Handedness was determined using a translated version of the Edinburgh inventory (Oldfield 1971). All participants reported that they had no clinical history of major diseases and that they had a normal sense of smell and hearing. Participants underwent screening tests for olfactory, auditory, and cognitive function similar to those conducted in Experiment 1. The experiment was explained to all participants in great detail, and informed written consent was obtained for participation.

Olfactory and auditory stimuli

As olfactory stimuli, one pleasant odor, 2-phenyethanol (PEA; Sigma-Aldrich), and one unpleasant odor, 4% dilution of 1-butanol (Merck) in 1,2-propanediol (Sigma-Aldrich Inc.), were used. Prior study has demonstrated that the odors of PEA and 1-butanol have been judged to be pleasant and unpleasant, respectively (Seo et al. 2010). As in Experiment 1, the olfactory stimuli (40%, v/v) diluted by humidified air were embedded in a constantly flowing airstream (7.0 L/min, 36 °C, and 80% RH). By using an olfactometer (OM6b, Burghart), odors were presented for 250 ms via a tube placed in the right-nostril of the participants. Participants were asked to perform the velopharyngeal closure breathing technique (Kobal 1981).

As auditory stimuli, 2 pleasant sounds, baby laughing (#FX-16212) and jazz drum (#23457), and another 2 unpleasant sounds, baby crying (#1908), and screaming (#23109), were employed. All sounds were obtained from a web provider of sound effects (http://free-loops.com). To eliminate a potential congruency effect between olfactory and auditory cues, we selected sounds irrelevant to the odors presented in this study. Using a sound editor program (Power Sound Editor Free, ver. 6.9.6., PowerSE Co., Ltd.), all sounds were edited to last for 5 s and were presented via a headphone at a loudness of 70 dB.

Procedure

Eight different combinations of olfactory and auditory cues (i.e., 2 odors by 4 sounds) were presented 48 times (i.e., 8 combinations by 6 repetitions) in an irregular order across participants.

As in Experiment 1, participants were presented with 1 of 4 auditory cues for 5 s. Subsequently, 4 s after the onset of auditory presentation, one of 2 odors was presented for 250 ms. After receiving the combined stimuli, participants were asked to immediately rate odor intensity and pleasantness on a VAS ranging between 0 (extremely weak; extremely unpleasant) and 10 (extremely strong; extremely pleasant). Instructions and scales were presented on a monitor. To minimize olfactory desensitization, 25–29 s were allowed to elapse between odor presentations. In addition, to eliminate the residual effects of previous odors and sounds, an odorless humidified airstream (7.0 L/min, 36 °C, 80% RH) and white noise (60 dB) were presented between odor presentations.

After the experimental session, participants were presented with 4 different sounds in an irregular order across participants. After listening to each sound, participants were asked to rate the pleasantness of the sound using an 11-point scale ranging from 0 (extremely unpleasant) to 10 (extremely pleasant).

Statistical analyses

Statistical software, SPSS 12.0 (SPSS Inc.) for Windows, was used to analyze the results. Descriptive analyses and paired t-tests were used wherever appropriate. To assess whether the hedonic valence of an auditory cue can modulate ratings of odor intensity or pleasantness, data were analyzed by using RM-ANOVAs. If the Sphericity assumption was violated via the Mauchly Sphericity test, the degrees of freedom were adjusted by using Huynh–Feldt correction. If a significant difference of means was indicated by RM-ANOVAs, post hoc comparisons between independent variables were performed using Bonferroni t-tests. Moreover, to examine correlations of individual ratings between auditory and olfactory pleasantness, Pearson correlation analyses were performed. The alpha level was 0.05.

Results

Effect of hedonic valence of auditory cue on odor intensity or pleasantness

As expected, paired t-tests found that mean hedonic ratings (mean ± SD = 7.52 ± 1.81) of pleasant sounds (baby laughing and jazz drum) were significantly higher than those (1.81 ± 1.73) of unpleasant sounds (baby crying and scream), t_{51} = 16.03, $P < 0.001$.

We first attempted to determine whether the hedonic valence of an auditory cue can influence odor intensity and/or pleasantness. RM-ANOVAs revealed that participants rated the presented odors as being more pleasant while listening to pleasant sounds, for example, baby laughing and jazz drum (mean ± SD = 5.29 ± 1.30), than while listening to unpleasant sounds, for example, baby crying and screaming (4.70 ± 1.41), $F_{1,25} = 16.32$, $P < 0.001$. As shown in Figure 2, odor pleasantness was amplified by pleasant sounds, regardless of whether the odor was rated as pleasant (PEA odor, $F_{1,25} = 16.86$, $P < 0.001$) or as unpleasant (1-butanol odor, $F_{1,25} = 10.88$, $P < 0.01$).

Table 1 presents mean ratings of odor intensity and pleasantness in relation to 4 different auditory stimuli. Interestingly, participants judged the PEA ("rose-like") odor as more pleasant in the presence of baby laughing than in the presence of baby crying, $F_{1,25} = 13.16$, $P = 0.001$. The baby laughing sound increased pleasantness ratings of the unpleasant odor (1-butanol) as compared with the baby crying sound, $F_{1,25} = 10.85$, $P < 0.01$.

However, auditory cues did not significantly modulate the intensity ratings of either pleasant odor, $F_{1,25} = 0.12$, P = 0.74, or unpleasant odor, $F_{1,25} = 0.07$, $P = 0.80$ (Table 1).

Correlations between hedonic ratings of auditory cues and ratings of odor intensity or pleasantness

We sought to determine whether individual hedonic ratings of sounds can correlate with individual ratings of odor intensity or pleasantness. Correlation analyses revealed that individual hedonic ratings of sounds significantly correlated with individual pleasantness ratings of a subsequently presented odor, $r_{208} = 0.17$, $P = 0.01$ but not with intensity

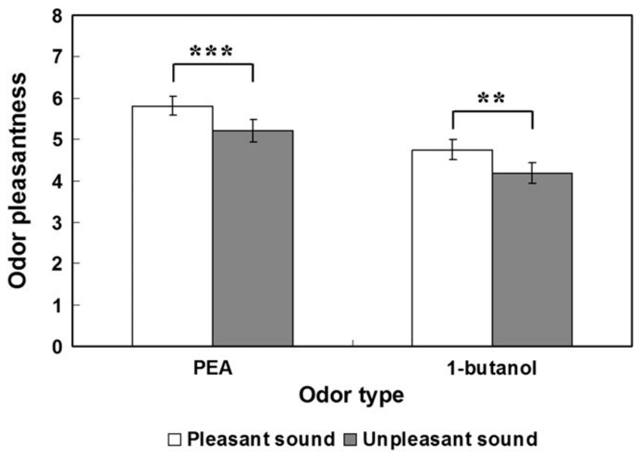

Figure 2 Mean ratings of odor pleasantness in relation to hedonic valence of preceding sounds. The pleasantness ratings of both phenylethanol (PEA) odor and 1-butanol odor was significantly higher when presented with pleasant sounds than when presented with unpleasant sounds. **and ***indicate significant difference at $P < 0.01$ and at $P < 0.001$, respectively. The error bars represent the standard errors of the means.

Table 1 Mean ratings of odor intensity and pleasantness in relation to hedonic valence of auditory cues

Odor type	Pleasant sounds		Unpleasant sounds	
	Baby laughing	Jazz drum	Baby crying	Screaming
Odor intensity				
PEA	4.13 ± 1.50[a]	4.04 ± 1.58	4.17 ± 1.77	4.08 ± 1.61
1-butanol	4.01 ± 1.80	4.01 ± 1.62	3.93 ± 1.62	4.02 ± 1.91
Odor pleasantness				
PEA	6.05 ± 1.00	5.58 ± 1.35	5.43 ± 1.36	4.99 ± 1.50
1-butanol	4.87 ± 1.40	4.64 ± 1.22	4.22 ± 1.30	4.14 ± 1.36

[a]Mean ± SD.

ratings of odors, $r_{208} = 0.04$, $P = 0.58$. That is, the more participants liked the preceding sound, the more pleasant the subsequent odor became.

When analyzed separately in relation to the hedonic tone of odors, the significant correlation of individual hedonic ratings between sounds and subsequent odors were observed for the pleasant PEA odor, $r_{104} = 0.21$, $P = 0.03$ but not for the unpleasant 1-butanol odor, $r_{104} = 0.16$, $P = 0.10$.

Discussion

For the first time, our results provide empirical evidence of the halo/horns effects of hedonic valence in auditory–olfactory integration. In other words, the hedonic tone of preceding sounds was carried over to subsequent odors unrelated to the sounds. In fact, previous cross-modal studies, apart from those on auditory–olfactory integration, have shown that the hedonic tone of a unimodal stimulus can alter the pleasantness rating of stimuli from other senses (Demattè et al. 2007; Pollatos et al. 2007; Logeswaran and Bhattacharya 2009). For example, Logeswaran and Bhattacharya (2009) addressed the significant effect of musical stimuli on the hedonic ratings of face stimuli. Specifically, listening to happy or sad music magnified the perceived happiness or sadness, respectively, attributed to a subsequently shown face. Additionally, this effect was present regardless of facial emotion, but the effect was greatest for emotionally neutral faces as compared with happy or sad faces.

In contrast to the absence of significant correlation in Experiment 1, the findings of Experiment 2 show that individual hedonic ratings of sounds significantly correlated with the pleasantness ratings of a subsequently presented odor. A plausible explanation for the discrepancy is that while the hedonic valences of the 2 sounds used in Experiment 1 were close to neutral, the hedonic valences of the sounds employed in Experiment 2 were distinctly pleasant or unpleasant, which may have stimulated more dynamic or powerful responses to the odors.

The current findings demonstrate that the hedonic valence of sounds does not modulate the intensity of subsequently administered odors, irrespective of the hedonic tone of odors; this result is to some extent consistent with earlier cross-modal studies using visual cues (Herz and von Clef 2001; de Araujo et al. 2005), where odor intensity appeared to be less or not at all influenced by positive or negative labels. Specifically, de Araujo et al. (2005) showed that positive (e.g., "cheddar cheese") or negative (e.g., "body odor") labels altered the pleasantness ratings of isovaleric acid mixed with cheddar cheese flavor but not the intensity ratings of that odor.

General discussion

Our study adds new evidence to a growing list of cross-modal integrations of different sensory channels. However, herein for the first time, we report an empirical demonstration that sounds can modulate intensity and/or pleasantness ratings of subsequently applied odors as a result of the "congruency effect" and the halo/horns effect produced by the auditory stimuli. The main findings of the current study were:

1. Compared with incongruent sounds, congruent sounds can increase pleasantness ratings, but not intensity ratings, of subsequently administered odors.
2. The degree of congruency between sounds and odors correlates to individual pleasantness ratings of odors.
3. The hedonic valence of sounds can be transferred to pleasantness ratings of subsequently administered odors, irrespective of the sounds.
4. The hedonic ratings of sounds correlate to the pleasantness ratings of subsequently applied odors, irrespective of the sounds.

Taken together, the results of the present study support the notion that congruency plays an important role in modulating cross-modal integrations in terms of intensity and/or pleasantness ratings (Frank and Byram 1988; Schifferstein and Verlegh 1996; Dalton et al. 2000; Gottfried and Dolan 2003; Small et al. 2004; Sakai et al. 2005; Welge-Lüssen et al. 2009; Seo et al. 2010) and extends its role to an auditory–olfactory association. Furthermore, the current study presents the first example of the halo/horns effect in the auditory–olfactory integration.

Notably, in both Experiments 1 and 2, in comparison with pleasantness ratings, the intensity ratings of odors were found to be less or not at all influenced by the congruency or hedonic tone of auditory stimuli, even though the odor intensity was judged to be more intense in the presence of congruent sound than in the presence of white noise. A plausible explanation for the lack of a significant result in odor intensity is that both congruency and hedonic valence are more dependent on a synthetic judgment than an analytical one. Indeed, intensity ratings are largely an analytical task, whereas pleasantness ratings are a synthetic task (Schifferstein and Verlegh 1996). Compared with incongruent or unpleasant sounds, congruent or pleasant sounds may lead participants to maintain positive attitudes and feelings of comfort, which could in turn lead participants to judge the accompanying odors more positively or pleasantly. In contrast, the emotional state elicited by sounds seems to have less effect on the execution of more analytical tasks like intensity ratings. Several neuroimaging studies have demonstrated that the particular brain areas activated by olfactory stimuli are dependent on the type of olfactory tasks, for example, intensity, hedonicity, detection, familiarity, or edibility (Zatorre et al. 2000; Royet et al. 2001). For example, Zatorre et al. (2000) demonstrated that the right OFC was activated during both intensity and pleasantness judgments and that the hypothalamus was also activated during pleasantness judgments. In addition, Royet et al. (2001) reported that regional cerebral blood flow was significantly increased in the left OFC during hedonic judgments, relative to blood flow levels during intensity judgments. Given those studies, we hypothesize that the affective attitudes induced by sounds influence synthetic tasks (pleasantness ratings) more strongly than they do analytical tasks (intensity ratings).

Compared with congruency or hedonic tone, intensity ratings seem to be more influenced by other attributes of an auditory cue. For example, Christensen and Vickers (1981) demonstrated that the loudness of sounds produced by mastication of foods significantly correlated with perceived crispness. In addition, in a study by Zampini and Spence (2004), participants were asked to judge crispness and staleness of potato chips by biting them with their front teeth while they received a real-time auditory feedback over the headphone produced during their biting. The auditory feedback was modified by changing the overall loudness and/or frequency composition. The study showed that participants rated the potato chips as being crisper and fresher when the overall sound level was increased or when the high-frequency component was amplified. Similarly, in their follow-up study, Zampini and Spence (2005) showed that sparkling water samples were evaluated as being more carbonated when either the overall sound level or high-frequency component of auditory cues was increased. Based on those studies, another possible explanation for the present lack of significance in the odor intensity ratings is that the auditory cues used in the current study were not different in terms of overall loudness. Because none of the odors used in Experiments 1 and 2 were very strong, in order to allow for a reliable decision (Alais and Burr 2004) on intensity ratings of odors, participants might rely on another sound cue during the judgments. In addition, the ''halo-dumping effect'' by Clark and Lawless (1994) may apply to intensity ratings. Specifically, the halo-dumping effect takes place when participants are presented with only one intensity scale (e.g., sweetness) to rate a mixture of 2 stimuli (e.g., sugar and strawberry flavor). Participants are forced to use one scale for 2 sensations and they dump the second sensation into the only available scale. Given those conditions, participants are likely to rely on auditory intensity to judge odor intensity. In our study, because the overall loudness of auditory stimuli was evenly controlled, no significant difference might be obtained in the ratings of odor intensity. Moreover, this assumption can explain why participants rated the odors as being more intense in the presence of either congruent or incongruent sound (70 dB) than in the presence of white noise with lower loudness (60 dB) in Experiment 1.

In summary, our findings demonstrated for the first time an auditory priming effect on pleasantness ratings of subsequently presented odors: congruent or pleasant sounds can enhance odor pleasantness compared with the pleasantness of odors paired with incongruent or unpleasant sounds. Further study using various olfactory and/or auditory stimuli is needed to generalize the current findings.

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