The Music of Perfume: Crossmodal Correspondences Between Musical Features and Olfactory Perception

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Reported studies about crossmodal correspondences between music and smell basically focus on individual musical parameters. An experiment was carried out to explore such correspondences emerging from musical improvisation elicited by 20 olfactory stimuli, which allows the study of multiple musical parameters at the same time. A group of 14 pianists was asked to smell each stimulus and to play a short free improvisation inspired by it. From each improvisation, 14 musical parameters were extracted. The same odorants were also described by a panel of 15 volunteers. The main outcomes were the following: 1) The mean sensory ratings on a scale of fresh vs. warm appeared correlated with the average pitch of the improvisation. 2) The four odorants perceived as somewhat camphoraceous like lavender and mint yielded more non legato/staccato articulation or rests. 3) The feminine odor character was negatively correlated with the ambitus of the improvisation, defined as the difference between the highest and lowest note, and was positively correlated with pitch-class entropy. 4) Pleasantness yielded a negative correlation with pitch-class entropy and dissonance, being positively correlated with the lowest note. The first outcome is consistent with earlier studies, but outcomes 2–4 were novel findings.

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Crossmodal correspondences have been defined as the associations that people tend to make between features, attributes, or dimensions of experience in different sensory modalities (Spence, 2020). Such correspondences have been found between auditory pitch and a wide range of different stimulus dimensions, including elevation, size, visual lightness, visual brightness, spatial frequency, visual hue, shape, and angularity (Spence, 2019). Pitch also shares correspondences with perceptual features of touch such as roughness and hardness (Eitan & Rothschild, 2011) as well as with the gustatory/flavorful stimuli (Crisinel & Spence, 2010; Holt-Hansen, 1968; Knöferle & Spence, 2012; Knöferle et al., 2015; Mesz et al., 2011; Wang et al., 2016).

Regarding the crossmodal correspondences between sound and smell, Piesse (1867) was the first to relate odorants and perfume ingredients to the notes of a diatonic scale spanning several octaves. Belkin et al. (1997) demonstrated that participants can match certain auditory pitches with specific odorants according to their odor quality, but not by odor intensity or hedonic tone. In a similar study (Crisinel & Spence, 2012), lemon and fruity scents were matched with notes yielding the highest auditory pitch. The lowest pitches corresponded to *smoked, musk* and *dark chocolate*, which can be matched with birch tar, civet, and caramel lactone, respectively, in the experiment of Belkin et al. (1997), revealing consistent results.

Taking into account that citrus scents are perceived as *light* and *fresh*, suitable for casual daytime wear in perfumes, while warm odors are preferred for nighttime wear (Zarzo, 2020), this *fresh* vs. *warm* odor dimension seems to be associated with auditory pitch. The interpretation of "fresh" in odor description is somewhat controversial because the meaning of this word in English is different compared to other languages like French (*frais*), interpreted as "moderately cool" and opposite to warm (Zarzo, 2013). Thus, the polarity of *fresh* vs. *warm* is basically equivalent to *light* vs. *heavy*, which is often preferred to avoid confusion. Actually, it is well known by perfumers that green and citrus notes are perceived as fresh and they tend to evaporate quickly, which justifies that *light* and *fresh* are commonly used as synonyms. By contrast, odors most dissimilar to *fresh* are described as tenacious, heavy, or rich. The polarity *light* vs. *heavy* has also been used in a reported study on the perception of musical qualities, as well as *cold* vs. *warm* (Murari et al., 2014).

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Consistent results were also reported by Ward et al. (2021) in a study where participants matched ten odorants with a continuous adjustable pitch varying in the full range of audible frequencies (20 Hz to 20 kHz). Peppermint (i.e., a light/fresh smell) appeared as the higher-pitched odor, while the lower-pitched smells corresponded to coffee and caramel, which are often described as balsamic and warm (Zarzo & Stanton, 2009). Another study (Crisinel et al., 2013) using seven odorants and note samples from different instruments showed that the three odors associated with the lowest pitch (ginger cookies, musk, and roasted coffee) were significantly different in their pitch associations from the two odors associated with the highest pitch (candied orange and iris flower). Moreover, odors judged as brighter were associated with higher pitch.

Correspondences of Other Auditory Features with Smell

Persson (2011) found that a high concentration of an odorant corresponded to a high loudness sound while, conversely, a low concentration was matched with a low loudness. In Stevenson et al. (2012), "loud" odors were judged as comparatively more intense, irritating, and unpleasant. Deroy et al. (2013) suggest that our senses have evolved to recognize when a common source gets closer or farther from the perceiver, which would explain the observed correlation between sound loudness and odor intensity. This odor-sound association could be explained by the amodal hypothesis (Deroy et al., 2013), which assumes a structural explanation based on common principles of neural encoding or representation (Stevens, 1957). Indeed, experimental evidence indicates that increasing the intensity of stimuli is coded as an increased neural firing rate across the senses (Nehrkorn et al., 2015).

Regarding the impact of pleasant vs. unpleasant sounds on olfactory perception, different studies have revealed that the hedonic valence of sounds transferred to the pleasantness of subsequently presented odors, irrespective of the hedonic tone of the odor itself, but did not affect their perceived intensity (Seo & Hummel, 2011; Seo et al., 2014).

Crisinel and Spence (2012) found that participants preferentially matched specific odors to certain types of instruments. Unpleasant stimuli seemed to be associated with brass instruments, while the piano was preferred for pleasant odors. In a study about the effect of musical consonance and dissonance on odor perception (Velasco et al., 2014), participants rated the six presented smells as less sweet and less pleasant when listening to white noise (i.e., a noise that contains all frequencies of the spectrum with equal energy), which was rated as unpleasant in a follow-up study.

The effects of musical tempo were investigated in a study about sound-odor congruence that focused on arousal (either high or low) on people's attitude and memory for products of a familiar and unfamiliar brand (Rit et al., 2019). Participants smelled high- and low-arousal odors and then saw an advertisement for a product of a familiar or unfamiliar brand, paired with a high- or low-arousal jingle. High-arousal jingles were clips of high-tempo music, while the low-arousal sounds were clips of low-tempo music. When a high-arousal odor was combined with a high-arousal music, the products they had seen before were recognized faster.

Expanding our understanding of odor-music correspondences is of interest in several fields. A recent study has reviewed examples showing how the knowledge of audio-olfactory associations can be incorporated into the design of multisensory experiences, in both the commercial and artistic spheres (Velasco & Spence, 2022). In music therapy, emotional effects may be increased by combining music with a crossmodally congruent scent (Zhou & Yamanaka, 2018). In a supermarket, light/fresh odors evoking daylight conditions, congruent with activating music, may improve the purchase experience of consumers (Mattila & Wirtz, 2001). Multisensory art and experiences involving smells and music may be enhanced and refined based on the existence of crossmodal odor–music correspondences, largely supported by empirical evidence starting with the pioneering work of Piesse (1867); see Di Stefano et al. (2022), Spence (2021), and Velasco and Obrist (2020) for some examples.

Objectives of the Research

The reported studies about crossmodal correspondences between music and smell basically focus on individual components of music like pitch or tempo, given the difficulty of exploring multiple musical parameters at the same time. However, even basic auditory parameters may not be independent, particularly within a musical context, which increases the complexity because such dependency may affect the results (e.g., via transitive relationships). By contrast, improvising music inspired by a set of odors allows one to study these correspondences in a more natural and ecologically valid manner, since participants engage in a typical musical activity, resulting in an integration of individual features in a complex fragment of music. In the present study we explore such correspondences emerging from free musical improvisation at the keyboard elicited by 20 odors commonly used as fragrance ingredients. This musical production paradigm, based on improvisation, is different from earlier perception-based studies of auditory–olfactory correspondence. Such paradigm, already used in the study of taste-music correspondences (Mesz et al., 2011), allows the study of multiple musical parameters simultaneously, which may affect the results compared with the standard perception-based approach. Moreover, when participants choose a particular music inspired by a given smell (Murari et al., 2020), this task involves a conscious act of thinking about the correspondence, but musical improvisation is a creative task where subjectivity, personal emotional nuances and memories may be freely displayed (Forbes & Cantrell, 2023).

The main goal was to investigate the interplay of many musical parameters operating simultaneously: basic features like pitch, duration, sound loudness, and consonance/dissonance, as well as higher-level parameters such as entropies of pitch class and duration distributions. The target was to study if, even in this context of free improvisation, odors are reliably associated with music in ways that are partly consistent with previous findings in studies that used much more restricted experimental designs and, moreover, if novel and possibly music-specific crossmodal correspondences also emerged.

Based on the body of research reviewed above, we formulated the following research questions on music-odor correspondences:

1. Is it still true, in the context of free improvisation, that fresh vs. warm (or light vs. heavy) scents are associated with higher vs. lower pitch, as suggested by earlier studies (Crisinel & Spence, 2012; Ward et al., 2021)?
2. Are there particular musical parameters associated with feminine or masculine scents?
3. Which musical features are affected by camphoraceous odors?
4. Did olfactory pleasantness affect the hedonic valence of improvisations as expected, according to previous research (Seo et al., 2014)?
5. Is olfactory intensity correlated with sound loudness (Persson, 2011; Wang et al., 2016)?

Method

PARTICIPANTS

A set of 14 trained pianists took part in the research (aged 22–40 years), two of whom were female. They were recruited from Buenos Aires, Argentina (federal capital) or the suburban area. Their formal music training ranged from 3 to 13 years, and their experience in playing piano was at least three years (Table 1). None of them were professional in the sense of playing regularly in concerts. Prior to the experiment, participants gave their informed consent and filled out a questionnaire about their sex, age, profession, formal music training, and experience (number of years) in playing piano or musical keyboard. They all had the keyboard as their

TABLE 1. *Basic Personal and Musical Information About the Pianists*

						Odors associated with:		
Code	Age	Sex	FMT	YCM	YEP	Low pitch	Mid-pitch	High pitch
P01	31	M	8	21	20	natural	sour or strong	natural
P02	27	M	10	14	8	woody		fruity, sour
P03	40	M	4	20	4			sour
P04	20	M	>10	15	13	weak		strong or lemon
P05	22	M	7	15	5	bitter	sweet	sour, mint
P06	38	M	6	31	10	sweet	fruity	citrus
P07	38	F	10	32	3	fresh, bitter	sweet	sour
P08	24	M	3	12	12		fruity	fruity, green
P09	39	F	10	30	25	weak		strong
P10	33	M	5	20	14			
P11	39	M	12	34	34	unpleasant		fresh or sweet
P12	27	M	11		11			
P13	23	M	13	13	13			
P14	23	M	10	20	20	weak		strong

Note. Musical information: years of formal music training (FMT), years of contact with music (YCM), and years of experience with piano (YEP). The YCM value is not available for P12. The last three columns contain information provided by the pianists after their improvisations and briefly summarize what odor qualities were associated with low, middle, or high pitch.

main instrument except for the pianist coded as P07, which explains the lowest value (3 years) of experience with piano (Table 1). None of the participants reported any impairment of their sense of smell or audition. They were compensated for their time with 200 ARS (Argentine Pesos).

Humans exhibit a considerable inter-individual variability regarding general sensitivity and threshold olfactory performance (Marin et al., 1988; Stevens et al., 1988). However, odor tests to quantify such variability were not carried out because it would become very difficult to control and assess all factors and variables that might affect the music freely inspired by pianists. For example, it is claimed that everyone is anosmic for some number of chemicals (Croy et al., 2015; Hirth et al., 1986), but such identification is complex. Even in the case that a given pianist would have perceived one of the odor stimuli somewhat differently due to specific partial anosmia, the use of a panel of participants compensates for such differences, so this effect was not regarded as important.

STIMULI

In total, 20 odorous materials were used. Six of them (orange blossom, cinnamon, cedarwood, vanilla, rosemary, and benzoin) were purchased from Aromatelier (http://soyaromas.com/aromatelier), six additional odorants (mint, lemon, jasmine, lavender, neroli, and orange) from Just (www.aromasyesenciasjust.com), three samples (dark chocolate, peach, and plum) from Spiritu (as part of a kit of wine aromas developed for olfactory training), cis-3-hexenol (as a reference for green leaves) was acquired from Cafypa SA (Munro, Argentina), smoke flavor from Grupo Saporiti SA (Buenos Aires, Argentina), and sandalwood essential oil from Gualumi (www.gualumi.com.ar). Cis-3-hexenol was the only mono-molecular odorant, the rest were complex mixtures of aroma chemicals. All these products were purchased in flasks of 10 ml. Additionally, two classical fragrances were also used: Ice Blue (Aqua Velva, from Williams) and Polo (from Ralph Lauren), both purchased from a local store. For the experiment, olfactory stimuli were kept in small glass bottles identified by a code number written on the side. It was decided to use the odorants in their original concentration, as directly purchased from the suppliers.

PROCEDURE

The experiment was carried out at the Universidad Nacional de Tres de Febrero (UNTREF) located in the city of Caseros, province of Buenos Aires, Argentina. It was approved by the Research Ethics Committee of UNTREF on March 17, 2022. Aromas were presented in random order, embedded on paper strips by applying one drop of the product per strip. The order was randomized for each participant. The strip containing the odorant was presented to each pianist, who was uninformed about the odor character. The strip, which was made freshly for each session, was held with a clamp attached to a handmade device (see Figure 1) resembling a headset microphone, so that the strip remained next to the nose, at a constant distance. The pianist was asked to smell the paper strip orthonasally while performing a short musical improvisation of approximately 20 seconds, freely inspired by the smell, on a MIDI keyboard (model Kawai CL 36). The sustain pedal was disabled to avoid uncertainty on note duration and articulation due to pedal resonance. The keyboard had

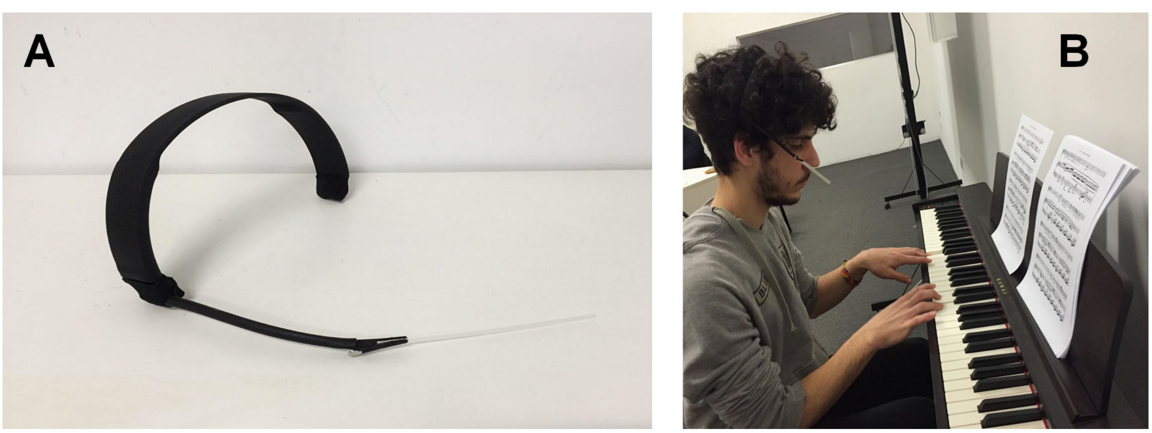

FIGURE 1. (A): Hand-made device with a clamp holding the paper strip containing the aroma. (B): Demonstration of the use of this device (note that this photo is not of an actual participant).

its own loudspeakers (no headphones were used) and the volume was kept at level 7, with 9 being the maximum volume. The improvisation was recorded on a PC as a MIDI file for ulterior analysis.

Taking into account that the conditions of the rehearsal room (e.g., size, light intensity, wall color, or temperature) might affect the results, it was decided to perform all improvisations under the same controlled conditions inside the room in order to reduce possible mediation effects of colors or other environmental aspects. The rehearsal room was medium in size, acoustically treated to minimize reverberation, with a temperature between 16 and 19 °C. Lights were very dim in order to reduce the visual influence of the environment and to mask the color of some stimuli on the strip (for instance, benzoin and chocolate gave the strip a brown color).

Each musician completed the experiment in one session that lasted about 60 minutes, except P12 who required two sessions. For each sample, pianists were requested to smell the strip and play, with 30 seconds between consecutive improvisations for resting, and a longer interval of 5 minutes after the tenth sample, trying to avoid olfactory fatigue. After completing the experiment, pianists were interviewed about the main differences among improvisations associated with the set of odorants according to tonality, pitch, dynamics, and harmony. Answers were recorded on a M4a audio file for subsequent analysis. The main outcomes are summarized in Supplementary Material S1 (all Supplementary Materials for this paper are available at the online version of this paper at mp.ucpress.edu). The chief dissimilarities in pitch evoked by the smells are indicated in Table 1.

Next, during the same day of the evaluation, each musician smelled the 20 olfactory stimuli again, in the same order as for the musical experiment and using the same procedure (i.e., strip attached to the handmade device, and 30 seconds of resting between consecutive samples), and filled out a form on an Excel spreadsheet by rating the perceived smell on a numeric scale from 0 to 9 according to the following amodal dimensions: *familiarity, pleasantness,* and *intensity.* For these scales, the value 0 was interpreted as "not at all," and the maximum, 9, as "extremely." They were instructed that *pleasantness* referred to the hedonic character (i.e., how much they liked the smell), and *intensity* was the range between weak and strong smells. The same three attributes were also used in a reported experiment aimed at exploring the psychological dimensions underlying odor-pitch associations (Crisinel & Spence, 2012). As discussed below, the ratings of *pleasantness* and *intensity* were used to investigate research questions (4) and (5), respectively. Participants were not trained in odor description, and they did not receive information about the odor character or sample code. Unfortunately, P13 was unable to perform this task. It took a total of 7 weeks to get the improvisations from the 14 participants.

Finally, in order to quantify the odor character of the 20 stimuli, they were assessed by 15 students from Universidad Tres de Febrero: eight were men, aged 22–31 years (M = 26.7, SD = 3.6) and seven women (aged 21–45 years, M = 32.4, SD = 8.9). Each participant evaluated 10 parameters on a 0–9 scale: the same three already mentioned, also assessed by pianists, and seven additional descriptors of odor character (*floral, woody, spicy, fruity, earthy, herbaceous,* and *sweet*). Moreover, two contrasting polarities were also rated on a scale from -4 to 4, which are the most salient dimensions in the description of fragrances (Zarzo & Stanton, 2009): *warm* (-4) vs. *fresh* (4), and *masculine* (-4) vs. *feminine* (4). These assessments were intended to address research questions (1) and (2), respectively.

ANALYSIS OF MUSICAL IMPROVISATIONS

Once all musical improvisations were recorded, the MIDI files were analyzed by means of the software MIDI Toolbox for Matlab (Eerola & Toiviainen, 2004). From each MIDI file, 14 musical parameters were extracted as described briefly below (for a more detailed description, see Supplementary Material S3). Pitch-class entropy and duration entropy quantify pitch and rhythmic uncertainty and complexity. As these parameters have been related to musical liking, predictability and novelty (Gold et al., 2019; Margulis & Beatty, 2008) we hypothesized that they could be associated to odor dimensions such as familiarity and pleasantness. The other selected parameters measure basic musical features and have been shown to be involved in music-smell or other crossmodal correspondences or to have an impact on smell perception.

Pitch Parameters

Highest note (N_{max}): The highest pitch of the improvisation, measured as MIDI note number.

Lowest note (N_{min}): MIDI note number of the lowest pitch of the improvisation.

Ambitus: the difference $N_{max} - N_{min}$.

Mean note (N_{mean}): average MIDI number of all notes in the improvisation.

Modal note (N_{mode}): MIDI number of the note most often selected.

Preferred octave (OCT): the octave most often chosen, ranging from 0 (MIDI notes 21–23 on the keyboard) to 8 (MIDI note 108 on the keyboard). For example, **OCT** = 4 was the octave comprising notes 60 to 71.

Note that $\mathbf{N_{mean}}$ is a continuous variable, while $\mathbf{N_{max}}$, $\mathbf{N_{min}}$, $\mathbf{N_{mode}}$, **OCT**, and **ambitus** are discrete random variables. See Supplementary Material S3 for more detailed definitions.

Parameters Related to Consonance and Dissonance of Melodic and Harmonic Intervals

Consonance and dissonance are strongly related to hedonic valence (Blood et al., 1999), which is naturally why they often have a role in crossmodal correspondences involving musical stimuli (Giannos et al., 2021; Mesz et al., 2011). These musical qualities seem especially relevant when studying music-smell associations, since hedonic valence is a salient dimension of odor descriptor space (Zarzo, 2008). To calculate these parameters for each improvisation, we first extract the sequence of chords (a chord is defined as the set of notes with a common onset time) and the highest voice (the sequence formed by selecting the highest note of each chord). The rationale for this approach is that the main melody tends to be placed in the highest voice (Huron, 2016).

Euler's *gradus suavitatis* (GR): measures the average dissonance of the consecutive melodic intervals of the highest voice (Euler, 1739/1968; Mesz et al., 2011; Wand, 2012). **GR** is high (low) if there is a large proportion of dissonant (consonant) intervals in this voice (Mesz et al., 2011).

Specifically, **GR** is computed according to the following algorithm:

i. For each consecutive pair of notes in the melody, find the interval determined by them as a frequency ratio $n: d$ in just intonation, where n and d are positive integers divisible by 2, 3 or 5. For instance, 1:1 (unison), 2:1 (octave), 3:2 (perfect fifth), 4:3 (perfect fourth), etc. (Large et al., 2016, Table 1).
ii. For the interval $n: d$, define $g = n \cdot d$.
iii. Compute the prime factorization of $g = \prod_i {p_i}^{\alpha_i}$. The quantity $s = 1 + \sum \alpha_i \cdot (p_i - 1)$ is computed (s is the *gradus suavitatis* of the interval). For example, if the interval is 45/32 (augmented fourth or diminished fifth), n= 45 and d = 32, then g = 1440 and its prime factorization is $1440 = 2^5 \cdot 3^2 \cdot 5$; its prime factors are $p_1 = 2$, $p_2 = 3$ and $p_3 = 5$, with $\alpha_1 = 5$, $\alpha_2 = 2$, $\alpha_3 = 1$, and consequently the *gradus suavitatis* of this interval is $s = 1 + 5\cdot(2 - 1) + 2\cdot(3 - 1) + 1\cdot(5 - 1) = 14$.
iv. GR is the average of s across all pairs of consecutive notes in the melody.

Dissonance (DISSO): measures the average dissonance of the chords. For each chord C_n, the dissonance D was computed as a weighted average of its interval vector IV = $(I_1, I_2, I_3, I_4, I_5, I_6)$, where I_1 is the number of minor seconds determined by pairs of pitch classes in the chord, I_2 is the number of major seconds, I_3 is the number of minor thirds, I_4 is the number of major thirds, I_5 is the number of fourths, and I_6 is the number of augmented fourths. The weights W_i $(1 \leq i \leq 6)$ are given by the *gradus suavitatis* of the corresponding interval. Then, D was averaged over all chords of the improvisation to get **DISSO**.

Interval dissonance rate (IDR): quantifies the average chord dissonance differently from **DISSO**, although it is also based on the interval vector of the chords (Mamedov & Peck, 2017). First, the interval vector (IV) of each chord C_n was determined. Next, the dissonant intervals of the IV are minor and major seconds and augmented fourths. **IDR** of C_n was computed as the ratio DI/TI, where DI is the sum of coordinates of the IV corresponding to dissonant intervals, and TI is the sum of all coordinates. Finally, this ratio was averaged over all chords. See Supplementary Material S3 for a more complete description of these parameters.

Time, Loudness, and Articulation Parameters

Duration: the average temporal extent of notes in seconds, after quantizing to 1/16 seconds.

Velocity: measured as the average MIDI velocity (range 1–127), it depends on the velocity of key depression which in turn relates to loudness (Dannenberg, 2006).

Articulation (ART): This parameter, calculated for each note or chord onset and averaged over the improvisation, is in the range $0 < \mathbf{ART} \leq 1$. It accounts for sound continuity (in musical terms, either *non legato/staccato/with rests* vs. *legato* and without rests). At each chord onset time O_n, **ART** = min $(1-(O_{n+1}-T_{max})/(O_{n+1}-O_n), 1)$, where T_{max} is the time when the last note active at O_n (i.e., belonging to C_n or earlier chords) is released. A value of **ART** = 1 corresponds to *legato* (no separation between consecutive notes or chords), while **ART** < 1 indicates either *non legato/staccato* or the presence of rests.

As the sustain pedal was disabled, the sound source stops when the key is released. However, note that room reverberation may prolong perceptual duration, though this reverberation time was short in our experiment due to the acoustically treated room. As a result, values of **ART** close to 1 can potentially be perceived as *legato*, so this parameter should be interpreted with caution from a *perceptual* point of view. However, a value of **ART** less than 1 means that the pianist released the keys before the next onset, stopping the sound source. Such articulation has been shown to be crossmodally related to salty taste (Mesz et al., 2011; Wang et al., 2021).

See Supplementary Material S3 for more information on these three parameters.

Parameters Related to Order and Complexity of Pitch and Rhythm Organization

Entropy is a concept from information theory that has been applied to quantify complexity, novelty, and uncertainty in music structure and perception (Gold et al., 2019; Margulis & Beatty, 2008). Gold et al. (2019) reported that entropy was non-monotonically related with musical liking, meaning that listeners preferred music with intermediate entropy. Here we consider, for each improvisation, entropy applied to pitch-class distribution (**pitch-class entropy**) and to duration distribution (**duration entropy**), denoted hereafter as **EN_pc** and **EN_d**, respectively.

EN_pc is calculated as the entropy of pitch-class distribution:

$$\mathbf{EN\_pc} = \sum_{i=1}^{12} -d_i \log d_i / \log 12$$

In this equation, d is pitch-class distribution (calculated by function **pcdist1** in the MIDI Toolbox), and *dlogd* is set to 0 when $d = 0$. This quantity ranges between 0 and 1. Note that **EN_pc** = 0 corresponds to extreme pitch polarization (only one pitch class is present), while **EN_pc** = 1 means that all pitch classes are used and equally represented.

Similarly, **EN_d** is the entropy of note duration distribution (calculated by the function **durdist1** in the MIDI Toolbox). A null **EN_d** implies that the duration of all notes is the same. Conversely, a value of **EN_d** close to 1 denotes high diversity and a more uniform distribution of note durations. See also Supplementary Material S3 for more information.

Statistical Data Analysis

When a certain parameter is evaluated by a sensory panel on a quantitative scale, the mean rating is usually considered to be the consensus assessment. An alternative approach consists of applying principal component analysis (PCA) to the sensory data matrix, considering the evaluations of panelists as variables. The first principal component (PC1) is the linear combination of variables that explains the largest amount of the data variability, which is quantified by R^2_x. It provides an estimation about the degree of consensus in the panel: a low value indicates a great variability among panelists, while R^2_x close to one reveals a high correlation between the variables (i.e., a high consensus). The goodness-of-fit for PC1 can also be calculated by cross-validation (Q^2), being less than R^2_x. A low value, even negative, indicates that PC1 is greatly modified if a subset of observations is randomly removed, which implies a lack of consensus in the panel. PC2 accounts for the remaining variability not explained by PC1, and so on for the rest of the components. In the case of PCA applied to sensory evaluations from different panelists, PC1 is expected to account for a large amount of the variability and, hence, PC2 is usually of little interest.

The projection of observations (tested samples) over PC1 and PC2 are called t[1] and t[2] scores, respectively. The contribution of variables in the formation of PC1 are called p[1] loadings, and likewise for each component. The t[1] scores are correlated with the mean value of the sensory characteristic, with such correlation being higher for greater values of R^2_x. These scores are more reliable than the mean because they are calculated as a weighted average, so that discordant panelists have a lower weight. Moreover, as the values are mean-centered prior to applying PCA, the biases of each individual panelist are corrected. Given the high variability between pianists in our experiment, this approach based on projection methods to latent variables seems appropriate.

The set of 14 parameters calculated from each improvisation leads to a three-way data structure comprised by 20 olfactory stimuli × 14 pianists × 14 musical parameters. This matrix, which does not contain missing values, was unfolded in three different ways:

- Unfolded matrix-1: comprised of 20 odorants (observations, in rows) by 196 variables in columns (14 pianists × 14 musical parameters).
- Unfolded matrix-2: comprised of 280 observations (20 odorants × 14 pianists) by 14 musical variables in columns.
- Unfolded matrix-3: comprised of 14 pianists (in rows) by 280 variables (20 odorants × 14 musical parameters).

First, the suitability of the 20 stimuli was discussed according to the sensory evaluations from the 15 students. Second, a univariate statistical analysis was carried out with each variable of matrix-2. For most of them, it was necessary to apply a mathematical transformation in order to achieve a normal distribution.

Third, the differences between pianists were studied by applying a two-way ANOVA (two factors: olfactory stimulus and pianist) for each musical parameter (unfolded matrix-2). The analysis was performed using the software Statgraphics 5.1. Those pianists yielding the highest or lowest values for each parameter were identified. Next, using the software SIMCA-P 10.0 by Umetrics, a PLS regression was fitted for the unfolded matrix-3, considering as response variables the musical expertise information available from participants: FMT, YCM, and YEP (Table 1).

Fourth, the most salient dimensions in matrix-2 were investigated by means of PCA using SIMCA-P. The data were normalized as already described, mean-centered and scaled to unitary variance prior to the analysis, which is the most common data pretreatment.

The olfactory compilation of Boelens and Haring (1981) was used in an attempt to characterize the underlying dimensions in the olfactory perception space of the 20 stimuli. This compilation, which will be referred to hereafter as the B-H database, contains 309 compounds rated by a panel of perfumers according to the odor similarity to 30 reference materials. The 20 stimuli used here were matched with equivalent odor descriptors from the B-H database, so that it was possible to estimate the *fresh* olfactory character (i.e., polarity of *fresh/light* vs. *warm/heavy*), the trigeminal/cool quality, and the *masculine* vs. *feminine* odor character. Next, using the unfolded matrix-1, PLS regression was applied to study if any of these three qualities was correlated with the musical parameters.

The sensory data obtained from the 15 students were averaged for each sensory parameter and each sample. Pearson's correlation coefficient between these parameters and the loadings from the B-H database was checked, as well as with key musical variables. PLS models were also fitted to identify relevant relationships between the sensory evaluations and musical characteristics. Finally, additional PLS regressions were carried out in order to find which musical parameters were correlated with familiarity, pleasantness, and intensity.

In all inference tests performed, the significance level considered was $\alpha = .05$. The observed significance level (p value) is commonly used when assessing the degree of linear relationship between two variables. A value greater than α implies that the observed correlation is by random sampling and, hence, not statistically significant. However, in the case of working with many observations, the correlation can be statistically significant with a low degree of correlation, which is of little practical use. For this reason, it is convenient to quantify the effect size, with Pearson's correlation coefficient (r) being commonly used in this regard. A value close to one indicates a high degree of correlation, regardless of the p value. This parameter has been considered to assess the effect size of the correlation.

Results & Discussion

SUITABILITY OF THE OLFACTORY STIMULI USED IN THE EXPERIMENT

The same number of 20 odorant materials has been used by similar studies (Belkin et al., 1997; Crisinel & Spence, 2012). The purpose here was to use pairs or triads of related odors: cedarwood – sandalwood (*woody*), lemon – orange (*citrus*), peach – plum (*fruity*), vanilla – cinnamon (*balsamic/sweet*), dark chocolate – benzoin (*balsamic/dry*), jasmine – neroli – orange blossom (*floral*), and lavender – mint – rosemary, which share certain camphoraceous-cool character. The perfumes Polo and Ice Blue are targeted to men and, according to the website of Fragrantica (2020a, 2020b), their main accords are *woody* and *aromatic*. Two additional samples, smoke and green leaves, cannot be directly compared with the others.

Numeric odor character descriptions were obtained from the group of 15 students, but not from the participating pianists because it was difficult to organize the improvisation trials and sensory evaluations of the stimuli during the same day, which would require enough time for resting to avoid olfactory fatigue. By calculating the average ratings from the 15 students, it turns out that the highest values for *floral* corresponded to jasmine, neroli, and orange blossom, which makes sense. Smoke and cinnamon yielded the highest ratings for *spicy*, which is intuitively appealing because smoky notes, cinnamon and spices are used as food seasonings. In the case of *fruity*, as expected, the highest scores corresponded to orange, peach, lemon, and plum. The samples mainly perceived as *herbaceous* were mint, rosemary, lavender, and green leaves, which is consistent with the literature (Zarzo & Stanton, 2009). Stimuli yielding the highest ratings of *sweet* were vanilla, peach, plum, jasmine, and orange blossom. Dark chocolate smelled woody but slightly sweet. Although cedar and sandalwood are materials extracted from aromatic woods, their woody odor quality was lower than expected. Generally speaking, the sensory evaluation suggests that the set of 20 olfactory stimuli was adequate in the sense that the two fruity samples were perceived as fruity, and so on.

EFFECT OF MUSIC TRAINING/EXPERIENCE OF PIANISTS ON THE RESULTS

Since piano technique is acquired over the years and has a strong impact on improvisation performance, some correlation was expected between YEP and the musical parameters. In order to investigate this issue, PLS regression was applied to matrix-3 considering FMT, YCM, and YEP simultaneously as dependent variables (Table 1). The sex is not balanced, and it could not be taken into consideration. According to the results, YEP was the parameter that could be better fitted. A new PLS was carried out to fit YEP, and the most relevant explicative variables were **IDR**, **EN_d**, and $\mathbf{N_{min}}$. By applying block-wise PCA, t[1] scores were extracted for each block of these musical parameters, which led to latent variables summarizing the consensus information from each block. It was found that PC1 from **EN_d** (R^2_x = .349) was the one yielding to a latent variable t[1] with the strongest correlation with YEP (r = .66, p = .009). Next, the mean values of **EN_d** were calculated for each pianist, and a similar correlation was found with YEP (r = .57, p = .03). This result suggests that, regardless of the odor quality, the five pianists with less piano experience tended to improvise music with lower entropy or variability in the duration of notes, which implies less complex rhythmic structures. Conversely, the most experienced pianists tended towards more complex rhythms, which might be explained by their higher training.

Supplementary Material S2 presents a statistical analysis carried out to identify pianists with an outlying performance. It was found that the pianist coded as P07 yields the maximum mean of **duration**, but the minimum of **ART**, **dissonance**, **pitch class entropy**, and **gradus**. By contrast, P03 yields the minimum average of **EN_d** and **velocity**, but the maximum of **preferred octave**, $\mathbf{N_{min}}$, $\mathbf{N_{mode}}$, and $\mathbf{N_{mean}}$. Moreover, P13 tended towards higher values of **ambitus**, which implies taking into account the opposite sides of the keyboard, which might be attributed to extensive training as a pianist (13 years). These results reveal that the music freely inspired by the odorants was highly variable between pianists (see Supplementary Material S2), which can be explained by the great variety in their experience and training (Table 1). Given the high subjectivity of inspiration, which is influenced by many personal and ambient factors, it was decided to work under controlled conditions with trained pianists having at least three years of experience in playing piano. Part of the variability in the results may stem from the limited ability of some participants to express their impressions or associations of the various scents through improvisation.

Considering that professional experience and personal factors might strongly affect the results, it would have been convenient to request detailed information from the participants. Some research papers use a single item measure focusing on just one musical aspect like expertise, but recent studies have incorporated multiple question items such as the Ollen or the Goldsmiths Musical Sophistication Indexes (Zhang & Schubert, 2019). Unfortunately, these indexes were not considered in the present research. Nonetheless, attempting to help in the interpretation of results, the information reported by pianists about their conscious strategies of association is summarized in Supplementary Material S1. Only partial consensus emerged, since each pianist focused on different smell features to represent them musically. The information from these interviews regarding pitch, which is indicated in Table 1, reveals a high variability between odor descriptors associated with low pitch.

Even experienced pianists might have their own stylistic conventions (e.g., if their background is in jazz, tango, classical music, etc.), which would partly affect the resulting musical parameters. Attempting to control such stylistic biases, pianists were instructed to try to avoid musical quotations (i.e., evocations of known musical works) and also to deliberately avoid style imitation. Unfortunately, the pianists' preferred musical genres were not examined. Using pianists who specialize in the same musical genre could have reduced variability and noise. Alternatively, a systematic comparison of two groups of pianists, each specializing in a different genre (e.g., jazz vs. classical pianists) could account for the effect of genre, as well as for cross-genre olfactory-musical correspondences. In summary, although a great effort was carried out for an appropriate selection of participants, there was a great variety in the pianists' experience and training.

MOST SALIENT CORRELATION STRUCTURE AMONG THE 14 MUSICAL PARAMETERS

Supplementary Material S2 contains a study about the statistical distribution of the musical parameters. Most of them did not reasonably follow a normal distribution, and mathematical transformations were applied in order to normalize the variables (Table S2). By applying PCA to the unfolded matrix-2, it turned out that PC1 and PC2 account for 25.6% and 20.4%, respectively, of the data variability. Both components provide relevant information because Q^2 is positive (PC1: Q^2 = 0.117; PC2: Q^2 = 0.088). Nevertheless, PC3 and PC4 were also considered in the loading plots depicted in Figure 2 in order to better account for the correlation structure.

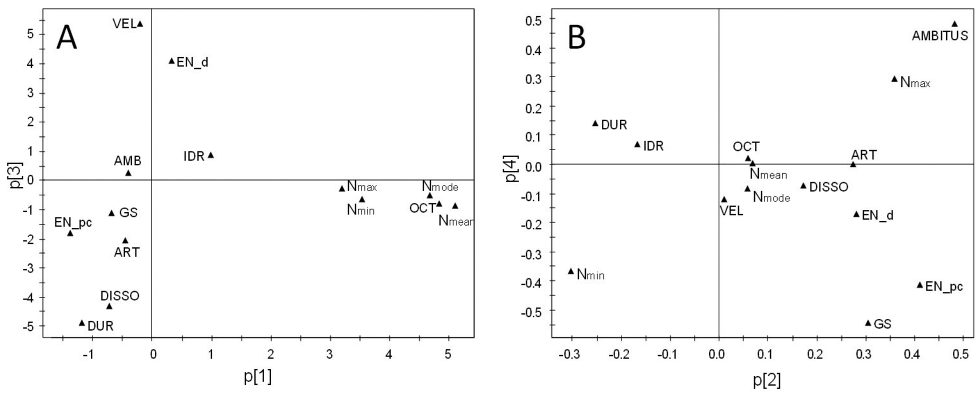

FIGURE 2. Loading plots derived from the unfolded matrix-2 (280 observations x 14 musical parameters); (A): p[3] vs. p[1]; (B): p[4] vs. p[2].

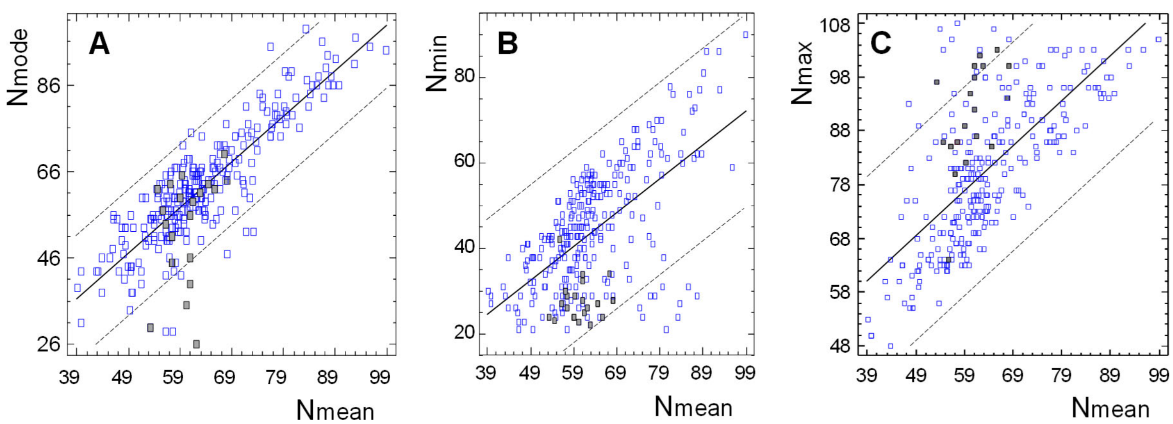

FIGURE 3. Scatterplots with fitted regression line showing the positive correlation between four variables from the pitch dimension (unfolded matrix-2); (A): N_{mode} vs. N_{mean}; (B): N_{min} vs. N_{mean}; (C): N_{max} vs. N_{mean}. In all 3 figures, the values corresponding to pianist P01 are highlighted as filled points. Dashed lines correspond to prediction limits at 95% confidence level.

According to Figure 2A, PC1 is determined by five variables with a positive correlation: $\mathbf{N_{mean}}$, **OCT**, $\mathbf{N_{mode}}$, $\mathbf{N_{min}}$, and $\mathbf{N_{max}}$. It was checked that the correlation between the other variables is low in most cases. Actually, the purpose was to extract musical parameters from the improvisations providing as much orthogonal information as possible. Nonetheless, some pairs of variables appearing close to each other in Figure 2 are also positively correlated, like **ambitus** vs. $\mathbf{N_{max}}$ (r = .66), which makes sense because **ambitus** is calculated as $\mathbf{N_{max}} - \mathbf{N_{min}}$.

The highest p[1] corresponds to $\mathbf{N_{mean}}$, which indicates that it is the most representative variable of PC1. $\mathbf{N_{mean}}$ yields a rather strong correlation with the octave most often selected, **OCT** (r = .88), because a higher octave implies preference for higher notes. Observed values of **OCT** range from 1 to 7, and the highest relative frequencies correspond to the values 4 (38.2%), 3 (31%) and 5 (13.6%), which is reasonable because 4 denotes the central piano octave. $\mathbf{N_{mean}}$ also appeared correlated with $\mathbf{N_{mode}}$ (r = .85, see Figure 3A), $\mathbf{N_{min}}$ (r = .61, p < .0001, Figure 3B), and with $\mathbf{N_{max}}$ (r = .68, Figure 3C), but this relationship was somewhat different for certain pianists like P01 (filled points in Figure 3). The ranges and other statistical information of these variables are indicated in Table S2.

The parameters $\mathbf{N_{mean}}$, $\mathbf{N_{mode}}$, $\mathbf{N_{max}}$, $\mathbf{N_{min}}$, and **OCT** can be regarded as a pitch dimension. PCA was applied to this cluster (unfolded matrix-1, 70 variables contained in the model), and it turned out that PC1 explained 17.3% of the overall data variability. Columns were mean-centered and scaled to unitary variance prior to the analysis. This pretreatment leads to centered variables with a null average, which implies that the bias between pianists is removed. This procedure seems a priori more appropriate than just calculating

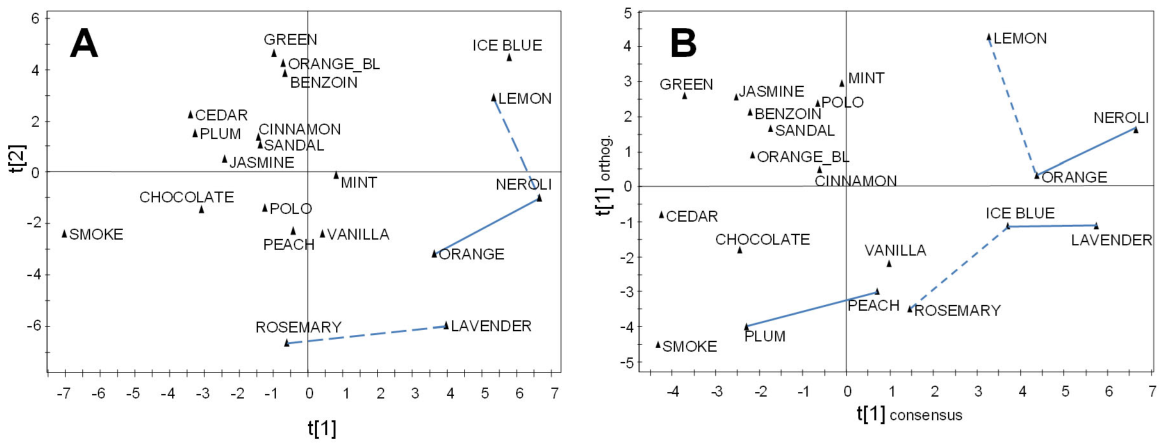

FIGURE 4. PCA results using the 5 pitch-related parameters (unfolded matrix-1); (A): score plot (t[2] vs. t[1]) considering the 14 pianists (14 x 5 = 70 variables); (B): Horizontal axis: t[1] scores from a PCA fitted with 8 pianists (consensus subgroup): P02, P05, P06, P07, P10, P11, P12, and P13 (8 x 5 = 40 variables). Vertical axis: t[1] scores from the PCA with the remaining 6 pianists, denoted as the orthogonal subgroup (30 variables). Samples of related smells appearing close to each other were joined with lines. Continuous lines indicate a stronger similarity than dashed lines.

average values because crossmodal correspondences involving pitch tend to be relative for each individual (Spence, 2019). For example, lemon tends to be associated with a higher pitch than smoke, but each pianist will choose different ranges of pitch to express such relationships.

The projection of odorants over PC1 and PC2 is depicted in Figure 4A. The highest t[1] scores correspond to neroli, Ice Blue, lemon, lavender, and orange. The position of lavender next to orange was somewhat unexpected because their smells are quite different, and the same applies to lemon appearing close to Ice Blue. A high variability is apparent by checking the interviews carried out with the pianists (Supplementary Material S1). According to Table 1, high-pitch music was evoked by strong smells for three pianists, but seven musicians associated high pitch to odorants with a fresh/light character (e.g., *sour, mint, citrus, green*, and *fruity*). Taking into account this information, it was decided to split the panel into two subgroups in an attempt to clarify the crossmodal correspondences. For this purpose, it was found that 42 out of the 70 variables in the model presented positive p[1] values. Curiously, such loadings were all negative for the five variables corresponding to pianists P03, P09, and P14, as well as for 4 out of the 5 variables from P08, and for 3 variables from P01. Considering this result and the fact that p[1] loadings for P04 were all close to zero, the set of 14 participants was split into two parts: an "orthogonal" group (P01, P03, P04, P08, P09, and P14) and a "consensus" cluster formed by the rest: P02, P05, P06, P07, P10, P11, P12, and P13.

It might be argued that this procedure to split the panel is post hoc based on the resulting improvisations, and not according to any attributes of the pianists (e.g., musical experience, preferred genre, or mood). This concern highlights the need for an appropriate characterization of the pianists in future studies. For example, the identification of musicians with synesthesia, partial anosmia, or other smell disorders might bias the results. Anyway, it can be deduced from Table 1 that P04, P09, and P14 consciously associated high-pitch improvisations with strong/intense scents, while most of the remaining pianists tended to improvise high-pitch music when smelling sour, citrus, or fresh odors, which are perceived as light (Zarzo & Stanton, 2009). Moreover, P01 linked high pitch with natural smells, which would explain the "orthogonal" performance of this participant, also revealed by Figure 3.

Next, PCA was repeated for each subgroup of pianists. Remarkably, for the consensus cluster, PC1 satisfies the cross-validation criterion (R^2_X = .270, Q^2 = .126), and a positive Q^2 was also obtained for the orthogonal group (R^2_X = .220, Q^2 = 0.035). Figure 4B plots on the vertical axis the t[1] scores from the "orthogonal" pianists vs. those from the "consensus" group on the horizontal axis. The highest p[1] loadings in Figure 4A correspond to three samples with a citrus character (neroli, lemon, and orange) as well as lavender and Ice Blue. A similar result is derived from the "consensus" group (Figure 4B, horizontal axis), but the three citrus samples are discriminated according to the information from the orthogonal group. Ice Blue smells woody – aromatic (Fragrantica, 2020a) and this sample appears in

Figure 4B next to *lavender*, which is consistent with their similar smell. By contrast, the fragrance Polo is classified as woody – chypre (Fragrantica, 2020b) and smells mainly woody and less aromatic, which agrees with the position of this fragrance close to sandalwood in Figure 4B, but far away from lavender.

CROSSMODAL ASSOCIATION OF THE LIGHT/FRESH ODOR CHARACTER WITH THE PITCH DIMENSION

When a wide range of odors is assessed, the most salient dimension usually discriminates pleasant vs. unpleasant smells. However, given that fragrances are obviously enjoyable scents, the dominant dimension in the context of perfumery often appears as a polarity that discriminates fresh vs. warm smells (Zarzo, 2013). Such interpretation applies to the most relevant latent variable of the B-H database. Thus, if PCA is applied to this database, the p[1] loadings of odor descriptors, which will be denoted as $p[1]_{B\text{-}H}$, can be interpreted as an indirect estimation of their fresh/light character (values available from Figure 2 of Zarzo & Stanton, 2009).

Most of the 20 odorants used in the present study can be directly matched with reference materials in the B-H database. Cedarwood and sandalwood were paired with *woody*; jasmine, neroli, and orange blossom were regarded as *floral*; peach and plum were matched with *fruity*; benzoin and dark chocolate were paired with *balsamic*; rosemary was linked with *coniferous* because such smells share certain camphoraceous notes (Zarzo & Stanton, 2009). Furthermore, cinnamon was regarded as intermediate between *sweet* and *spicy* (Table 2) because the reference for the latter in the B-H database (eugenol) smells slightly sweet. Polo was considered in between *woody* and *lavender*, and a similar criterion was adopted for Ice Blue based on the main accords of both scents (Fragrantica, 2020a, 2020b). Orange was paired with lemon, but slightly sweeter. Once the 20 stimuli were matched as indicated, we calculated the loadings corresponding to PC1 up to PC4, which were denoted as $p[i]_{B\text{-}H}$ ($1 \leq i \leq 4$, values in Table 2). The values $p[1]_{B\text{-}H}$ can be regarded as an indirect estimation of their light/fresh odor character, $p[2]_{B\text{-}H}$ discriminate masculine vs. feminine scents, while $p[4]_{B\text{-}H}$ account for those odors sharing camphoraceous notes. Regarding PC3 of the B-H database, it accounts for materials with a fatty smell, but such character was not considered in the present work.

TABLE 2. *List of olfactory stimuli used in the experiment, which are matched with related odor descriptors in the database reported by Boelens & Haring (1981), denoted as the B-H database*

		PCA of the B-H database							
Olfactory stimuli	Descriptors of the B-H database	$p[1]_{B\text{-}H}$	$p[2]_{B\text{-}H}$	$p[3]_{B\text{-}H}$	$p[4]_{B\text{-}H}$	X_{fem}	X_{fresh}	Z_{pitch}	N_{mean}
Green leaves	green	**0.279**	−0.116	0.086	−0.265	−0.98	−0.33	−0.93	57.9
Lemon	citrusy (lemon)	**0.189**	0.010	−0.032	0.167	**1.75**	**2.40**	**0.40**	**64.6**
Orange	0.9 citrus + 0.1 sweet	**0.143**	0.030	−0.005	0.140	0.86	**1.73**	**0.42**	**65.9**
Lavender	lavender	**0.128**	−0.076	0.127	**0.393**	−0.62	−0.40	**0.91**	**67.5**
Peach	fruity	**0.085**	**0.248**	**0.276**	−0.019	**1.40**	−0.27	0.21	64.5
Plum	fruity	0.085	**0.248**	**0.276**	−0.019	**1.33**	−0.40	−0.69	59.4
Rosemary	coniferous	0.061	−0.199	0.010	**0.396**	−1.09	**3.67**	**0.71**	**66.5**
Ice Blue	0.7 lavender + 0.3 woody	0.052	−0.131	0.067	**0.329**	**1.45**	−0.13	0.06	63.5
Mint	minty	0.045	−0.120	**0.152**	**0.286**	−0.51	**3.07**	0.11	64.4
Polo	0.5 woody + 0.5 lavender	0.002	−0.167	0.027	**0.286**	−0.33	0.87	−0.01	63.1
Neroli	floral	−0.010	**0.223**	−0.094	−0.215	0.20	**1.13**	**0.84**	**68.4**
Orange blossom	floral	−0.010	**0.223**	−0.094	−0.215	**1.75**	0.80	−0.47	60.7
Jasmine	floral	−0.010	**0.223**	−0.094	−0.215	0.62	0.67	−0.57	61.2
Cedarwood	woody	−0.124	−0.258	−0.073	0.179	−1.22	−0.60	−0.84	57.8
Sandalwood	woody	−0.124	−0.258	−0.073	0.179	−0.27	−0.27	−0.04	63.5
Smoke	smoky	−0.144	−0.265	−0.041	−0.141	−0.80	−0.13	−0.75	59.4
Vanilla	aromatic (vanillin)	−0.221	0.122	**0.322**	−0.114	1.16	−2.33	−0.05	63.1
Cinnamon	0.5 spicy +0.5 sweet	−0.231	0.015	**0.208**	−0.141	−0.62	−1.13	−0.37	60.8
Benzoin	balsamic	−0.249	−0.043	0.001	0.049	−1.27	−1.80	−0.84	57.8
Dark chocolate	balsamic	−0.249	−0.043	0.001	0.049	−0.80	−3.07	−0.78	58.5

Note. The loadings $p[i]_{B\text{-}H}$ correspond to the four principal components (i = 1, 2, 3, 4). Rows are sorted by decreasing order of $p[1]_{B\text{-}H}$. X_{fem} contains the average ratings from experiment-2 (15 volunteers) on a scale from masculine (-4) to feminine (4). Likewise, X_{fresh} are the average ratings from warm (-4) to fresh (4). Z_{pitch} contains the t[1] scores derived from a PCA applied to the five pitch-related variables (unfolded matrix-2), after averaging these scores for the group of all pianists (except P03). $\mathbf{N_{mean}}$ contains the average values of this parameter from all pianists except P03. In all columns, the five highest values are highlighted in bold to facilitate the comparison.

Starting from the unfolded matrix-2, PCA was applied after selecting the 5 variables corresponding to the pitch dimension, and it was found that PC1 explains 69.4% of the data variability ($Q^2 = 0.555$). The odor stimuli yielding the highest average t[1] scores (variable Z_{pitch} in Table 2) are lavender, neroli, rosemary, orange, and lemon, which share a certain refreshing or cooling character. This result is consistent with Figure 4B. The correlation between Z_{pitch} and $p[1]_{B\text{-}H}$ is lower than expected ($r = .39$, $p = .09$) due to the presence of one outlier: *green leaves*. This stimulus corresponds to a fresh scent, but it was associated with low-pitch tones probably due to its unpleasant smell (Cuskley & Kirby, 2013). It was actually rated by pianists as the least familiar odor, and the second one regarded as more intense and unpleasant. Such disagreeable character was not intended when the sample was chosen for the experiment, because the descriptor "herbal, green, cut grass" is usually regarded as pleasant (see Table 1 of Zarzo, 2008). The reason seems to be that the reference material for *green leaves* (cis-3-hexenol) smells somewhat pungent, but such unpleasant character is not common in fresh scents. Moreover, mono-molecular odorants tend to smell somewhat artificial, not natural. Therefore, it is reasonable to regard this sample as an outlying stimulus. If this observation is disregarded, $p[1]_{B\text{-}H}$ yields a statistically significant correlation with Z_{pitch} ($r = .63$, $p = .004$) as well as with $\mathbf{N_{mean}}$ ($r = .61$, $p = .006$).

The values of Z_{pitch} can be interpreted as an estimation of the pitch dimension, which justifies the strong correlation ($r = .987$) with the average values of $\mathbf{N_{mean}}$. Taking into account the sensory evaluation of the fresh odor character obtained from the panel of 15 students, it turns out that X_{fresh} is significantly correlated with $p[1]_{B\text{-}H}$ ($r = .608$, $p = .004$), which validates the interpretation of such loadings as an indirect estimation of the fresh/light character. Moreover, X_{fresh} is also correlated with $\mathbf{N_{mean}}$ ($r = .570$, $p = .009$), revealing that fresh scents tended to evoke improvisations with a higher pitch.

In the pioneering experiment of Belkin et al. (1997) by matching auditory frequencies with odors commonly used in perfumery, the highest pitch corresponded to bergamot, 2-ethyl fenchol, and neroli oil, two of which smell citrusy. By contrast, the lowest frequencies were matched with rosalva, birch tar, civet, and caramel lactone, all of which except rosalva (a fresh rosy scent) are perceived as dissimilar to citrusy scents (Zarzo & Stanton, 2009). Hence, this was probably the first work reporting that light/fresh scents were associated with a higher pitch. As a reminder, the odor descriptors light and fresh are used in the present work as synonyms (Zarzo, 2013, 2020).

Taking into account that fresh vs. warm is a polarity semantically associated with temperature, as discussed earlier, it is of interest to discuss sound-temperature crossmodal correspondences. Wang and Spence (2017) found that a higher pitched soundtrack was associated with lower temperature drinks. Such correspondence would be consistent with our results if *fresh* is interpreted as *cool*, which is the usual meaning of the Spanish term "fresco" that was used in our experiment. It should be noted that Spanish was the mother tongue of all participants in our research. However, odor-temperature associations do not appear to be consistent overall (Wnuk et al., 2017). By considering the light/heavy polarity instead, our findings are also consistent with a reported study (Walker et al., 2017): objects that feel heavier are judged to make lower pitched sounds than objects feeling less heavy.

In summary, regarding research question (1) proposed as a target of the research, pitch appeared as the most salient correlation structure among the 14 musical parameters, and it was associated with the fresh/light character of the odor stimuli. In the context of perfumery, odors most dissimilar to *fresh* are described as tenacious or heavy. The *light* vs. *heavy* polarity is often the most salient in the description of fragrances (Zarzo, 2013) and, remarkably, it is crossmodally associated with auditory pitch, which appeared in the present study of free improvisation as the most salient dimension of the musical parameters.

ASSOCIATIONS OF MUSICAL PARAMETERS WITH FEMININE SCENTS

The average sensory ratings of odor stimuli provided by the 15 students about the *masculine* vs. *feminine* polarity, which were denoted as X_{fem} (Table 2), are of interest because such odor character has not received much attention yet in sound – odor correspondences. Nonetheless, experimental evidence has shown that colors associated with the odors of fine fragrances are influenced by the perceived masculinity/femininity of those fragrances (Zellner et al., 2008).

In the B-H database, PC2 discriminates descriptors most frequently encountered in women's fragrances vs. those more common in men's fragrances. Therefore, $p[2]_{B\text{-}H}$ (values in Table 2) can be regarded as an indirect estimation of the masculine vs. feminine character of the stimuli. It turns out that the correlation between $p[2]_{B\text{-}H}$ and X_{fem} is statistically significant ($r = .669$, $p = .001$), which validates the overall performance of the sensory panel. However, lemon was the sample with the highest X_{fem} (Table 2), which is not consistent with the unisex character of this scent (Zarzo & Stanton, 2009). Furthermore, jasmine and neroli were rated as moderately feminine (X_{fem} = 0.62 and 0.2, respectively), though we expected a higher feminine character because floral scents are typically encountered in women's fragrances.

PLS was applied to the unfolded matrix-1 in order to fit $p[2]_{B\text{-}H}$ and X_{fem} as a function of the musical parameters available for the 14 pianists. The first component appeared as slightly relevant (Q^2 = 0.098), and the highest loadings corresponded to **EN_pc**, **gradus**, and **ambitus**. Taking into account that sweet scents are preferred for women's fragrances, similar results were expected for X_{sweet} (i.e., the average sensory ratings of *sweet* from the 15 students). However, PLS was carried out to predict this variable as a function of the musical parameters, but the first component did not provide relevant information (Q^2 = -0.202).

Next, the t[1] score vector was extracted by applying PCA to the block of **EN_pc** for the 14 pianists, and likewise for **gradus** and **ambitus**. It was found that the latent variable from **gradus** yields a negative Q^2 (R^2_x = .196, Q^2 = -0.14), which implies a poor consensus among the pianists.

Regarding the latent variable from **pitch-class entropy**, it was found that the correlation between t[1] scores from this parameter and $p[2]_{B\text{-}H}$ was statistically significant (r = .67, p = .001). This relationship indicates that masculine scents evoked music with lower values of **EN_pc**, which correspond to more pitch-class polarization and less complexity of pitch organization. Conversely, feminine smells evoked improvisations with higher **EN_pc**, which implies further complexity and a more uniform pitch-class distribution. Taking into account that most pianists were men and that greater **EN_pc** indicates more "novelty, complexity, and surprise" (Margulis & Beatty, 2008), it is intuitively appealing that feminine scents evoked, for men, music with such characteristics. Further studies using a balanced panel according to sex should be necessary in order to better understand these relationships.

It turned out that t[1] from **ambitus** was negatively correlated with X_{fem} (r = -.52, p = .019). Considering that masculine scents tend to be associated with activity and stimulation (Zarzo & Stanton, 2009), this observed correlation suggests that such smells inspired melodies with a higher ambitus.

In summary, with respect to research question (2), the mean ratings on a scale of *masculine* vs. *feminine* were negatively correlated with the ambitus of the improvisation. Moreover, a positive correlation was also found with **pitch-class entropy**, but the interpretation of results is unclear because only two pianists were women.

ASSOCIATIONS OF MUSICAL PARAMETERS WITH CAMPHORACEOUS SCENTS

Starting from the unfolded matrix-1, another PLS was conducted to simultaneously predict $p[3]_{B\text{-}H}$, $p[4]_{B\text{-}H}$, and $p[5]_{B\text{-}H}$ as a function of the musical parameters available from the 14 pianists. As the best goodness-of-fit was achieved with $p[4]_{B\text{-}H}$, an additional PLS was carried out to fit this variable, and it turned out that **articulation** was the musical parameter yielding the highest contributions. Next, the mean values of **articulation** were calculated for each odorant, and the lowest values corresponded to lavender < mint < Ice Blue < cinnamon < rosemary. The statistical distribution of this musical parameter is strongly negatively skewed, and an appropriate transformation was used to normalize the values (Table S2). Working with normalized values, the lowest **ART** corresponded to lavender < Ice Blue < Polo < rosemary. Interestingly, all these four odorants share a certain camphoraceous character and are perceived as cool. Actually, according to Fragrantica (2020a), the main olfactory ingredients of Ice Blue are mint and lavender. Such odor similarity is explained by the activation of the trigeminal nerve.

In the B-H database, the descriptors *lavender*, *coniferous,* and *minty* yield the highest p[4] loadings. In the odor effects diagram (Zarzo & Stanton, 2009), descriptors referring to odors sharing camphoraceous notes like *minty*, *coniferous,* and *lavender* appear close to "stimulating" and "active." Consistent with this association, a previous study on music and emotion has reported that music inducing faster breathing, skin conductance, and heart rate (i.e., which could be regarded as stimulating music) was fast, accentuated, and *staccato* (Gomez & Danuser, 2007).

This observed correspondence between camphoraceous notes and **ART** < 1 raises the question about how to discriminate between the contribution of the trigeminal perception and that of the activation of olfactory receptors. Actually, the interaction between the olfactory and trigeminal systems is an important factor involved in odor sensations (Hummel & Livermore, 2002), and camphor-like notes are commonly used in commercial fragrances for providing a cooling effect in winter-type fragrances (Zarzo, 2020). Unfortunately, this issue is unclear from our research because the trigeminal perception was not quantified properly.

Minty odors are often described as cool, which refers to the special cooling effect of camphoraceous notes produced by the activation of trigeminal nerve receptors. Such receptors are responsible for different sensations in the nasal cavity like tactile, pressure, pain, and temperature. Many trigeminal odorants produce effects described as irritating, tingling, pungent, cooling (e.g., menthol), or hot (capsaicin). Therefore, the association between camphoraceous notes and **ART** < 1 reveals that the discontinuity in music (i.e., presence of silences) measured by **ART** has a crossmodal correspondence with certain "discontinuity" in olfactory perception space, because the trigeminal nerve provides sensory information about touch-position and pain-temperature, independent from the senses of smell, sight, taste, or hearing, which are processed by different cranial nerves and sent through different pathways to the cerebral cortex.

In summary, regarding the correspondence of camphor-like scents with musical parameters (research question 3), it turned out that camphoraceous/trigeminal notes were associated with a more *non legato/staccato* articulation or rests. Nonetheless, the results involving articulation should be considered with precaution because the articulatory technique is best controlled by professionals, and the experience in playing piano was rather variable among the musicians who took part in this research. Hence, this observed association between trigeminal odors and **ART** < 1 needs to be confirmed with expert pianists in further experiments, with an appropriate quantification of the trigeminal perception of the odor stimuli.

ASSOCIATIONS OF MUSICAL PARAMETERS WITH OLFACTORY PLEASANTNESS

As expected, a positive correlation was found for the ratings of familiarity from pianists vs. naive participants (n = 20, r = .69), and a similar value turned out in the case of pleasantness (r = .60). As the correlation is not very strong, the average values represent a consensus construct for the assessment of such aspects. It turns out that the sensory average values of pleasantness and familiarity yield a rather strong correlation (r = .82, p < .0001) because familiar scents perceived in our everyday life tend to be regarded as pleasant, though some exceptions may be encountered. Such a relationship has been discussed by Distel et al. (1999). Many fragrant materials, essential oils, and aroma chemicals can smell quite artificial/cheap, which reduces the familiarity character.

Green leaves was the stimulus most disliked and less familiar, probably because this material (cis-3-hexenol) smells somewhat pungent. *Smoke* was the second stimulus most disliked, which is consistent with the scarce use of such notes in perfumery (Zarzo & Stanton, 2009). Remarkably, both odors regarded as the most unpleasant were also the ones with a stronger smell. This fact produces a certain confusion of effects, though intensity and pleasantness, in the present work, were intended to account for independent dimensions of odor perception.

In our experiment, the mean values of pleasantness and familiarity were 5.6 and 6.1, respectively. Both are greater than 4.5 (i.e., the midpoint of the 0-9 scale), which implies that the set of olfactory stimuli was biased towards pleasant and familiar scents. This issue was a prerequisite of the study because such odors are more likely to evoke olfactory memories associated with emotions, which are expected to be correlated with particular musical parameters. The use of unfamiliar smells would surely lead to other types of musical relationships that will require further investigation.

PLS regression was applied to fit pleasantness as a function of the musical parameters (unfolded matrix-1). It turned out that the first component did not provide relevant information (Q^2 = -0.17), which forced us to apply a different statistical approach. For each stimulus, the mean value of the musical features was calculated for the set of 14 pianists. By calculating the correlation coefficient with pleasantness, such correlation was statistically significant (at α = 5%) for the parameters: **EN_pc** (Figure 5A: r = -.59, p = .006), **DISSO** (Figure 5B: r = -.50, p = .02), and $\mathbf{N_{min}}$ (Figure 5C: r = .49, p = .03).

The negative correlation between **EN_pc** and pleasantness reveals that unpleasant odors evoked music with higher values of **EN_pc**, which implies "novelty, complexity, and surprise." The fact that *green leaves* yields the highest value of this parameter is noteworthy (Figure 5A). The reason could be that, when sniffing a blind sample, people usually expect a pleasant smell, or at least not excessively unpleasant, because most odors commonly encountered in our everyday life are regarded as agreeable. Nonetheless, this hypothesis requires further investigation because PC1 from the block of **EN_pc** variables yields a negative goodness-of-fit by cross-validation (Q^2 = -0.14), which implies a poor consensus among the panel.

In the case of $\mathbf{N_{min}}$ (Figure 5C), the latent variable extracted from this block, which explains 21.5% of the data variability, is also correlated with pleasantness (r = .46, p = .04). Hence, pianists tended to reach lower pitches when smelling the most disagreeable samples. Figure 5B reveals that the two most unpleasant stimuli (i.e., *green leaves* and *smoke*), which also yielded the strongest odor, were the ones evoking the most dissonant music. However, this relationship is markedly influenced by *green leaves*. Another drawback of this relationship is the high variability of the panel regarding this musical parameter. Actually, if PCA is carried out

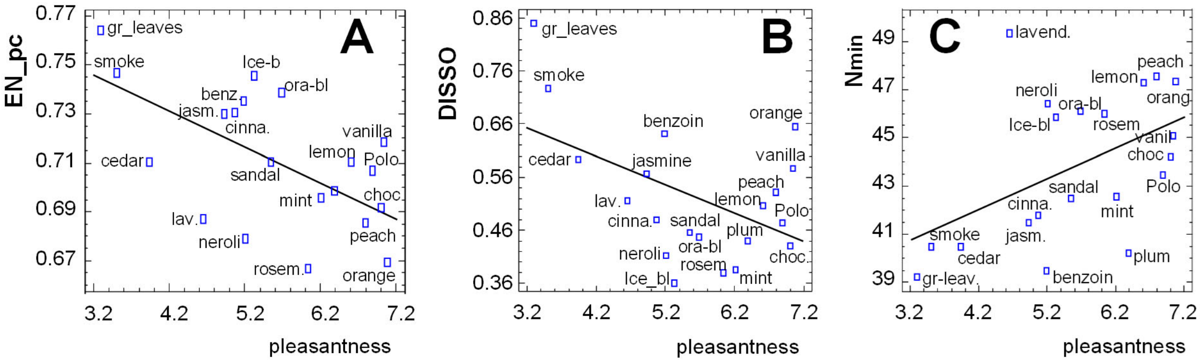

FIGURE 5. Scatterplot of fitted regression model between odor pleasantness of the 20 stimuli vs. three musical features (average values from the 14 pianists) extracted from the improvisations; (A): pitch-class entropy; (B): dissonance; (C): minimum note.

with the block of the 14 **dissonance** variables, PC1 does not provide relevant information (Q^2 = -0.17) and it is not significantly correlated with pleasantness (p = .20).

In summary, with respect to the effect of olfactory pleasantness on the hedonic value of the improvisations (research question 4), a certain correlation was expected between **DISSO** and the sensory evaluation of odor pleasantness because dissonance in music tends to be judged as unpleasant, harsh, or unstable, while consonance is typically associated with pleasantness (Mesz et al., 2011). The observed negative correlation between mean values of olfactory pleasantness and **dissonance** reflected by Figure 5B (r = -.50) is consistent with this hypothesis, but the consensus regarding this parameter was very weak among the pianists. Therefore, further research is required to investigate such a relationship as well as the observed correlation with pitch-class entropy (r = -.59) and $\mathbf{N_{min}}$ (r = .49).

ASSOCIATIONS OF MUSICAL PARAMETERS WITH OLFACTORY INTENSITY

In many olfactory experiments, one step is to dilute the stimuli in order to reach a similar perceived odor intensity for all samples. However, in this experiment, odorants were used in their original concentration, resulting in a variability in the odor intensity. Such perceptual feature was sensory evaluated on a 0–9 scale, and it was found that 58.9% of the values were $\geq$ 7.

As described earlier, **velocity** is related to the depression force when the key is pressed down, which affects the loudness of the improvisation. Wang et al. (2016) found a positive correlation between the intensity of taste and sound, which is explained by neurophysiological mechanisms (Nehrkorn et al., 2015). Hence, the purpose of using olfactory stimuli in their original concentration was to study the effect of intensity on the musical parameters, and the same criterion has been followed by other studies about music and smell or taste (Crisinel & Spence, 2011; Levitan et al., 2015). In the latter work, intensity appeared as a relevant variable in a regression model explaining the association between music and aroma. However, in our experiment, average values of **velocity** were not correlated with odor intensity (r = .08), and PLS regression did not provide relevant information (Q^2 = -0.2).

Next, one PLS model was applied to fit odor intensity for each block of the other musical parameters, and the one yielding the highest Q^2 was **IDR** (Q^2 = 0.21). By applying PCA to the block of **IDR** variables, the resulting latent variable t[1] was moderately correlated with odor intensity (r = -.48, p = .03). However, the correlation between average **IDR** values and intensity is not statistically significant (p = .60).

In summary, although strong tastes are matched consistently with louder musical notes (Wang et al., 2016), no clear relationships appeared between musical parameters and olfactory intensity (research question 5). Based on the results, it would be convenient to carry out this kind of study (i.e., music freely inspired by smells) with stimuli at a similar odor intensity, which is a common practice in many other olfactory studies. The fact that some pianists associated pitch with intensity (e.g., P09 and P14, see Table 1) reveals the enormous complexity of attempting to relate too many olfactory dimensions with the musical parameters.

General Discussion

MAIN OUTCOMES OF MUSIC – ODOR CORRESPONDENCES

Unlike most earlier studies, the experiment reported here investigates a music-specific context while using musical improvisation. The musical context, as well as the production paradigm, which was used in previous research on crossmodal correspondences (Mesz et al., 2011), presents advantages and disadvantages. A positive aspect, apart from the increased ecological validity, is that it enables free exploration of the musical parameter space in a natural musical setting, which allows the observation of a rich collection of correspondences, some previously unsuspected, which can form the basis of more systematic experiments of perception like the ones suggested earlier. However, it was found that the variability among the pianists' rendering was extreme, such that the pianists' experience affected musical variables considerably and much of the data proved quite noisy. A similar context and production paradigm was used by Murari et al. (2020), but participants were just requested to indicate which piece of music came to mind (title and composer) when experiencing a given sensory stimulus (i.e., they did not play the music).

Despite the high variability in the musical patterns found in this experiment of music freely inspired by a set of odors, it was possible to find crossmodal correspondences between particular musical features and perceptual dimensions of odor space. Regarding the scents evoking high-pitch music (research question 1), it turned out that pitch was the most salient dimension among all musical parameters evaluated (Figure 2) and, remarkably, a crossmodal association was found with the olfactory fresh/light character, which is the most salient perceptual dimension in perfumery scents (Zarzo, 2013). This relationship is consistent with previous studies about crossmodal odor – sound associations (Belkin et al., 1997; Crisinel & Spence, 2012; Crisinel et al., 2013; Ward et al., 2021). However, such correspondence was not consistent for all participating pianists, and the interpretation of results improved when the panel was split into two subgroups.

With respect to the musical parameters associated with feminine/masculine scents (research question 2), the results reported earlier suggest that masculine stimuli evoked melodies with a higher **ambitus**, though this correlation was not strong (r = -.52, p = .02). By contrast, a rather significant correlation was found between the masculine/feminine character of odor stimuli with **EN_pc** (r = .67, p = .001), indicating that masculine odors evoked melodies with a lower **pitch-class entropy** (i.e., music putatively perceived as less complex in its pitch organization). Given that scents can be rated as masculine vs. feminine (i.e., more suitable to men's or women's fragrances), a feminine smell will be perceived as more noteworthy for a man. Such relationships, which were tentatively identified thanks to the music-specific context and the production paradigm used in the present research, are novel findings because the perception of scents as masculine vs. feminine has not received much attention yet in the context of crossmodal odor – sound associations.

Regarding the musical features affected by camphoraceous odors (research question 3), it was found that the lowest values of **ART** corresponded to *lavender*, *Ice Blue*, *Polo*, and *rosemary*, all of which share a certain camphor-like character. Hence, camphoraceous scents evoked music that was more *non legato/staccato* or had rests. This association, which is reported here probably for the first time, is intuitively appealing because camphor-like odors account for certain "discontinuity" in our perceptual space, as discussed above.

Concerning how the improvisations were affected by pleasant vs. unpleasant scents (research question 4), it was found that pleasantness yielded the strongest negative correlation with **pitch-class entropy**. This result suggests that unpleasant smells inspired music with "novelty, complexity, and surprise." A statistically significant correlation was also observed between pleasantness vs. **dissonance** and $\mathbf{N_{min}}$, which is partly consistent with earlier studies because dissonance in music tends to be judged as unpleasant.

Finally, with respect to the effect of olfactory intensity (research question 5), a moderate correlation was identified with **IDR**, but such relationship is uncertain. Sound loudness is associated with odor intensity (Deroy et al., 2013; Persson, 2011; Stevenson et al., 2012), but such correspondence could not be identified in the present research.

SUGGESTIONS FOR FURTHER STUDIES

The results lead to some suggestions regarding how to improve the experimental design in future similar studies. In order to attenuate the observed great variability among the pianists' improvisations, a more careful selection of trained pianists with the same musical background and level of training should be required, which would also allow to relate that variability to specific features. Using professional pianists with experience in improvisation is preferable, though improvisation is a complex skill and even professional, highly trained classical pianists are not necessarily competent improvisers. Alternatively, better control of participants' music training (e.g., selecting and comparing two sharply distinct groups of pianists, like professional musicians vs. beginners) could enable a better examination of the effect of music training. Another possibility would be to replicate the experiment with the same pianists and odor stimuli. Presenting odorants to improvisers more than once, in random order, would facilitate an examination of within-subject consistency, and thus of the experiment's reliability.

Detailed information about the preferred musical genre of pianists, their expertise in improvisation, musical background, and other personal factors should be surveyed quantitatively in future studies to better account for the variability in the results. For example, one musician used to improvising jazz will probably lead to different results compared with another pianist trained in classical music. On the other hand, given that personal and psychological aspects affect the results, it would be necessary to use a comprehensive questionnaire to evaluate the psychological state of musicians. Hence, it is important to keep record of all factors that might affect the inspired music. One way to examine whether the pianists' olfactory-musical associations were not merely idiosyncratic could have been a perceptual experiment in which a new group of participants listens to each improvisation previously played by the pianists and then chooses the odor stimuli that best matches with the music.

It is also convenient to quantitatively assess the perception of odor stimuli by each participant. In the present research, it was not investigated which particular stimuli used in the experiment evoked past memories in most participants, and which type of emotions were associated with those memories. However, some episodic memories emerged in the interviews with the pianists (see Supplementary Material S1). This issue should be taken into consideration in future studies.

Aimed at properly studying the musical parameters evoked by masculine vs. feminine scents, it would be convenient to use a balanced panel according to sex, and to compare the results between male and female pianists. Finally, the results reported here also recommend the use of stimuli at a similar odor intensity because strong smells can be annoying and disturbing, particularly in the case of unpleasant stimuli.

MECHANISMS UNDERLYING SOUND – ODOR CORRESPONDENCES

What are the possible mechanisms proposed to explain these sound – odor associations? Spence (2011) suggested three different types of crossmodal correspondences: *structural*, *semantic,* and *statistical*. The former are based on common neural encoding across the senses (e.g., of stimulus intensity). Semantic (or lexical) correspondences are based on a common vocabulary describing stimuli in different sensory modalities, as in the use of "sweet" to describe music and taste (Mesz et al., 2011), or in common connotative meaning (Walker et al., 2012). Statistical correspondences come from the statistical regularities of the multisensory environment such as, for example, the physical correlation between pitch and size. This explanation is straightforward between odors and tastes commonly encountered together (Deroy et al., 2013). However, the concurrence of music and smells is quite unusual, and this interpretation does not properly explain the association between fresh/light odors and bright/daytime conditions. There might be a partial dependence with temperature because daytime conditions are warmer and brighter than during the night, but such relationships will require further investigation.

Spence (2011) also points out that crossmodal correspondences between features of stimuli can be established according to the emotional effects these stimuli have on an observer. Such emotionally mediated correspondences are thought to be based on the matching of similar emotions or hedonic valence related to each of the associated stimuli (Palmer et al., 2013). Stimuli that often give rise to (strong) emotional responses such as music and fragrances are therefore likely to develop emotionally mediated crossmodal correspondences. Levitan et al. (2015) explored this hypothesis of emotional congruence of odors and music. Their participants were asked to make matches between musical selections in different styles with a set of 15 odorants and, subsequently, to rate both music and smells according to eight emotional dimensions. It was found that similarity in the emotional response evoked was able to predict the strength of the match between music and odors.

The human perceptual space of smells is not structured into orthogonal dimensions, which might explain the complexity for the interpretation of odor – music correspondences. This issue was illustrated graphically in a sensory 3-D map of odor descriptors developed by Zarzo (2015). Regarding the interpretation of odor – music associations, it is important to take into consideration whether a given scent evokes a very specific odor imagery linked to personal experiences. On the contrary, sometimes the smell does not evoke a particular odor object or a vivid past memory, which is usually the case with commercial fragrances because they are complex mixtures of fragrant ingredients. In that case, the underlying dimensions of olfactory perception come into play: the scent may evoke daytime vs. nighttime conditions or be perceived as more suitable to men's vs. women's wear, or as sweet vs. non-sweet.

The association of high pitch with fresh smells can be analyzed as a semantically based correspondence by framing it in the scheme described by Walker et al. (2012). These authors proposed that cross-sensory correspondences can arise between dimensions of connotative meaning, being therefore independent of the specific sensory channels. According to this scheme, high pitch and fresh smells would be associated because both are linked with "bright" (Crisinel et al., 2013; Hubbard, 1996) and "light" in weight (Eitan & Timmers, 2010; Zarzo & Stanton, 2009). Stevenson et al. (2012) found that odors described as high-pitched tended to be easier to name and more familiar while, in contrast, loudness was associated with perceptual dimensions. However, in our research, $\mathbf{N_{mean}}$ was not correlated with familiarity (p = .80). The fact that there were inconsistencies between the pianists regarding this dimension also suggests a type of correspondence, such as semantic or emotional, which is more prone to individual differences than correspondences that happen to be structural or statistical in origin, which can be expected to be more universal (Spence, 2022).

A related mechanism that may underlie the freshness – high pitch correspondence, but not necessarily based on semantics, is *transitivity of associations*. It refers to the associations that emerge as transitive connections between previously associated pairs of stimuli with a common element (i.e., C is related to A as a result of A being associated with B, and B to C) (Deroy et al., 2013; Fields et al., 1984). This mechanism would imply a transitive association of citrus odors with high pitch: (i) citrus scents yield a correspondence with visual brightness (Crisinel et al., 2013) and are preferred for daytime fragrances (Zarzo, 2020), suggesting that they evoke daytime conditions; (ii) some studies have suggested that most subjects match high pitch to visual brightness (Hubbard, 1996; Marks, 1974), which would imply that such stimuli evoke daylight conditions; (iii) as a result, citrus scents are often matched with high pitches (Belkin et al. 1997). The notion of sensory brightness of odors related with greyscales was put forward long ago (Von Hornbostel, 1931).

In connection to emotional correspondences between musical features and fragrances in the present study, musical complexity parameters, as measured by entropy and consonance/dissonance, have been shown in several studies to be related to pleasantness and liking (Gold et al., 2019; Margulis & Beatty, 2008). The negative correlation reported here between olfactory pleasantness and **EN_pc** and **DISSO** suggest that the hedonic valence of fragrances may have influenced the likability or pleasantness of the improvisations. In this way, these correlations could be correspondences mediated by emotion or hedonic valence. These results can also be compared with previous experimental studies reporting, conversely, that the hedonic valence of sounds transferred to the pleasantness of subsequently presented odors (Seo & Hummel, 2011; Seo et al., 2014).

In summary, a positive correlation was found between pitch and the fresh/light odor character, but such association was only valid for part of the panel. Regarding the feminine/masculine odor character, certain correlations were identified, but the interpretation of results is uncertain because most participants were men. Further research with an appropriate selection of men's and women's fragrances should be necessary to better understand how such polarity affects the inspired music.

Emotional mediation may also explain why camphoraceous fragrances were associated with more *non legato/staccato* music, or the presence of silences, which was one of the novel findings of the present work. Such odors are perceived as active and stimulant (Zarzo & Stanton, 2009), while *staccato* music tends also to be judged as active and associated with high arousal (Gomez & Danuser, 2007).

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