Abstract

In the present study, we explore the existence of cross-cultural differences in odour-colour correspondences between two European countries with geographic proximity and shared history: England and France. Moreover, we test whether a single chromatic arrangement can be used to represent an odour in both countries, even if the odour-colour association for this odour differed. The responses of 59 British and 60 French participants to the same set of odorants were compared. Significant colour characterizations were observed for each and every one of the odours tested in both populations. Moreover, both commonalities and differences were reported between the two populations in terms of the odour-colour associations that they exhibited. In the second part of the study, the ability of "chromatic cards" to represent odours was tested. Those "chromatic cards" are objective coloured arrangements generated by a new patented scientific tool developed at Lorraine University (patent FR n°1255688). This tool is based on a neural network algorithm for colour forecasting. It generates a chromatic card that represents any odour from its chemical composition and sensory description. In this study, participants were presented with three cards obtained from an analysis of lavender, cucumber, and peppermint odours. First, the participants had to name the odour evoked by each card. Next, they selected from amongst three different olfactory stimuli the one that best matched each card. The chromatic representations evoked the appropriate odour percept and were significantly associated to their related odours in both of the populations. These findings highlight the existence of common colour representations of odours amongst French and British participants, though some differences were also found. Despite these differences, we were able to validate the relevancy of using single chromatic arrangements in both countries in order to communicate odour information. The latter result may open-up the way for a number of potentially important applications in the design and marketing of both food and non-food products.

Key words: colour, cross-cultural difference, cross-modal correspondences, odour, odour-colour interactions modelling, odour representation

1. Introduction

In our everyday lives, our senses constantly interact with each other in order to enable us to better perceive, understand, and ultimately predict the world around us. Indeed, most people (even those who are not synesthetic[1]), experience a number of crossmodal correspondences (or associations) between the senses. Crossmodal correspondences is the name given to the tendency for our brain to associate information from one sensory modality with information in other modalities, often in ways that may initially seem surprising (see Marks, 1978; Spence, 2011, for reviews). Recently, several studies on crossmodal correspondences have been conducted in order to start to map out the various correspondences that exist. For example, a number of interactions between sounds and flavours (Crisinel and Spence, 2010; Knöferle and Spence, 2012), sounds and odours (Belkin et al., 1997; Seo and Hummel, 2011), tastes and shapes (Spence et al., 2013; Spence and Deroy, 2014; Velasco et al. 2015) and even tactile stimuli and colours (Ludwig and Simner, 2013; Spector and Maurer, 2012) have been documented. A number of suggestions have also been made as to the mechanism(s) underlying such correspondences (see Deroy et al., 2013; Parise 2014; Velasco et al., 2016, for reviews). For the purposes of the present study, we will focus specifically on the case of the crossmodal correspondences that exist between colours and odours.

Although humans have an outstanding sense of smell (Sela and Sobel, 2010), we often find it difficult to understand and investigate olfaction due to the difficulties in communicating about our olfactory experiences by means of language (Auffarth, 2013; Kaeppler and Mueller, 2013; though see Koulakov et al., 2011; Majid and Burenhult 2014). In fact, it has been suggested that olfactory experience (odour identification, discrimination, or even just the perception of an

[1] Synaesthesia is a rare condition in which the stimulation of one sensory modality leads to automatic secondary sensory experiences, often in another modality (see Ward, 2013, for a review).

odour's intensity and pleasantness) may benefit substantially from the availability of visual cues, specifically colour cues, thus suggesting the importance of the crossmodal effects that may take place between these two sensory modalities (see Spence et al., 2011; Zellner, 2013, for reviews).

To date, several studies have been conducted in order to document odour-colour associations. Robust associations have been revealed between odours and colours (colour names and colour patches) in both explicit and implicit association tasks, and such results have been demonstrated in a variety of different populations (see Demattè et al., 2006, English; Gilbert et al., 1996, US; Kemp and Gilbert, 1997, US; Maric and Jacquot, 2013, French; Schifferstein and Tanudjaja, 2004, Dutch; and Spector and Maurer, 2012, Canadian participants). Unfortunately, in many of these previous studies, the materials, the procedures (colour names *vs.* colour patches) and the odorants presented differed. Consequently, it is difficult to compare the reported associations and hence to assess the extent to which there are robust cross-cultural differences in terms of odour-colour correspondences. Moreover, most of the aforementioned studies have studied the association between single colours and odours whilst smells are generally part of objects with multiple colours.

In fact, culture specific experiences exert a profound influence on various basic aspects of odour perception (Ayabe-Kanamura, 1998; Ferdenzi et al., 2011). As a consequence, it may be reasonable to expect variations of odour-colour associations as a function of the culture (or country) in which people live or have grown-up, especially when the functions of odours, culinary habits, and the symbolism of colours can differ so markedly between countries. Nehmé et al. (2016) have compared odour/colours associations in France, Lebanon, and Taiwan. They found that both perceptual (intensity, irritancy of odours, and hedonics) and semantic factors (nameability, familiarity of odours) appear to play a role in the odour–colour associations in each country. According to Stevenson, Rich, and Russell (2012), to determine whether the

crossmodal correspondence arise as a consequence of the semantic and/or perceptual mechanisms, one must first examine which odour characteristics co-vary with which crossmodal matches. If crossmodal correspondences seem to rely on odour characteristics that relate more to semantic processes (nameability, familiarity), one may infer that semantic processes may be involved in mediating that correspondence. Similarly, if a crossmodal match was associated with a perceptual (intensity, irritancy, and hedonics) odour characteristic this would suggest that some form of perceptual communality might have mediated that match. In Néhmé et al.'s (2016) study, when participants recognize a smell, they will tend to choose a colour that represents the recognized olfactory source. This first model of association seems to be rather of the semantic type. However, when this recognition does not take place, participants will focus on odour pleasantness and make an object categorization of the smell into a perceptual group. This second mode of association seems to be rather of perceptual type in that the Categorical Perception[2] is a fundamental process in perception and will influence the construction of the olfactory perception. In this case, the participant will select a colour according to this categorization as a function of some more abstract olfactory characteristics such as floral, fruity, vegetable or animal … Culture-dependent experiences affect our capacity to use, identify/classify, like, and consume odours or fragranced products. Thus odour–colour associations can vary between countries. These variations not only occur for olfactory information. Research from the field of colour perception has demonstrated that colour preferences are by no means universal (Sorokowski et al., 2014; Taylor et al., 2012), with different colours being interpreted differently as a function of culture (Jacobs et al., 1991; see Cyr et al., 2010, for an example in the context of web design). Colour interpretation may also play a role in odour-colour associations. Here, it is worth considering the fact that the emotions

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[2] Categorical perception is the phenomenon by which the categories possessed by an observer influences the observers' perception (Goldstone and Hendrickson, 2010)

evoked by odours could also have an impact on the choice of colour (Schifferstein and Tanudjaja, 2004), possibly indicating that odour/colour associations may be, at least in part, explained by a common affect shared by both visual and olfactory information.

Importantly, though, it appears that the complexity and multi-dimensional aspects that underpin odour-colour correspondences are currently not yet fully understood. Nevertheless, there seems to be an agreement in that many of these associations may have been acquired on the basis of associative learning. Over-and-above such learned associations, some have suggested that there might also be natural biases, or correspondences, operating across sensory systems (see Deroy et al., 2013, for a review). The idea that odour-colour associations might result from our brains picking up on the statistical regularities of the environment (and hence from prior experience) is supported, for instance, by the fact that a particular flavour that people matched to a coloured drink varies from culture to culture (Shankar et al., 2010).

In conclusion, many studies have shown cultural differences but most of the time, the populations have been very different (Europe, America, Asia, etc.). In the present study, we wanted to investigate the extent to which odours and colours are commonly associated in 2 European countries with geographic proximity and shared history: England and France. But moreover, we wanted to test whether a single chromatic arrangement could be used to represent an odour in both countries even if the odour-colour association differed. Recent research points to the idea that, whereas one colour can represent chemosensory information to a certain degree, a colour arrangement may also capture such information, and potentially lead to more accurate representations (Schifferstein and Howell, 2015).

Here, we first conducted an odour-colour experiment on two European population-based samples in order to investigate the existence any odour-colour associations, as well as any possible cultural difference between these countries in terms of those associations. Second, we

tested the existence of odour-chromatic card associations for three odorants namely lavender, cucumber, and peppermint. Those odour-chromatic cards are built with a new patented scientific tool base on neural network algorithms (patent FR n°1255688, see the Methods section, for further details).

We wanted to investigate if using an objective chromatic card generated with our process could allow a good odour-colour association and if participants could "imagine" the type of odours represented by these cards although the odour-colour experiment have shown significant differences between countries.

2. Materials and Methods

2.1. Participants

59 British participants (42 females, 17 males) and 60 French participants (47 females, 13 males), ranging in age from 18 to 55 yrs, were recruited from the University populations of the University of Oxford (United Kingdom) and the Université de Lorraine (France). The experiment complied with the Declaration of Helsinki for Medical Research involving Human Subjects and was reviewed and approved by the Central University Research Ethics Committee of the University of Oxford. All of the participants signed a standard informed consent form. All were naïve with regard to the stimuli and the purpose of the study. The participants were instructed not to wear any fragrance on the day of the sessions and not to have a meal, coffee, or to smoke in the 30 minutes preceding their session. We only tested those participants who reported having a normal sense of smell with no olfactory dysfunction. The participants were also screened for colour vision anomalies using the Ishihara colour vision test.

2.2. Odour-colour association test

146 *2.2.1. Olfactory stimuli*

147 The olfactory stimuli were the same as those used by Maric and Jacquot (2012, 2013). The
148 materials consisted of 16 odour samples, namely caramel, cucumber, lavender, lemon, lime,
149 mint chlorophyll, mirabelle plum light, mirabelle plum strong, orange blossom, peppermint,
150 pineapple, rose, shallot, smoked, violet and strawberry. Five of these odorants were previously
151 tested in research on odour-colour correspondences by Dematté et al. (2006). The odour
152 samples were chosen to be representative of the 4 basic groups into which populations generally
153 classify odours (Chrea et al., 2005), namely, flower, sweet, bad, and nature. We also included
154 a fifth group, hesperide, absent in Chrea and colleagues' study, however very common in other
155 odour classifications. The samples were prepared by injecting 1mL of each odorant into a small
156 piece of carded cotton that had been placed into a 2mL opaque glass vial, and identified by a
157 randomly selected 3-digit code. Consequently, there were no salient visual cues available to the
158 participants. The odours were refrigerated between uses and were allowed to warm up to room
159 temperature 15 min prior to testing.

160 *2.2.2. Colour samples*

161 The colour stimuli were exactly the same as those used by Maric and Jacquot (2012, 2013). The
162 colour chart consisted of a white A3 size page containing 21 colour patches arranged in a circle
163 from red to purple, and three achromatic colour patches (white, grey, black) presented
164 separately in the lower left corner. The colour samples differed not only in hue, but also in
165 lightness and in chroma. Each colour patch (4 cm in diameter) was identified by a code (one
166 capital letter and one figure). Colour charts were printed on coated paper. L*a*b coordinates
167 were measured for each colour chip by means of a Datacolour system (Pantone®
168 ColourVision™ Spyder Master Suite Spectro), and converted in L*C*H (Lightness, Chroma,
169 Hue) coordinates, to get the exact position in the CIELAB colour space.

2.2.3. Procedure

Each participant was presented with the 16 olfactory stimuli in a random order, while viewing the colour chart. For each olfactory stimulus, the participants had to open the 2mL opaque glass vial. They had to sniff its contents slowly and orthonasally by passing it under their nostrils. Afterwards, the participants were instructed to select from among the 24 colour patches the colour that they felt most closely matched the odour. After having made their choice, they rated the difficulty of making the odour-colour association, the perceived intensity, familiarity, pleasantness, and edibility of the odour.

2.3. Chromatic cards-odours association test

2.3.1. Olfactory and colours samples

Three odorants were selected to be represented by the chromatic cards: lavender, peppermint and cucumber. Previous research has demonstrated that these odours tend to be associated with green hues in North-America and Northern Europe (Gilbert et al., 1996; Maric and Jacquot, 2013; Spector and Maurer, 2012). In such research, these three odours could not be differentiated by participants using only one colour. Moreover, the peppermint and lavender odours both have an aromatic/fresh side and are familiar odours (previous behavioral studies carried out in our laboratory had indicated that these two odorants were rated as very familiar by 155 French participants: mean = 9; SD = 2 on an 11-point scale). We chose the cucumber odorant as it is the least familiar odour of the set (mean = 5.5; SD = 2.9). It is known that familiarity can influence the strength of the association between odours and colours. As a consequence, it is possible to hypothesize that more familiar smells may result in a less variable chromatic card match rate whereas a less familiar may result in higher variability. Finally,

peppermint is one of the three odours that have significant difference in odour-colour associations made in France and in UK in the first part of this study.

The samples of lavender, peppermint, and cucumber odours were prepared using the same procedure described earlier. Then, each odour has been analysed by ultrafast gas double chromatography in order to create its chromatic card with our patented process. This new patented process based on the modelling of odour-colour associations has been created in 2012 in France (patent FR n°1255688). Based on the behavioural studies that have been conducted in Lorraine University since 2004, a sensory database of odour-colour experiments carried out on more than 200 simple and complex smells has been built. Each of these odorants was analysed by ultrafast gas double chromatography to identify their chemical composition, allowing us to create a second chemical database. Those two databases are linked by artificial neural network modelling. This process enables one to generate for any odorant product, after its chemical analysis using ultra-fast Gas Chromatography, a chromatic card combining in a specific way the colours that are associated with it for a given population.

Chromatic cards were generated for each of the selected olfactory stimuli (cucumber, lavender, and peppermint) on the basis of the French database (18-55 yrs, unisex) (see Figure 1). For the purpose of this study, British and French participants were presented with the same chromatic cards that are the cards based on French database.

- INSERT FIGURE 1 ABOUT HERE -

2.3.2. Procedure

Each participant was presented with the 3 chromatic cards in a random order. First, the participants were instructed to look at the chromatic cards individually and to write down the

name of the odour, or odour category, that came to mind upon viewing them. Afterwards, the participants were presented with the olfactory stimuli in a random order. They were instructed to smell each one orthonasally and to associate it with the chromatic card that they felt most closely matched it. In France, the odour-colour association test and the chromatic cards-odour association test were separated from one another by a period of six months and carried out with different participants. In the United Kingdom, the two tests were conducted in a row by the same participants.

2.4. Data analysis

Chi-square and Fisher exact tests did not reveal any significant differences between the male and female participants on either the odour-colour or the chromatic cards-odours associations. Therefore, the data were all collapsed across gender.

With regard to the first part of the experiment, Chi-square tests were conducted to assess whether odours influenced the choice of colours. Fisher's Exact Tests were used to assess whether there are any differences between the choices of colour made by the French and British participants for each odorant. We did not take into account colours that were not selected by anyone in both countries. P-values were estimated using 100,000 Monte Carlo simulations. In order to evaluate correlations between the mean ratings of the 4 odour descriptors (perceived intensity, familiarity, pleasantness, and edibility of the odour) and the mean LCH coordinates of the matched colours, Pearson correlation coefficients were used. 3x4 correlation coefficients were calculated for each country.

The comparison of chromatic cards and odours-colours association test in France was made with the Hellinger distance calculation between both probability distributions for lavender, peppermint, and cucumber:

$$H(P,Q) = \frac{1}{\sqrt{2}}\sqrt{\sum_{i=1}^{k}(\sqrt{p_i} - \sqrt{q_i})^2}$$

With $0 \leq H(P,Q) \leq 1$, $k = 24$ and P = French choices distribution, Q = Neural network colours distribution.

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In the last part of the study, the French and British participants made similar choices in terms of odour semantic associations for each chromatic card. The same groups of descriptors were chosen by both of the populations tested. Groups of descriptors were formed for each chromatic card. For the lavender chromatic card, three groups were formed from the odour labels that were evoked: flower (including lavender), fruit, and gourmand odours. For the peppermint chromatic card, the groups were: green (including mint) and water odours. For the cucumber chromatic card, the groups were: green (including cucumber), citrus, and fruit odour. For each card, a group "other" was created. Chi-square tests were then used to assess if there are differences between French and British odour semantic associations for each chromatic card. A comparison test of proportions was also used in order to compare the French and British odour-chromatic card associations. The absence of any significant difference between the results obtained in France and England allowed us to ignore the impact of the two tests conducted without a delay between them in the UK population.

All of the data analyses were performed using XLSTAT. An alpha value of .05 was taken as the level of significance throughout the analysis. Every Chi-square test was associated with the Yates correction in order to remedy the expected value being less than 5.

3. Results and discussion

3.1. Odour-colour association test

262 ***3.1.1. Odour-colour correspondences***

263 Chi-square and Yates tests for goodness of fit were performed in order to determine which
264 odours resulted in a distribution of colour choices that was different from that expected by
265 chance in both countries. The results confirmed that the participants did not choose colours
266 uniformly but rather tended to choose some colours over others when matching the odours.
267 Indeed, all 16 olfactory stimuli led to significant preferences in the choice of colour (χ^2 (23), p
268 < .05 in all cases).

269 Afterwards, Fisher's Exact Tests were conducted in order to investigate whether different
270 colours were associated by the 2 populations with each olfactory stimulus. No significant
271 differences were reported between the French and British groups in terms of the odour-colour
272 associations that were realized for 13 of the odours (rose, $\chi^2(23)=25$, $p=0.349$; violet,
273 $\chi^2(21)=21.2$, $p=0.446$; orange blossom, $\chi^2(22)=18.61$, $p=0.669$; lavender, $\chi^2(21)=21.02$,
274 $p=0.458$; cucumber, $\chi^2(19)=25.17$, $p=0.155$; strawberry, $\chi^2(19)=19.36$, $p=0.434$; lemon,
275 $\chi^2(16)=20.59$, $p=0.195$; lime, $\chi^2(22)=22.09$, $p=0.335$; pineapple, $\chi^2(21)=17.30$, $p=0.692$; smoke,
276 $\chi^2(17)=25.37$, $p=0.087$; shallot, $\chi^2(20)=12.91$, $p=0.881$; mirabelle plum light, $\chi^2(22)=23.33$,
277 $p=0.383$; mirabelle plum strong, $\chi^2(23)=31.56$, $p=0.110$). These results are in agreement with
278 previous findings (Demattè et al., 2006; Maric and Jacquot, 2013).

279 Interestingly, however, significant differences were observed for 3 of the stimuli: caramel,
280 $\chi^2(18)=43.67$, $p< .0001$, Cramer's V=0.455, mint chlorophyll, $\chi^2(19)=35.76$, $p=.001$, Cramer's
281 V=0.412, and peppermint, $\chi^2(19)=42.79$, $p< .0001$, Cramer's V=0.600, odorants (see Figure 2).

282

283 - INSERT FIGURE 2 ABOUT HERE -

284 For the mint chlorophyll odorant, a difference was found between the two populations in terms
285 of the main associated colour: blue-green (33.9% of choices) for the British *vs.* green colour
286 (40.0% of choices) for the French participants. For the peppermint odour, no differences were

found in terms of the main colour that was associated, but rather in the secondarily associated colours. Indeed, peppermint was mainly associated with blue-green (23.7% of choices in UK – 18.3% in France) in both countries. The fact that the British participants mainly associated blue-green whatever the kind of mint tested (note that mint chlorophyll is less aromatic/fresh than peppermint, which contains menthol) could be explained by culturally dependent colour symbolism and people's prior exposure to specific combinations of stimuli. With regard to the peppermint odour's less strongly associated colours, quite surprisingly, 11.8% of the British participants chose dark purple whereas none of the French participants chose this colour. One possible explanation for this association could be different exposures to commercial products with a similar flavour but different packaging colours between the two populations (e.g., Schifferstein and Howell, 2015). A second possible explanation could be that the peppermint odour evoked the mint flower for the British participant and not the mint leaves. The mint flower is a small purple flower forming slender spikes.

Finally, the caramel odour was mainly associated with light brown and pale orange colours in both countries (see Figure 2). Differences also occurred in the secondarily associated shades: pale yellow in UK, *vs*. orange in France. These results seem to suggest that prior learned associations may play a role in driving odour-colour correspondences and that one colour is often simply not sufficient to describe all of the shades of an odour.

3.1.2. Relationships between odour descriptors and colour coordinates

Pearson correlation coefficients were used to assess the common relationships between the mean ratings of the odours for each of the evaluated descriptors (familiarity, pleasantness, intensity, and edibility) and the mean lightness, saturation, and hue of the matching colours that were chosen. In both countries, significant positive relationships were found between

pleasantness and lightness (r_{UK}=0.595, p_{UK}=0.015; r_F=0.538, p_F=0.031), and also between pleasantness and chroma (r_{UK}=0.483, p_{UK}=0.051; r_F=0.532, p_F=0.033). The odours that were rated as more pleasant were generally matched to colours exhibiting a higher lightness and saturation. Moreover, pleasantness and familiarity were strongly correlated in both countries (r_{UK}=0.545, p_{UK}=0.028; r_F=0.765, p_F=0.0005). The results also indicated that colour saturation is positively correlated to perceived odour edibility (r_{UK}=0.592, p_{UK}=0.015; r_F=0.483, p_F=0.049), and that colour hue varies inversely with perceived odour edibility (r_{UK}=-0.520, p_{UK}=0.038; r_F=-0.467, p_F=0.068). The more an odour was judged as edible, the more the hue tended toward yellow and toward saturated colours. On the other hand, less edible odours were preferentially matched with less saturated colours and with blue hues, which are less often encountered in food and beverage products. Interestingly, the present results also confirm the existence of correlations between perceptual dimensions in olfaction and vision. Specifically, colour lightness varies inversely with perceived odour intensity in both populations (r_{UK}=-0.556, p_{UK}=0.025; r_F=-0.461, p_F=0.071), as demonstrated previously by Kemp and Gilbert (1997).

3.2. Comparison of chromatic cards and odours-colours association test

The lavender chromatic card (see figure 1) comprised of 5 colours: three shades of purple (mauve=40%, purple=12%, dark purple=23), one shade of blue (light blue=13%) and one shade of green (brilliant yellowish green=12%). These colour combinations~~could be compared~~are comparable to those colours obtained ~~with the results obtained~~ in France for the odours-colours association test.

- INSERT FIGURE 3 ABOUT HERE -

~~We could easily note that~~It is possible to observe here that the colours of the card correspond to the main colours chosen by the French participants for lavender (see F~~f~~igure 3). The Hellinger distance between both distributions is 0.25 demonstrating the important proximity between both distributions. The ~~M~~most ~~important~~ frequent colour choice~~ frequencie~~s (I1 and I3) ~~are also~~correspond to the most important colours of the card. Note, however, that ~~T~~the most significant difference is the lack of G3, F2, and B4 colours in the card.

The peppermint chromatic card comprised also of 5 colours: three shades of green (green=32%, very light yellowish green=23%, strong yellowish green=11%) and 2 shades of blue (light blue=20%, blue=14%). The main colours of the card (green, very light yellowish green and light blue) ~~are~~ here also ~~the highest~~correspond to the most frequent colour ~~choice frequencies~~choises (see F~~f~~igure 3). The Hellinger distance between both distributions is 0.43. The proximity is less important than for lavender card due to the lack of H3 and D3.

The cucumber chromatic card presents also three shades of green as peppermint (strong yellowish green=31%, green=21% and yellowish green=18%) and two shades of yellow (vivid yellow green=16% and light yellow=14%). The comparison with the French colour choices demonstrate~~d~~ that the first three colours are the same (F2, F3, and G3). The Hellinger distance equals 0.51. The cucumber card is the ~~furthest~~ most distant one. Differences are due to the lack of D2, A1, and J1.

For the three odours, the neural network answers are simpler representations than the responses of odour-colour test. The last part of the study will help ~~us~~ to understand if this simpler representation could after all be sufficient to represent an odour.

3.3. Chromatic cards-odours association test

3.3.1. Testing the ability of chromatic cards to evoke the appropriate odour labels

In France, the participants used 21, 26, and 36 different words to describe the odours evoked by the lavender, peppermint, and cucumber cards, respectively. In UK, the participants used 17, 18, and 24 words to describe the odours evoked by the lavender, peppermint, cucumber cards, respectively. Tables 1 to 3 present the proportions of each semantic association for each chromatic card and group of descriptors. Each card's result is then discussed separately.

- INSERT TABLES 1-3 ABOUT HERE –

3.3.1.1. Lavender chromatic card

With 54.2% for French and 42.4% for British panels, both populations primarily associated the lavender chromatic card with flowery odours. Furthermore, this card evoked the correct odorant, lavender, for about 20% of participants in both countries (see Table 1). This is an interesting finding in light of previous results. When Spector and Maurer (2012) tested the identification and categorization performance for 22 different odours smelled twice by the participants, they found that lavender odorant was correctly identified by only 10% of their participants, and categorized as floral by just 22%.

However, about half of each population associated the lavender card with another category than flower odours. This card was, indeed, associated with fruity odours (mainly berries, fruit or grape) by 32.2% and 28.8% of French and British participants respectively, and then to gourmand odours like sweet at 8.5% and 15.2%, respectively. For the fruity associations, participants may have focused on only one or two colours (pink or darker purple) and not on the whole card. These colours may have evoked the fruit's colour itself like a purple berry, a purple grape or a pink raspberry. The taste-related odours associated with the lavender card are mostly sweet odours. Participants may have not associated colours with a fruit, like previous, but with candies, a manufactured product often made with a fruity taste. In conclusion, it appears that in both countries, about 40% of the participants did not interpret the card evoked-

odour but tried to find a coloured odorant object. This finding is interesting and could be compared with those obtain during classical odours/colours tests.

For example, Néhmé *et al*. (2016) have shown that during odour/colour association, when a participant recognizes a smell, he/she will tend to choose a colour which, for him, represents the recognized olfactory source. This first model of association seems to be rather of the semantic type. However, when this recognition does not take place, the participant will then categorize the smell on a more abstract odour class (floral, fruity, vegetable, animal, etc.), and then lean on this categorization to determine the colour which best represents this category. Both perceptual and semantic models of association are also encountered in our results, thus, consistent with the view that both modes may operate when it comes to the associations of colours and odours. Semantic associations were for example revealed for fruity evoked-odours and the perceptive type for floral evoked-odours. The predominance of one or the other one is not completely clear. Both perceptive and semantic models affect odour-colour associations but also colour-odour associations revealing the complexity and the multi-dimensional aspects of these linkages. The last group of descriptors gathers together associations that could not be classified in the other 3 categories or that have no relations between each other. There are mainly non-food odours.

3.3.1.2. Peppermint chromatic card

This card evoked the intended odour category (green) in roughly 70% of the French and British participants. The participants mostly associated the peppermint chromatic card with plant odours such as grass, garden, or leaves. Obviously, the participants associated this chromatic card with mint odours using descriptors such as mint, fresh mint, and peppermint at 45.8% and 35.6% for the British and the French populations, respectively (see Table 2). This high level of correct identification can be explained by the fact that peppermint is a familiar odour (Spector

and Maurer, 2012) and that people are more likely to have been exposed to typical odour-colour combinations that involve this particular olfactory stimulus and the shades of the chromatic card. This representation was also associated, to a lesser degree, with watery odours (17.0% in France; 20.0% in the United Kingdom). The association with water may be explained by the fact that participants have made a semantic association for the blue shades of this card. As one knows, water is frequently represented by shades of blue (Akcay et al., 2011) which are quite important in the peppermint chromatic card. The last group of descriptors gathers terms that have a fresh side such as lemon or apple and includes terms that refer to products such as bleach.

3.3.1.1. Cucumber chromatic card

More words were generated to describe the card evoked-odour (36 in France, 24 in UK). Moreover, the proportion of association with correct category odour is lower than for the 2 other chromatic cards. Both populations associated this representation with green odour sources more than 40% of the time (see Table 3). The participants mostly used descriptors such as grass, vegetables, and fields. The greater difficulty in retrieving the appropriate odour category might be explained by the fact that cucumber is the less familiar odour. It might thus have been more difficult for our participants to have retrieved this specific label, class, or affiliation from memory.

Some other associations were also present though. Indeed, 13.3% of the British participants and 15.3% of the French participants linked this card to fruity odours such as watermelon, peach, or apple (see Table 3). Those associations are very likely due to the yellow and orange colours of the card that represent the colours of the fruits quoted. Moreover, 28.3% of the British and 16.9% of the French participants associated this card with the odour of citrus fruit. Participants should have made a semantic association between lemon odour and yellow colour. About 20%

of each population have generated terms in the "other" category. Mostly, the terms described something yellow in colour but with no connections with the 3 others groups of descriptors.

3.3.2. Comparison of semantic associations between populations

As the chromatic cards were generated on the basis of a database of French odour-colour tests, chi-square tests for independence were carried out in order to assess whether there is any difference in terms of verbal associations between the two populations. The results highlight the absence of significant differences between French and British participants for each one of the chromatic cards (χ^2 (3) = 6.648, p = 0.223 for lavender; χ^2 (3) = 4.386, p = 0.084 for peppermint, and χ^2 (3) = 4.000, p = .261 for cucumber). These results indicate that odour labels generated by these cards are common in both of the tested populations, even though the classical odour-colour test reveals difference in odour-colour associations as in the case of peppermint. These results and the card/evoked-odours correspondences analysis have demonstrated that the colour-odour transcription mechanisms are probably identical in both countries based sometime on a perceptual interpretation of the card and sometime on a semantic interpretation of colours.

3.3.3. Odour-chromatic card associations

In both countries, participants had to smell an odour sample and to choose the best card to represent this perception. In this section, we present the results from that task for each country.

- INSERT FIGURE 4 ABOUT HERE -

451 *3.3.3.1. France*

452 The results revealed that the French participants matched odours to their corresponding
453 chromatic cards ($\chi^2(4) = 120.71$, $p<.0001$; Cramer's V=0.584); 76.3%, 71.2%, and 67.8% of
454 the participants, respectively, realized the expected associations for the lavender, peppermint,
455 and cucumber chromatic card (see Figure 4). The most common inversion (made by 22.0% of
456 participants) was to associate the cucumber odour with the peppermint chromatic card. This
457 result is probably attributable to the fact that the green colour is frequently associated with plant
458 odours in France, as discussed earlier. Moreover, the odour of cucumber used in this study
459 presented fresh olfactory notes, which might have misled our participants.

460

461 *3.3.3.1. United Kingdom*

462 Similar to the French participants, the British participants who took part in this study made non-
463 random odour-chromatic card associations ($\chi^2(4) = 101.26$, $p<.0001$; Cramer's V = 0.535).
464 They actually made the intended matches cards/odorants at 67.8% for the lavender chromatic
465 card and 69.5% for the peppermint and cucumber chromatic cards (see Figure 4). In the UK,
466 the most common inversion (18.6%) was to associate the peppermint odour with the lavender
467 chromatic card. This could be linked with the association reported previously in the odour-
468 colour test between peppermint and dark purple colour within British group.

469

470 *3.3.3.1. Comparison between populations*

471 A comparison test of proportions was conducted in order to test whether there was a significant
472 difference between correct associations made by French and British participants and thus assess
473 whether this new tool for representing odours could be relevant to the consumers in both

markets. The results for the lavender (p=.303), peppermint (p=.840), and cucumber chromatic cards (p=.843) revealed p-values that were greater than the alpha value of .05. Consequently, it can be concluded that there was no significant difference between the odour-chromatic card associations for the French and British participants. What is more, even if some cultural differences were reported between the two populations in terms of their odour-colour associations, especially for the peppermint odour, these coloured representations are clearly understandable by British participants as well as French participants.

4. CONCLUSION

A growing number of studies have reported the existence of a wide range of robust crossmodal correspondences between odours and colours over the last couple of decades. These intriguing correspondences appear to be both robust across individuals (within a culture, see Levitan et al., 2014) and stable over time (Gilbert et al., 1996). The results of the present study confirm the existence of a number of odour-colour associations that are common to participants from France and Britain (which is critical given the replication crisis that some fields are currently facing, e.g., Open Science Collaboration, 2015). Such a pattern of results is certainly consistent with the idea that there may be a core representation, or imagery, of odours, which might be common across European cultures (see Stevenson and Case, 2005, for a review of olfactory imagery; and Spence and Deroy 2013, on the topic of crossmodal mental imagery). Notably, our results would appear to point to the idea that people may match odours and colours as a function of prototypical objects in which both the odour and colour converge, but also more general odour classes of groups (floral, animal, etc.), and also more abstract features such as intensity and hedonics (see also Velasco et al., 2016, for similar results in the context of taste/shape associations).

How to explain the fact that certain associations are consistent while others differ between France and the UK? As mentioned before, various different types of, and potential mechanisms associated to, crossmodal correspondences have been proposed: statistically mediated correspondences (those that are learnt from the crossmodal regularities present in the environment), structural mediated correspondences (putatively hard-wired in the brain), and linguistically mediated correspondences (based on the common use of language to describe sensory information) (Parise and Spence, 2013; Spence, 2011). It has also been suggested that some correspondences may be mediated by our affective responses to those stimuli (Palmer et al., 2013; Schifferstein and Tanudjaja, 2004). Importantly, the different types of correspondences are not mutually exclusive in that people can learn associations from the statistical regularities of the environment that may, in the long-term, become structural. These mechanisms may help to explain, the matching between odour features and colour features (such as intensity, hedonics, brightness, hue, and so on). Nevertheless, an object-based and class-based association may also be driving the way in which people associate odours and colours. In those countries with geographical proximity, shared experiences with a similar environment, cuisine, and commercial products, a small difference can be expected in terms of odour-colour correspondences. With these ideas in mind, it is possible to think that, at least in part, odour-colour associations reflect the learned associations that people pick from objects in which both odours and colours converge (e.g., products in the supermarket), far beyond, the existence of a core coloured representation of odours among populations.

Zellner (2013) argued that colours may exert a crossmodal effect on our olfactory experience via their ability to generate odour imagery, and that colour can facilitate the retrieval of odour labels from memory, which can also activate an odour image. Besides, the quality of an odour could be modified in a negative way if the colour-induced percept happens not to be congruent with the actual odour of a product. Using congruent colours for the design of the packaging of

products with a significant olfactory component could, for instance, enable customers to better guide their buying and thus lead to an increased pleasantness of the product. On the other hand, incongruent colours could induce a violation of sensory expectation and thus reduce the customer's satisfaction, what is often referred to as a disconfirmation of expectations (Yeomans et al., 2008; see Piqueras-Fiszman & Spence, 2015, for a review).

The present study also demonstrated that, in both population-based samples, the chromatic representations of odours, generated by the process developed in the laboratory of the Université de Lorraine, enabled the participants to retrieve the appropriate odour category at a rate from 40 to 70%, and even the exact odour label at a rate of 20 to 40% for familiar simple odours such as lavender and peppermint. Moreover, about 70% of our participants were able to associate odours with their corresponding representations regardless of the odour's familiarity. This is a striking result when compared with identification and categorization performance measured by Spector & Maurer (2012) on 22 different odours. For information, only 10% of their participants has recognized the lavender smell and categorized as floral by just 22% (Spector & Maurer, 2012). Certainly, other categories of odour, but also real product fragrances should be tested in future research. That said, we can assume that this new tool seems to be relevant to predict colours of odorant products. Those colours ~~could~~ may, for example, ~~then~~ be used in packaging development to better tailor products and optimize sensation transference by means of the use of colour/odour correspondences.

To conclude, the rapid growth of research on the topic of crossmodal correspondences over the last few years has enabled researchers to gain a better understanding of the mechanisms that are inherent to our perception of the world around us. Nevertheless, based on the available information on crossmodal correspondences, it is possible to consider their applications, in particular to the field of marketing. The robustness of the odour-colour associations reported here allows one to imagine other means of product communication that go beyond words and

548 pictures, and that are based on consumers' multisensory information processing. Indeed, the
549 majority of all new products launched in the marketplace fail. Several reasons can be given for
550 this. Products must of course be suitable for the market in which they are introduced. Moreover,
551 marketers often do not have the tools needed to understand how consumers perceive products
552 on the basis of packaging design, where colours play a significant role (see Gelici-Zeko et al.,
553 2012, for a study on dairy products). These new insights will allow for the development of a
554 less intuitive and hence hopefully more efficient means of communication for companies, as
555 they offer possibilities to design packaging that better aligns with consumer expectations, thus
556 contributing to higher consumer product satisfaction.

557

558 Compliance with Ethical Standards

559 The experiment complied with the Declaration of Helsinki for Medical Research involving
560 Human Subjects and was reviewed and approved by the Central University Research Ethics
561 Committee of the University of Oxford. All of the participants signed an informed consent
562 form.

563

564 References

565 Akcay O., Dalgin MH, Bhatnagar S. 2011. Perception of colour in product choice among
566 college students: a cross-national analysis of USA, India, China and Turkey. *International*
567 *Journal of Academic Research in Business and Social Sciences*. *2*(21):42-48.

568 Auffarth, B., 2013. Understanding smell-the olfactory stimulus problem. *Neuroscience &*
569 *Biobehavioral Reviews*. *37*(8):1667-1679.

570 Ayabe-Kanamura S., Schicker I., Laska M., Hudson R., Distel H., Kobayakawa T., Saito S.,
571 1998. Differences in perception of everyday odors: a Japanese–German cross-cultural study.
572 *Chemical Senses*. *23*:31-38.

573 Belkin K., Martin R., Kemp S.E., and Gilbert A.N., 1997. Auditory pitch as a perceptual
574 analogue to odor quality. *Psychological Science*. *8*:340-342.

575 Chrea C., Valentin D., Sulmont-Rosse C., Hoang Nguyen D., Abdi H., 2005. Semantic,
576 typicality and odor representation: a cross-cultural study. *Chemical Senses*. *30*:37-49.

577 Crisinel AS., Spence C., 2010. As bitter as a trombone: synesthetic correspondences in
578 nonsynesthetes between tastes/flavors and musical notes. *Attention, Perception, &*
579 *Psychophysics. 72*: 1994-2002.

580 Cyr D., Head M., Larios H., 2010. Colour appeal in website design within and across cultures:
581 a multi-method evaluation. *International Journal of Human-Computer Studies*. *68*:1-21.

582 Dematte M.L., Sanabria D., Spence C., 2006. Cross-modal associations between odors and
583 colours. *Chemical Senses*. *31*:531-538.

584 Deroy O., Crisinel A.S., Spence C., 2013. Cross-modal correspondences between odors and
585 contingent features: odors, musical notes, and geometrical shapes. *Psychonomic Bulletin &*
586 *Review*. *20*:878-896.

587 Ferdenzi C., Schirmer A., Roberts S.C., Delplanque S., Porcherot C., Cayeux I., Velazco M.I.,
588 Sander D., Scherer K.R., Grandjean D., 2011. Affective dimensions of odor perception: a
589 comparison between Swiss, British, and Singaporean populations. *Emotion*. *11*:1168-1181.

590 Gelici-Zeko M.M., Lutters D., ten Clooster R,. Weijzen P.L.G., 2013. Studying the influence
591 of packaging design on consumer perceptions (of dairy products) using categorizing and
592 perceptual mapping. *Packaging Technology & Science*. *26*:215-228.

593 Gilbert A.N., Martin R., Kemp S.E., 1996. Cross-modal correspondence between vision and
594 olfaction: the colour of smells. *American Journal of Psychology*. *109*:335-351.

595 Goldstone RL & Hendrickson AT, 2010. Categorical perception. *Wiley Interdisciplinary*
596 *Revue: Cognitive Science*, *1*(1): 69–78.

597 Jacobs L, Koewn C, Worthley R, Kyung-Il G. 1991. Cross-cultural colour comparisons: global
598 marketers beware! *International Marketing Review*. *8*(3):21-30.

599 Kaeppler K & Mueller F. 2013. Odor classification: a review of factors influencing perception-
600 based odor arrangements. *Chemical Senses*. *38*:189-209.

601 Kemp SE & Gilbert AN. 1997. Odor intensity and color lightness are correlated sensory
602 dimensions. *American Journal of Psycholo*gy. *11*:35-46.

603 Knöferle KM & Spence C. 2012. Cross-modal correspondences between sounds and tastes.
604 *Psychonomic Bulletin & Review*. *19*:992-1006.

605 Koulakov AA, Kolterman BE, Enikolopov AG, Rinberg D. 2011. In search of the structure of
606 human olfactory space. *Frontiers in Systems Neuroscience*. *5*:65.

607 Ludwig VU & Simner J. 2013. What colour does that feel? Tactile-visual mapping the
608 development of cross-modality. *Cortex*. *49*:1089-1099.

609 Majid, A., & Burenhult, N. (2014). Odors are expressible in language, as long as you speak the
610 right language. *Cognition*, *130*(2), 266-270.

611 Maric Y, Barbar R, Jacquot M. 2012. As pink as an orange blossom odour: a French-Lebanese
612 cross-cultural study. Proceedings of AIC Colour 2012. Interim Meeting of the International
613 Colour Association.

614 Maric Y & Jacquot M. 2013. Contribution to understanding odour colour associations. *Food*
615 *Quality and Preference*. *27*:191-195.

616 Marks, L.E., (1978). *The unity of the senses: Interrelations among the modalities*. New York,
617 NY: Academic Press.

618 Nehmé L., Barbar R., Maric Y., Jacquot M. 2016. Influence of odor function and color
619 symbolism in odor-color associations: a French - Lebanese - Taiwanese cross-cultural study.
620 *Food Quality and Preference*, 33-41 (DOI 10.1016/j.foodqual.2015.11.002)

621 Open Science Collaboration., 2015. Estimating the reproducibility of psychological science.
622 *Science*, *349*(6251), aac4716.

623 Parise C.V., 2016. Crossmodal correspondences: Standing issues and experimental guidelines.
624 *Multisensory Research*, *29*, 7-28.

625 Schifferstein, H.N. & Howell, B.F., 2015. Using color–odor correspondences for fragrance
626 packaging design. *Food Quality and Preference*, *46*, 17-25.

627 Schifferstein H.N.J. & Tanudjaja I., 2004. Visualising fragrances through colors: the mediating
628 role of emotions. *Perception*. *33*:1249-1266.

629 Sela L. & Sobel N., 2010. Human olfaction: a constant state of change-blindness. *Experimental*
630 *Brain Research*. *205*:13-29.

631 Seo H.S. & Hummel T., 2011. Auditory–Olfactory Integration: congruent or pleasant sounds
632 amplify odor pleasantness. *Chemical Senses*. *36*:301-309.

633 Shankar M.U., Levitan C.A., Spence C., 2010. Grape expectations: The role of cognitive
634 influences in colour-flavour interactions. *Consciousness and Cognition. 19*(1):380-390.

635 Sorokowski P., Sorokowska A., Witzel C., 2014. Sex differences in color preferences transcend
636 extreme differences in culture and ecology. *Psychonomic Bulletin & Review*. DOI
637 10.3758/s13423-014-0591-8.

638 Spector F. & Maurer D., 2012. Making sense of scents: the colour and texture of odours. *Seeing*
639 *Perceiving*. *25*:655-677.

640 Spence C., 2011. Cross-modal correspondences: a tutorial review. *Attention, Perception, &*
641 *Psychophysics. 73*:971-995.

642 Spence C., Deroy O., 2013. Cross-modal mental imagery. In Lacey S, Lawson R, editors.
643 *Multisensory imagery: Theory and applications* (pp. 157-183). New York, NY: Springer.

644 Spence C., Ngo M.K., Percival B., Smith B., 2013. Cross-modal correspondences: assessing
645 shape symbolism for cheese. *Food Quality and Preference*. *28*:206-212.

646 Spence C., Deroy O., 2014. Tasting shapes: A review of four hypotheses. *Theoria et Historia*
647 *Scientiarum*. *10*:207-238.

648 Stevenson R.J. & Case T.I,, 2005. Olfactory imagery: a review. *Psychonomic Bulletin &*
649 *Review*. *12*(2):244-264.

650 Stevenson R.J., Rich A., Russell A., 2012. The nature and origin of cross-modal associations
651 to odours. *Perception*, *41*(5), 606-619.

652 Taylor C., Clifford A., Franklin A., 2012. Color preferences are not universal. *Journal of*
653 *Experimental Psychology*. *142*:1015-1027.

654 Velasco C., Woods A.T., Deroy O., Spence C., 2015. Hedonic mediation of the crossmodal
655 correspondence between taste and shape. *Food Quality and Preference*. *41*:151-158.

656 Velasco C., Woods A.T., Petit O., Cheok A.D., Spence C., 2016. Crossmodal correspondences
657 between taste and shape, and their implications for product packaging: A review. *Food Quality*
658 *and Preference*. *52*:17-26.

659 Ward J., 2013. Synesthesia. *Annual Review in Psychology. 64*:49-75.

660 Yeomans M., Chambers L., Blumenthal H., Blake A., 2008. The role of expectancy in sensory
661 and hedonic evaluation: The case of smoked salmon ice-cream. *Food Quality and Preference*.
662 *19*:565-573.

663 Zellner D., 2013. Color-odour interactions: a review and model. *Chemosensory Perception*.
664 *6*:155-169.

665