Chem. Senses 31: 291–300, 2006
doi:10.1093/chemse/bjj031
Advance Access publication February 1, 2006

Cross-Modal Interactions Between Olfaction and Touch

M. Luisa Demattè[1,2], Daniel Sanabria[1], Rachel Sugarman[1] and Charles Spence[1]

[1]Department of Experimental Psychology, University of Oxford, South Parks Road, Oxford OX1 3UD, UK and [2]Dipartimento di Scienze della Cognizione e della Formazione, Università degli Studi di Trento, Rovereto, TN, Italy

Correspondence to be sent to: M. Luisa Demattè, Department of Experimental Psychology, University of Oxford, South Parks Road, Oxford OX1 3UD, UK. e-mail: dematte@form.unitn.it

Abstract

We report two experiments designed to investigate the nature of any cross-modal interactions between olfactory and tactile information processing. In Experiment 1, we assessed the influence of olfactory cues on the tactile perception of fabric softness using computer-controlled stimulus presentation. The results showed that participants rated fabric swatches as feeling significantly softer when presented with a lemon odor than when presented with an animal-like odor, demonstrating that olfactory cues can modulate tactile perception. In Experiment 2, we assessed whether this modulatory effect varied as a function of the particular odors being used and/or of the spatial coincidence between the olfactory and tactile stimuli. The results replicated those reported in Experiment 1 thus further supporting the claim that people's rating of tactile stimuli can be modulated by the presence of an odor. Taken together, the results of the two experiments reported here support the existence of a cross-modal interaction between olfaction and touch.

Key words: fabric perception, multisensory integration, olfaction, roughness, softness, touch

Introduction

The last few years have seen a rapid growth of interest in the multisensory aspects of texture perception (see Lederman and Klatzky, 2004, for a recent review). However, this research has typically focused on interactions between touch and vision (e.g., Werner and Schiller, 1932; Guest and Spence, 2003a,b) and to a lesser extent on interactions between touch and audition (e.g., Werner and Schiller, 1932; Lederman, 1979; Guest *et al.*, 2002; Lederman and Klatzky, 2004). Tactile perception and texture perception, in particular, have been shown to be strongly influenced by multisensory information (e.g., Heller, 1982). For instance, Guest *et al.* (2002) have demonstrated that people's perception of the roughness of abrasive sandpapers can be systematically altered by changing the sounds that they hear when they touch different sandpapers.

Olfactory information has been shown to interact with both visual (e.g., Börnstein, 1936; Allen and Schwartz, 1940; Gilbert *et al.*, 1996; Morrot *et al.*, 2001) and gustatory inputs (Rolls, 2004; Stevenson and Boakes, 2004), giving rise to our rich multisensory experience of the stimuli in the surrounding environment (e.g., see Dalton *et al.*, 2000). For instance, Morrot *et al.* (2001) have shown that visual cues (i.e., coloring a glass of white wine red) can bias the olfactory judgments of even experienced wine tasters. Meanwhile, Stevenson, Boakes, and many others have highlighted the influence of odor on the perceived sweetness of beverages. However, despite the existence of an extensive body of research on cross-modal interactions between olfaction and many of our other senses, there is a paucity of research regarding the nature of any multisensory interactions specifically between olfaction and touch.

In the present study, we therefore investigated the nature of cross-modal interactions between olfactory cues and tactile perception. In particular, we explored the possible effect of the presence of different odors on the perception of fabric softness. We assessed the validity of previous claims suggesting that tactile judgments can be influenced by the presence of olfactory cues (e.g., see Laird, 1932; Cox, 1967; Byrne-Quinn, 1988; Fiore, 1993). For instance, more than 70 years ago, Laird (1932) reported that women's judgments of the quality of silk stockings depended on the scent with which the stockings were impregnated. The housewives in Laird's study were shown to prefer stockings with a narcissus scent over those with a "natural" scent, even though the stockings were otherwise identical. When asked for the reason behind their preference for one pair of stockings over the others, the majority of housewives pointed to differences in durability, sheen, or weave (i.e., to the tactile and/or visual properties of the stockings), rather than to differences in their olfactory properties.

In Experiment 1, we took inspiration from the study of Laird (1932), to address the question of whether olfactory cues could influence tactile judgments using a computer-controlled stimulus presentation procedure and a more objective measure of participants' perception, namely, ratings of fabric softness. To achieve this, we presented tactile stimuli (fabric swatches that participants could distinguish solely on the basis of their tactile attributes; cf. LaMotte, 1977) by means of a computer-controlled carousel, and we delivered olfactory stimuli through a custom-built olfactometer. The participants were asked to rate the perceived softness of each fabric sample, while an odor or clean air was delivered directly to their nostrils. Note that our measure of tactile perception did not depend on people's subjective preference/liking for one fabric sample over another (contrary to the study of Laird, 1932). If olfactory cues do indeed influence tactile judgments of fabric softness, we would expect to find differences in the mean ratings of fabric softness on the basis of the presence/absence of odor information.

Experiment 1

Methods

Participants

Seventeen untrained participants (15 female and 2 male), with a mean age of 22 years (range of 18–35 years), from the University of Oxford took part in this experiment. All of the participants reported having a normal sense of smell, no history of olfactory dysfunction, and normal or corrected-to-normal vision in a confidential questionnaire. All the participants were naive to the purpose of the experiment. Sixteen of the participants received course credit for their participation, and one participant received a £5 gift voucher.

Apparatus and materials

Cotton fabric swatches (17 × 17 cm) treated with one of three different chemicals (Aminosilicone, Comfort, and Starch; Unilever Research, Port Sunlight, UK) or else untreated were used as the tactile stimuli. Previous pilot experiments conducted in this laboratory had shown that the different types of fabric swatches were highly discriminable on the basis of their perceived softness. The fabrics were treated (i.e., washed) using a different quantity of each product (expressed in percent on the basis of the weight of each fabric): Aminosilicone at 1%, Comfort at 0.25%, and Starch at 0.5%. No product was added to the untreated fabric samples. The different treatments allowed us to obtain four different naturalistic tactile stimuli (and so give participants a sufficiently demanding task), with the fabric treated with Aminosilicone being perceived as the softest, followed by the fabric washed with Comfort, then by the untreated one, and last (i.e., perceived as the roughest) the fabric washed with Starch. One fabric swatch of each type was attached to a custom-built automated fabric carousel (see Figure 1). The fabrics were changed after every three participants in order to avoid any deterioration in the quality of the swatches' physical properties as a function of extended touching by participants.

One of two odors (lemon or animal; respectively, 406803 and AB 0394; Quest International, Ashford, UK) was delivered before (and during) the presentation of the fabric swatch on odor-present trials. We chose two odorants that were highly discriminable from each another. There was also a no-odor condition in which only clean air was presented. The onset of the odor occurred 2500 ms before the participants touched the fabric swatch and was presented continuously until the participants made their rating response regarding the softness of the fabric swatch. A custom-built computer-controlled olfactometer was used to deliver the odorants, each diluted at a concentration of 10% in diethyl phthalate (529633; Quest International) as recommended by Quest International. The flow rate of medical air through the olfactometer was set at 8 l/min using a flow regulator (CONCOA 03-054, Utrecht, The Netherlands) connected to the gas cylinder (Medical Air Size G, BOC Gas). The instructions and the response scale on which the participants were to make their rating responses were presented on a computer monitor situated directly in front of them. The E-Prime software (Schneider *et al.*, 2002a,b) was used to control stimulus presentation and to collect the participant's responses.

Design

The experiment consisted of a within-participants repeated-measures design, with the factors of odor (animal odor, lemon odor, or clean air) and fabric treatment (Aminosilicone, Comfort, Starch, or No-treatment). The experimental session consisted of four blocks of 36 trials (three trials per each condition) and lasted for approximately 45 min. The presentation of the three odor conditions and the four fabric swatches was randomized on a trial-by-trial basis, with the constraint that neither the same odor nor the same fabric was ever presented on consecutive trials.

Procedure

The participants sat in a comfortable chair 50 cm from the computer screen. The fabric carousel was positioned directly to the right of the computer monitor. The participants were instructed to insert their right hand under a curtain that hid the fabric samples from direct view. Using this setup, the participants were able to touch the fabric swatches without seeing them (hence eliminating any visual contributions to texture perception). Every movement of the wheel corresponded to the presentation of a different fabric swatch. The participants were instructed to place their right hand

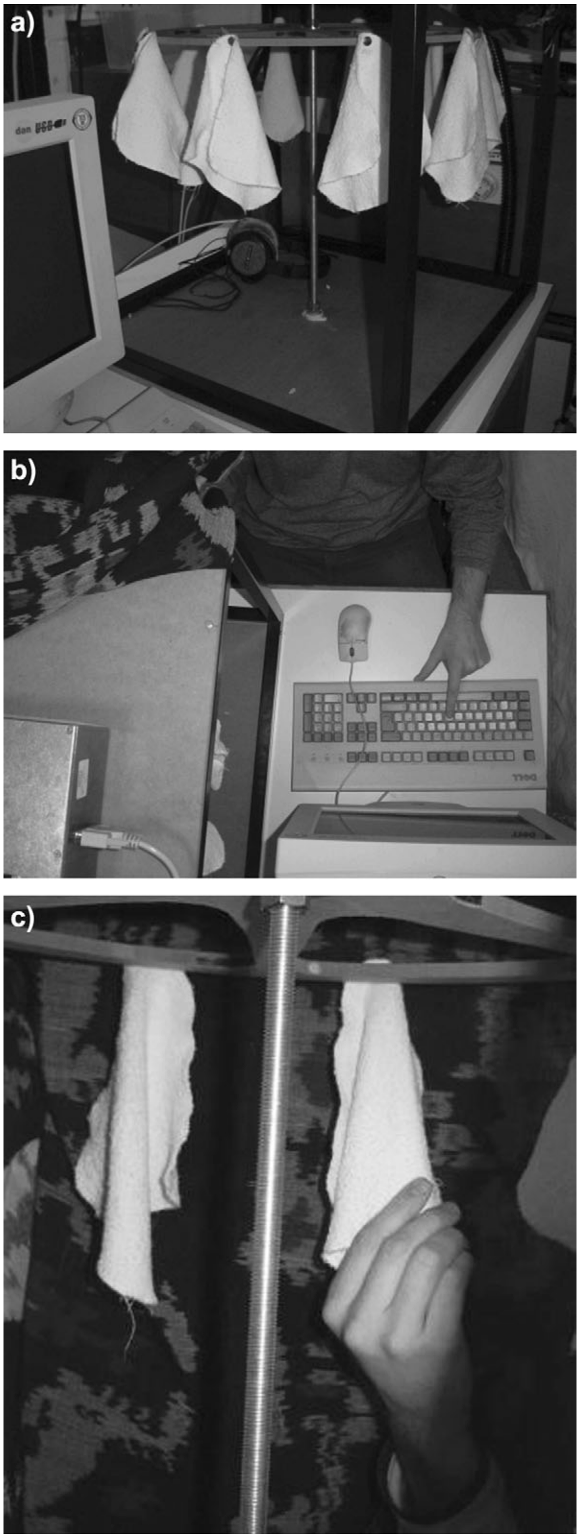

Figure 1 **(a)** Experimental setup used in Experiment 1. Note that during the experiment itself, the fabric carousel was always covered with a curtain in order to hide the fabric samples from the direct view of the participant. **(b)** Bird's-eye view of the position of the participants relative to the fabric carousel and computer screen. **(c)** Naturalistic hand movement used by participants to evaluate fabric softness. Participants used their right hand to rub the fabric sample and their left hand to respond.

in a particular position below the occluding curtain and to touch the fabric directly above their hand only after the wheel had stopped moving. The fabric carousel made an audible ''click'' when it stopped, at which time the participants were instructed to touch the fabric for a few seconds by rubbing it between their right thumb and index finger using a naturalistic movement (see Figure 1c). The participants then had to press the space bar on the computer keyboard with their left hand in order to show the response scale on the monitor that ranged from 1 to 20 (1 = ''soft'' and 20 = ''rough'' extremes of the roughness scale). The participants were instructed to touch the fabric and to indicate their perception of its softness by pressing the key corresponding to their choice with their left hand. Twenty keys on the computer keyboard, labeled from 1 to 20, were used to collect the participants' responses. After making their response, the participants again pressed the space bar in order to move the experiment onto the next trial.

Before rating the softness of each fabric swatch, the participants were instructed to classify any odor that had been presented as either pleasant, unpleasant, or else respond that no-odor had been detected by pressing one of three response keys on the keyboard with their left hand. In this manner, we were able to ensure that the participants paid attention to any odor stimuli that were presented before judging the softness of the fabric on each trial (i.e., rather than simply ignoring the odorants as participants might otherwise have done given that they were irrelevant to their tactile discrimination task). In order to minimize any possible carryover effects from the presentation of the odors, the intertrial interval was set at 5000 ms. During the intertrial interval, clean air was delivered to participants.

Results

The participant's mean responses to each of the four fabrics on the roughness scale were submitted to a repeated-measures analysis of variance (ANOVA), with the factors of fabric treatment (Aminosilicone, Comfort, Starch, or No-treatment) and odor (lemon, animal, or no smell). This analysis revealed that the participants were able to discriminate between the softness of the different fabrics, giving rise to a main effect of fabric treatment, $F(3,48) = 95.89$, $P < 0.001$. Subsequent t-test comparisons (Bonferroni-corrected, where $P < 0.05$ prior to correction) showed that the participants could discriminate between all four types of fabric (all comparisons were significant at $P < 0.01$). Crucially, there was also a significant main effect of odor, $F(2,32) = 5.78$, $P < 0.01$, and subsequent t-test comparisons (Bonferroni-corrected) revealed that participants rated the fabric swatches as feeling significantly softer when evaluated in the presence of the lemon odor ($M = 10.64$) than when evaluated in the presence of the animal odor ($M = 11.08$), $P < 0.01$. The no-smell condition ($M = 10.79$) did not differ significantly (NS) from either the animal or lemon odor conditions. The interaction between fabric treatment and odor was not significant, $F(6,96) = 1.23$, NS (see Table 1).

The analysis of participants' responses to the odors revealed that they generally classified the lemon odor as pleasant, the animal odor as unpleasant, and the clean air as odorless in the majority of trials (see Table 2). However, three of the participants classified the lemon odor as unpleasant in the majority of trials ($M = 92\%$, 96%, and 83%), and two different participants classified the animal odor as pleasant in a majority of the trials ($M = 58\%$ and 100%). Interestingly, even these five participants showed a tendency to rate the fabrics as softer when presented together with the lemon odor than with the animal odor (mean rating difference of 0.13, 0.42, 0.75, 0.17, and 0.06 points, respectively). Note also that in 13% of the trials, participants classified the clean air as unpleasant. When analyzing participants' mean responses to the fabrics based on their judgments of the pleasantness of the odors (rather than on the identity of the odors themselves) using a repeated-measures ANOVA with the factors of fabric treatment (Aminosilicone, Comfort, Starch, or No-treatment) and perceived pleasantness (pleasant, unpleasant, or no-odor), the results did not differ significantly from those presented earlier (note that the data from three participants were not analyzed because the data corresponding to certain conditions were missing). That is, there was still a significant main effect of odor (now representing the perceived factor of pleasantness), $F(2,26) = 14.85$, $P < 0.001$, with participants rating the fabrics as feeling softer in the presence of an odor that had been subjectively classified as pleasant than when presented with an odor that had subjectively been classified as unpleasant ($P < 0.01$; Bonferroni-corrected *t*-test comparison). There was also a significant main effect of the fabric treatment factor, $F(3,39) = 114.20$, $P < 0.001$, but no interaction between perceived pleasantness and fabric treatment, $F(6,78) = 1.05$, NS. However, remember that the main reason for participants being asked to classify the odors was simply to ensure that they had processed any odor that had been presented (i.e., to ensure that they did not simply ignore them), prior to making their rating of the fabric, rather than because we were interested in the response that they made *per se*. Taken together, the results of Experiment 1 therefore support the view that the presence of an odor can influence tactile judgments and, what's more, that this effect appears to be independent of any subjective awareness of its existence.

Table 1 Mean ratings (+SE) of the perceived roughness (1 = soft and 20 = rough) of the fabric samples as a function of the fabric treatment and odor factors in Experiment 1

Odor	Fabric treatment			
	Aminosilicone [6.07]	Comfort [8.23]	No-treatment [13.01]	Starch [16.04]
Lemon [10.64]	5.99 (0.82)	7.87 (0.80)	12.95 (0.67)	15.74 (0.77)
Animal [11.08]	6.23 (0.73)	8.53 (0.69)	13.29 (0.66)	16.27 (0.77)
No-odor [10.79]	5.99 (0.74)	8.29 (0.66)	12.79 (0.66)	16.09 (0.78)

The marginal means are reported in square brackets.

Table 2 Mean pleasantness classifications (in percentages) for each of the three odor conditions in Experiment 1

Odor	Perceived pleasantness		
	Pleasant	Unpleasant	Odorless
Lemon	77	20	3
Animal	14	73	13
No-odor	5	13	82

Discussion

The results of Experiment 1 demonstrate a significant effect of the presence of an odor on judgments of the tactile properties of fabric swatches. In particular, fabric swatches were judged as feeling slightly but significantly softer in the presence of a pleasant odor (lemon) than in the presence of an unpleasant animal-like odor. To our knowledge, Experiment 1 represents the first empirical demonstration that the presence of an odor can influence the tactile perception of fabric softness. Our results are consistent with those reported more than 70 years ago by Laird (1932). However, in Laird's study, the participants were given the somewhat counterintuitive task of judging/rating fabric samples that were actually physically identical. In contrast to Laird's experiment, we used fabric swatches that were actually physically discriminable in terms of their tactile qualities (as shown by the main effect of fabric treatment), allowing us to rule out the possibility that the effect reported in our study depended solely upon the participant's liking of the pleasant odor as compared to the unpleasant odor, rather than because of a genuine influence of odor cues on the perception of the tactile properties of the fabric swatches tested. Moreover, the presence of participants who showed the same tendency as the others to rate the fabrics as feeling softer during the presentation of the lemon odor despite the fact that they classified the lemon odor as unpleasant or the animal odor as pleasant supports the claim that participants were actually responding to the fabrics' tactile properties and not to their hedonic value.

One might argue that the odor-induced effect reported in Experiment 1 was quite small (a change of approximately 0.5 units on the 1-to-20 response scale). However, this is actually equivalent to about a 2.5% change in perceived fabric softness (assuming that the participants were using the scale in a linear manner). What's more, the relatively small magnitude of this cross-modal effect may reflect the fact that we used a relatively arbitrary pairing of lemon odor with the fabric swatches. In fact, it might be possible that the use of a different odor (e.g., a lavender odor) would lead to a more pronounced effect on tactile perception.

In our study, the environmental sources of the olfactory and tactile stimulation were distinct: The tubes coming from the olfactometer (which we used to deliver the olfactory stimuli) were visible and were obviously located in a different spatial location from the tactile stimuli felt by participants. While this experimental setup gave us very precise control over the stimulus timings (i.e., allowing us to control the relative time of onset of the olfactory and tactile stimulation), one might wonder to what extent the spatial incongruency between the olfactory and the tactile stimuli may have broken any ''unity assumption'' that has been suggested by researchers as potentially providing one of the cues for multisensory integration (e.g., Welch and Warren, 1980; Welch, 1999; Meredith, 2002; Bertelson and de Gelder, 2004; Macaluso *et al.*, 2004; Murray *et al.*, 2004). Therefore, in order to unequivocally rule out any possible effect of an hypothetical break of the unity assumption and, second, in order to use a more ecological setting (i.e., a setup more similar to that of the pioneering study of Laird, 1932, that had inspired the present research), we conducted the next experiment, in which the olfactory stimuli originated directly from the fabric swatches being touched by participants (i.e., from exactly the same environmental object). A third issue that we also assessed in our second experiment was whether the tactile modulation observed in Experiment 1 was directly linked to the particular pairing of odors used there. Therefore, in Experiment 2, we used lavender and animal odor.

Experiment 2

Methods

Participants

Forty new untrained participants (21 female and 19 male), with a mean age of 22 years (range of 18–49 years), took part in this experiment. All the participants reported having a normal sense of smell, no history of olfactory dysfunction, and normal or corrected-to-normal vision in a confidential questionnaire. All the participants were naive as to the purpose of the experiment. None of them had taken part in the previous experiment.

Apparatus and materials

Only two of the cotton fabric swatches were chosen as tactile targets from among the four used in Experiment 1 since there was no difference in the effect of the presence of an odor among the different fabrics. The fabric treated with Aminosilicone constituted the soft stimulus, while the fabric treated with Starch was used as the rough stimulus. The two fabrics were chosen on the basis of the results of Experiment 1, where the participants perceived the Aminosilicone-treated fabric as being the softest and the Starch-treated fabric as the roughest of the four fabrics that had been presented. An olfactant was applied to certain fabric swatches but not to others. The animal odor (AB 0394, Quest International) was used to provide the unpleasant olfactory stimulus, as suggested by the wide consensus concerning its unpleasant hedonic valence among the participants in our previous experiment, while lavender (441142, Quest International) was used as the pleasant olfactory stimulus (e.g., see Degel and Köster, 1999; Degel *et al.*, 2001). One drop of odorant (approximately 0.06 ml) was applied using a micropipette to two opposite corners of the square fabric swatches, and these corners were then marked in order to make sure that neither the experimenter nor the participants touched them during the experimental session itself. Pilot testing confirmed that at the odor concentration used the animal- and lavender-odorized fabrics were perceived as having approximately the same intensity. Before the start of their experimental session, participants saw the 10-point response scale (1 = soft and 10 = rough) that they were asked to use afterward, when making their verbal ratings concerning the roughness of the fabrics. We chose to use a simpler rating scale than that used in Experiment 1 because the participants in Experiment 2 were not allowed to see the scale during the experimental session. In particular, we thought that a 10-point scale would prove simpler for the participants to use while blindfolded since the smaller range (i.e., from 1 to 10 rather than from 1 to 20) should have allowed them to remember the associations between the digits and their meaning more easily (e.g., ''1'' meaning soft and ''10'' meaning rough). The participants were not provided with any information about the identity of the odors and the total number of stimuli before the end of the experimental session.

Design

The experiment consisted of a within-participants repeated-measures design, with the factors of odor (animal odor, lavender odor, or no-odor) and fabric treatment (Aminosilicone vs. Starch). The experimental session consisted of one block of 30 trials (five trials per condition) that lasted for approximately 20 min. The conditions were presented to participants in a randomized order.

Procedure

The participants sat in a chair in front of the experimenter. After the presentation of a sample response scale, the participants were blindfolded and the elbow of their dominant hand was placed on a table. The experimenter presented the participants with one fabric swatch on each trial by holding it on one corner and by placing the opposite corner in the participant's hand (neither corner had been scented). The participants were instructed to rub the thumb and index fingers of their dominant hand on the corner that was presented by the experimenter and then to classify the odor of the fabric as being "pleasant," "unpleasant," or else as having "no-odor." Immediately after having made their classification response, the participants were asked to rate the roughness of the cloth using the scale they had seen at the beginning of the experimental session. The experimenter took note of each classification and rating response manually on a response sheet. After coding the participant's olfactory classification response, the experimenter waited approximately 20 s before presenting the next trial in order to minimize any possible carryover effects from the odor presented on the swatch on the preceding trial.

Results

The mean rating responses concerning fabric roughness were submitted to a repeated-measures ANOVA with the factors of fabric treatment (Aminosilicone vs. Starch) and odor (animal, lavender, or no-odor). There was a significant main effect of fabric treatment, $F(1,39) = 283.33$, $P < 0.001$, with participants finding it easy to discriminate between the two differently treated fabrics in terms of their roughness (Aminosilicone fabric, $M = 3.73$, vs. Starch fabric, $M = 6.91$). The main effect of odor was once again significant, $F(2,78) = 9.63$, $P < 0.001$, as expected given the results of Experiment 1: The Bonferroni-corrected *t*-test comparisons (where $P < 0.05$ prior to correction) revealed that the fabrics treated with the animal odor were rated as feeling significantly rougher that those scented with lavender ($M = 5.54$ vs. 5.15, respectively; $P < 0.01$), while the perceived roughness of the non-odorized fabric ($M = 5.26$) differed significantly from the animal-scented fabric, $P < 0.01$, but not from the lavender-scented fabric, NS. The interaction between these two factors was not significant, $F < 1$ (see Table 3).

Subsequently, the mean fabric roughness ratings were grouped according to each participant's classification of the hedonic valence of the odor that was applied to the fabrics. Note that, as in our previous experiment, the participants consistently judged the animal-odorized fabrics as having an unpleasant smell ($M = 86\%$). The lavender-odorized fabrics were judged as having a pleasant smell ($M = 85\%$) and the odorless fabrics as having no smell ($M = 87\%$; see Table 4). Among the participants, one judged the animal-odorized fabrics as having a pleasant odor overall ($M = 90\%$), one as having no odor ($M = 80\%$), four judged the lavender odor as being unpleasant on a majority of trials ($M = 60\%$, 60%, 80%, and 90%, respectively), and two judged the odorless fabrics as having a pleasant smell on a majority of trials ($M = 70\%$ and 80%, respectively). Interestingly, none of the participants showing a reversed pattern of results (i.e., lower ratings in response to the animal-odorized fabrics than to the lavender-odorized fabrics) showed a perfect correspondence between the direction of the olfactory effect and their hedonic judgments (i.e., perceiving both the lavender odor as being unpleasant and the animal odor as being pleasant), suggesting the existence of a certain independence between the olfactory effects on tactile ratings and the participants' explicit evaluations of the odors' hedonic values. The data were analyzed using an ANOVA with the factors of fabric treatment (Aminosilicone vs. Starch) and olfactory classification (pleasant, unpleasant, or no-odor). The data from three participants were not included in the analysis because the data corresponding to certain of the conditions were not available. The pattern of results was exactly the same as that observed in the analysis described earlier. In fact, the participants could clearly distinguish between the two tactile targets, $F(1,35) = 384.83$, $P < 0.001$, as the Aminosilicone-treated fabric ($M = 3.66$) was rated as being significantly softer than the Starch-treated fabric ($M = 6.97$). The main effect of odor was also significant, $F(2,70) = 11.52$, $P < 0.001$, with participants rating the unpleasantly scented fabrics ($M = 5.58$) as being significantly rougher than both the pleasantly scented ($M = 5.16$) and the unscented fabrics ($M = 5.21$; both the Bonferroni-corrected *t*-test comparisons were significant at $P < 0.001$). The difference between the no-odor and the pleasant category failed to reach statistical significance, NS. Just as for the previous analysis, there was no interaction between fabric treatment and olfactory classification, $F < 1$.

Table 3 Mean ratings (+SE) of the perceived roughness (1 = soft and 10 = rough) of the fabric samples as a function of the fabric treatment and odor factors in Experiment 2

Odor	Fabric treatment	
	Aminosilicone [3.73]	Starch [6.91]
Lavender [5.15]	3.62 (0.17)	6.68 (0.22)
Animal [5.54]	3.88 (0.16)	7.20 (0.19)
No-odor [5.26]	3.68 (0.17)	6.85 (0.21)

The marginal means are reported in square brackets.

Table 4 Mean pleasantness classifications (in percentages) for each of the three odor conditions in Experiment 2

Odor	Perceived pleasantness		
	Pleasant	Unpleasant	Odorless
Lavender	85	10	5
Animal	6	86	8
No-odor	8	5	87

Discussion

The results of Experiment 2 once again support the existence of a systematic effect of olfactory stimulation on tactile perception. In particular, the participants in this study judged the fabrics as feeling softer overall when they were odorized with the lavender odor rather than with the animal odor.

These results are consistent with both the pattern of results and with the magnitude of the effect reported in Experiment 1, thus successfully replicating our previous study but now using a more ecologically valid (though less tightly controlled) experimental setup. The possible existence of a different odor effect between the two experiments was assessed by a between-experiments analysis, which once again highlighted the significant effect of the presence of an odor on the tactile ratings, $F(2,110) = 9.09$, $P < 0.001$. However, the analysis revealed no difference between the two experiments and no interaction between experiment and odor (both Fs < 1). The results of our two experiments are consistent with those reported by Laird (1932) more than 70 years ago, with the major difference being that our experimental setup was more controlled in as much as that the participants were required to perform a specific task (i.e., to discriminate between differently treated fabrics) using response scales and that we used a repeated-measures design (while Laird's participants had to give only a single response).

A second important point addressed by the results of our second experiment concerns the putative role of the unity assumption in multisensory integration. Crucially, the fact that the modulatory effect of the olfactory stimuli on tactile perception was found to be significant in both the experiments reported here would appear to suggest that the spatial colocation of stimuli in different sensory modalities may not be that important for multisensory interactions involving olfactory stimuli. Moreover, given that neither the temporal onset of an odor (e.g., Stevenson and Boakes, 2003) nor the spatial location of its source are precisely coded in the olfactory system (e.g., Kobal *et al.*, 1989; Spence *et al.*, 2000), it would seem probable that the brain may rely upon different rules (such as perhaps the development of cross-modal associations) in order to facilitate multisensory integration involving olfactory stimulation. However, it should also be noted that performance on a number of other audiovisual tasks, such as those requiring stimulus identification judgments rather than stimulus localization are ''not'' always influenced by whether the sources of multisensory stimulation actually come from the same location or not (e.g., see Welch *et al.*, 1986; Regan and Spekreijse, 1977; Bertelson, 1994; Colin *et al.*, 2001; Recanzone, 2003; Vroomen and Keetels, 2006).

Finally, given the extensive experimental evidence demonstrating a greater sensitivity to odors in women than in men (e.g., Choudhury *et al.*, 2003; see also Brand and Millot, 2001; Spence, 2002, for reviews), we thought it worthwhile to test whether the olfactory modulation of fabric perception effects reported in our experiment might be more evident in females than in males (remember that in the study of Laird, 1932, only females were tested). We addressed this question by reanalyzing our data but now including gender as a between-participants factor. Interestingly, we neither found any significant main effect of gender [$F(1,38) = 1.71$, NS] nor any significant interaction between gender and any of the other factors [gender × fabric, $F < 1$; gender × odor, $F(2,76) = 1.31$, NS; gender × fabric × odor, $F < 1$]. These null results are consistent with a number of previous studies, where no significant difference in performance between female and male participants was reported (e.g., Koelega and Köster, 1974; Richardson and Zucco, 1989). One possible explanation for this lack of any gender effects might be related to the fact that in our experiment the participants' performance did not directly involve the olfactory stimuli (i.e., the participants responded by making tactile rating responses), as opposed to the studies concerning gender differences that used, for instance, olfactory identification or olfactory threshold tasks (see Brand and Millot, 2001).

General discussion

In the two experiments reported here, we investigated the influence of olfactory stimuli on tactile perception. Our results demonstrate the existence of a cross-modal interaction between olfaction and touch. The results of Experiment 1 revealed that the presence of an odor can modulate the tactile perception of fabric softness (see also Laird, 1932; Cox, 1967; Byrne-Quinn, 1988; Fiore, 1993). In Experiment 2, we further investigated the nature of any cross-modal associations between tactile and olfactory stimuli by using a slightly different (and more ecologically valid) experimental setup. The results once again revealed a systematic modulation of tactile perception driven by the presence of an odor.

One possible explanation for the cross-modal interactions established by the present study is in terms of an association between tactile and olfactory stimuli that may have been learned through everyday experience. Indeed, the literature on olfactory perception contains numerous examples of bias effects exerted by stimuli presented in one sensory modality on people's responses to stimuli presented in another modality (e.g., Stevenson *et al.*, 1998; Stevenson and Boakes, 2004). It has been suggested that these influences may develop through a process of associative learning (e.g., Engen, 1982; Van den Bergh *et al.*, 1999; Herz, 2002; Stevenson and Boakes, 2003) and that this can affect an individual's subsequent perceptual experience. For instance, Stevenson *et al.* (1998) reported that an unfamiliar odor (such as that of water chestnut for the Australian participants tested in their study) was systematically judged as being sweeter after having been paired previously with a sucrose solution than after having been paired with water. Stevenson and his colleagues argued that taste–smell associations of this kind may be learned through repeated exposure to particular odor–taste combinations. Cross-modal interactions between odors and fabrics may therefore rely upon a similar associative mechanism, giving rise to expectancies about the co-occurrence of tactile and olfactory stimuli.

A second possible explanation for the existence of cross-modal links between olfaction and touch would be to suggest that they should be attributed to another common feature linking the two stimuli. Given that there was a general agreement among participants in classifying the hedonic valence of the olfactory stimuli (i.e., as being either pleasant or unpleasant), it is possible that the cross-modal effects reported here may have been mediated by each target's particular hedonic valence. For example, smelling a pleasant odor could have biased participants' tactile judgments, thus resulting in a tendency for them to report the fabrics as being softer than was actually the case. This bias could have been driven by an assumption of correspondence between a soft tactile feeling and a pleasant experience (cf. Bone and Jantrania, 1992; though see also Schifferstein and Michaut, 1999). These multisensory correspondences may derive from our everyday experience of intensely odorized household products that may create an association between ''pleasant odor'' = ''better product'' (i.e., most effective, softest, and cleanest).

One might also argue that the presentation of the odor or the affective valence associated with it could have induced a general change in participants' mood that would have been reflected in their responses (i.e., in their softness ratings). For instance, Kirk-Smith *et al.* (1983) argued that odors have a robust hedonic connotation that can be learned through a process of classical conditioning. The affective connotation of an odor can then trigger a similar emotional state when that odor is encountered in a different situation (see also Baeyens *et al.*, 1996). Although olfactory stimuli appear capable of rapidly modulating a person's mood (i.e., after approximately 2–5 min of olfactory stimulation; see Villemure *et al.*, 2003), this appears to provide an unlikely explanation for our results since the odors were changed on a trial-by-trial basis in the present study and each trial lasted for less than a minute.

It is important to note that the perceived pleasantness of the stimuli cannot be used to explain all the results reported in the present study, given that in both the experiments the participants' performance appeared to be unrelated to their pleasantness judgments concerning the odors in a number of cases. Indeed, a growing number of studies now show that the information perceived through one sensory modality can actually affect people's perception of stimulus attributes associated with other sensory modalities (e.g., Driver and Spence, 2000; Schifferstein and Michaut, 2002; Calvert *et al.*, 2004). Therefore, it is possible that the effects of the olfactory cues on participants' ratings of the softness of the fabric swatches may also reflect a cross-modal perceptual interaction, whereby the olfactory stimulation affected the actual ''feel'' of the fabric swatches that the participants touched.

Taken together, therefore, the results of the two experiments reported in the present study support the existence of cross-modal interactions between olfaction and touch. Crucially, the present study is the first to demonstrate such interactions between the particular pairing of olfactory and tactile stimuli. We suggest that such links may be learned through everyday experience (cf. Maga, 1974; Zellner and Kautz, 1990). These cross-modal interactions may rely on our prior knowledge concerning the likelihood of co-occurrence of those stimuli or could be facilitated by their shared hedonic valence. Alternatively these interactions may also take place at a more perceptual level (e.g., see Allen and Schwartz, 1940). Nevertheless, whatever the correct theoretical interpretation of our results turns out to be, our study represents a first step toward a better understanding of the cross-modal influence of olfaction on touch by demonstrating the existence of robust cross-modal links in information processing between these two senses.

Acknowledgements

M.L.D. was supported by a grant from the Università degli Studi di Trento. We would like to thank Unilever Research Portsunlight Laboratory and Quest International for generously providing the olfactants used in this study.

References

Allen, F. and **Schwartz, M.** (1940) *The effect of stimulation of the senses of vision, hearing, taste, and smell upon the sensibility of the organs of vision.* J. Gen. Physiol., 24, 105–121.

Baeyens, F., Wrzesniewski, A., De Houwer, J. and **Eelen, P.** (1996) *Toilet rooms, body massages, and smells: two field studies on human evaluative odor conditioning.* Curr. Psychol.: Dev. Learn. Pers. Soc., 15, 77–96.

Bertelson, P. (1994) *The cognitive architecture behind auditory-visual interaction in scene analysis and speech identification [commentary on Radeau].* Curr. Psychol. Cogn., 13, 69–73.

Bertelson, P. and **De Gelder, B.** (2004) *The psychology of multimodal perception.* In Spence, C. and Driver, J. (eds), Crossmodal Space and Crossmodal Attention. Oxford University Press, Oxford, UK, pp. 179–220.

Bone, P.F. and **Jantrania, S.** (1992) *Olfaction as a cue for product quality.* Mark. Lett., 3, 289–296.

Börnstein, W. (1936) *On the functional relations of the sense organs to one another and to the organism as a whole.* J. Gen. Psychol., 15, 117–131.

Brand, G. and **Millot, J.-L.** (2001) *Sex differences in human olfaction: between evidence and enigma.* Q. J. Exp. Psychol., 54B, 259–270.

Byrne-Quinn, J. (1988) *Perfume, people, perceptions and products.* In Van Toller, S. and Todd, G. (eds), Perfumery: The Psychology and Biology of Fragrance. Chapman and Hall, New York, pp. 205–216.

Calvert, G.A., Spence, C. and **Stein, B.E.** (eds) (2004) The Handbook of Multisensory Processes. MIT Press, Cambridge, MA.

Choudhury, E.S., Moberg, P. and **Doty, R. L.** (2003) *Influences of age and sex on a microencapsulated odor memory test.* Chem. Senses, 28, 799–805.

Colin, C., Radeau, M., Deltenre, P. and **Marais, J.** (2001) *Rules of intersensory integration in spatial scene analysis and speechreading.* Psychol. Belg., 41, 131–144.

Cox, T.F. (1967) *The sorting rule model of the consumer product evaluation process.* In Cox, T.F. (ed), Risk Taking and Information Handling in Consumer Behavior. Graduate School of Business Administration, Harvard University, Boston, pp. 324–371.

Dalton, P., Doolittle, N., Nagata, H. and **Breslin, P.A.S.** (2000) *The merging of the senses: integration of subthreshold taste and smell.* Nat. Neurosci., 3, 431–432.

Degel, J. and **Köster, E.P.** (1999) *Odors: implicit memory and performance effects.* Chem. Senses, 24, 317–325.

Degel, J., Piper, D. and **Köster, E.P.** (2001) *Implicit learning and implicit memory for odors: the influence of odor identification and retention time.* Chem. Senses, 26, 267–280.

Driver, J. and **Spence, C.** (2000) *Multisensory perception: beyond modularity and convergence.* Curr. Biol., 10, R731–R735.

Engen, T. (1982) The Perception of Odors. Academic, New York.

Fiore, A.M. (1993) *Multisensory integration of visual, tactile, and olfactory aesthetic cues of appearance.* Clothing Text. Res. J., 11, 45–52.

Gilbert, A.N., Martin, R. and **Kemp, S.E.** (1996) *Cross-modal correspondence between vision and olfaction: the color of smells.* Am. J. Psychol., 109, 335–351.

Guest, S., Catmur, C., Lloyd, D. and **Spence, C.** (2002) *Audiotactile interactions in roughness perception.* Exp. Brain Res., 146, 161–171.

Guest, S. and **Spence, C.** (2003a) *Tactile dominance in speeded discrimination of pilled fabric samples.* Exp. Brain Res., 150, 201–207.

Guest, S. and **Spence, C.** (2003b) *What role does multisensory integration play in the visuotactile perception of texture?* Int. J. Psychophysiol., 50, 63–80.

Heller, M.A. (1982) *Visual and tactual texture perception: intersensory cooperation.* Percept. Psychophys., 31, 339–344.

Herz, R.S. (2002) *Influences of odors on mood and affective cognition.* In Rouby, C., Schaal, B., Dubois, D., Gervais, R. and Holley, A. (eds), Olfaction, Taste, and Cognition. Cambridge University Press, Cambridge, UK, pp. 160–177.

Kirk-Smith, M., Van Toller, C. and **Dodd, G.** (1983) *Unconscious odour conditioning in human subjects.* Biol. Psychol., 45, 136–148.

Kobal, G., Van Toller, S. and **Hummel, T.** (1989) *Is there directional smelling?* Experientia, 45, 130–132.

Koelega, H.S. and **Köster, E.P.** (1974) *Some experiments on sex differences in odor perception.* Ann. N. Y. Acad. Sci., 237, 255–246.

Laird, D.A. (1932) *How the consumer estimates quality by subconscious sensory impressions: with special reference to the role of smell.* J. Appl. Psychol., 16, 241–246.

LaMotte, R.H. (1977) *Psychophysical and neurophysiological studies of tactile sensibility.* In Hollies, N.R.S. and Goldman, R.F. (eds), Clothing Comfort: Interaction of Thermal, Ventilation, Construction and Assessment Factors. (The Fiber Society, Inc., Comfort Symposium Proceedings.) Science Publishers, Ann Arbor, MI, pp. 83–105.

Lederman, S.J. (1979) *Auditory texture perception.* Perception, 8, 93–103.

Lederman, S.J. and **Klatzky, R.L.** (2004) *Multisensory texture perception.* In Calvert, G.A., Spence, C. and Stein, B.E. (eds), The Handbook of Multisensory Processes. MIT Press, Cambridge, MA, pp. 107–123.

Macaluso, E., George, N., Dolan, R., Spence, C. and **Driver, J.** (2004) *Spatial and temporal factors during processing of audiovisual speech: a PET study.* Neuroimage, 21, 725–732.

Maga, J.A. (1974) *Influence of color on taste thresholds.* Chem. Senses Flavor, 1, 115–119.

Meredith, M.A. (2002) *On the neuronal basis for multisensory convergence: a brief overview.* Cogn. Brain Res., 14, 31–40.

Morrot, G., Brochet, F. and **Dubourdieu, D.** (2001) *The color of odors.* Brain Lang., 79, 309–320.

Murray, M.M., Molholm, S., Michel, C.M., Heslenfeld, D.J., Ritter, W., Javitt, D.C., Schroeder, C. and **Foxe, J.J.** (2004) *Grabbing your ear: rapid auditory-somatosensory multisensory interactions in low-level sensory cortices are not constrained by stimulus alignment.* Cereb. Cortex, 15, 963–974.

Recanzone, G.H. (2003) *Auditory influences on visual temporal rate perception.* J. Neurophysiol., 89, 1078–1093.

Regan, D. and **Spekreijse, H.** (1977) *Auditory-visual interactions and the correspondence between perceived auditory space and perceived visual space.* Perception, 6, 133–138.

Richardson, J.T.E. and **Zucco, G.M.** (1989) *Cognition and olfaction: a review.* Psychol. Bull., 105, 352–360.

Rolls, E.T. (2004) *Multisensory neuronal convergence of taste, somatonsensory, visual, olfactory, and auditory inputs.* In Calvert, G.A., Spence, C. and Stein, B.E. (eds), The Handbook of Multisensory Processes. MIT Press, Cambridge, MA, pp. 311–331.

Schifferstein, H.N.J. and **Michaut, A.M.K.** (1999) *Effects of (in)congruent product odors on buying decisions.* In paper presented at the 28th EMAC Conference, 11–14 May 1999, Humboldt University, Berlin.

Schifferstein, H.N.J. and **Michaut, A.M.K.** (2002) *Effects of appropriate and inappropriate odors on product evaluations.* Percept. Mot. Skills, 95, 1199–1214.

Schneider, W., Eschman, A. and **Zuccolotto, A.** (2002a) E-Prime User's Guide. Psychology Software Tools Inc, Pittsburgh, PA.

Schneider, W., Eschman, A. and **Zuccolotto, A.** (2002b) E-Prime Reference Guide. Psychology Software Tools Inc, Pittsburgh, PA.

Spence, C. (2002) The ICI Report on the Secret of the Senses. The Communication Group, London.

Spence, C., Kettenmann, B., Kobal, G. and **McGlone, F.P.** (2000) *Selective attention to the chemosensory modality.* Percept. Psychophys., 62, 1265–1271.

Stevenson, R.J. and **Boakes, R.A.** (2003) *A mnemonic theory of odor perception.* Psychol. Rev., 110, 340–364.

Stevenson, R.J. and **Boakes, R.A.** (2004) *Sweet and sour smells: learned synesthesia between the senses of taste and smell.* In Calvert, G.A., Spence, C. and Stein, B.E. (eds), The Handbook of Multisensory Processes. MIT Press, Cambridge, MA, pp. 69–83.

Stevenson, R.J., Boakes, R.A. and **Prescott, J.** (1998) *Changes in odor sweetness resulting from implicit learning of a simultaneous odor-sweetness association: an example of learned synesthesia.* Learn. Motiv., 29, 113–132.

Van den Bergh, O., Stegen, K., Van Diest, I., Raes, C., Stulens, P., Eelen, P., Veulemans, H., Van de Woestijne, K.P. and **Nemery, B.** (1999) *Acquisition and extinction of somatic symptoms in response to odours: a Pavlovian paradigm relevant to multiple chemical sensitivity.* Occup. Environ. Med., 56, 295–301.

Villemure, C., Slotnick, B. and **Bushnell, M.C.** (2003) *Effects of odors on pain perception: deciphering the roles of emotion and attention.* Pain, 106, 101–108.

Vroomen, J. and **Keetels, M.** (2006) *The spatial constraint in intersensory pairing: no role in temporal ventriloquism*, J. Exp. Psychol. Hum. Percept. Perform. in press.

Welch, R.B. (1999) *Meaning, attention, and the "unity assumption" in the intersensory bias of spatial and temporal perceptions.* In Aschersleben, G., Bachmann, T. and Müsseler, J. (eds), Cognitive Contributions to the

Perception of Spatial and Temporal Events. North-Holland, Amsterdam, pp. 371–387.

Welch, R.B., DuttonHurt, L.D. and **Warren, D.H.** (1986) C*ontributions of audition and vision to temporal rate perception*. Percept. Psychophys., 39, 294–300.

Welch, R.B. and **Warren, D.H.** (1980) *Immediate perceptual response to intersensory discrepancy.* Psychol. Bull., 88, 638–667.

Werner, H. and **Schiller, P.V.** (1932) *Untersuchungen über Empfindung und Empfinden: 5. Rauhigkeit als intermodale Erscheinung [Investigations concerning sensation and sensing: 5. Roughness as an intermodal phenomenon].* Z. Psychol., 127, 265–289.

Zellner, D.A. and **Kautz, M.A.** (1990) *Color affects perceived odor intensity.* J. Exp. Psychol. Hum. Percept. Perform., 16, 391–397.

Accepted January 7, 2006