LEARNING AND MOTIVATION **29,** 113–132 (1998)
ARTICLE NO. LM980996

Changes in Odor Sweetness Resulting from Implicit Learning of a Simultaneous Odor-Sweetness Association: An Example of Learned Synesthesia

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In two experiments the smelled sweetness of odors was increased by using them as flavorants of sucrose solution. Experiment 1 used blind experimenters to compare a target odor mixed with sucrose with a control odor mixed with water during masked training trials. The increased sweetness of the target odor was unaffected by whether or not subjects revealed some explicit knowledge of the contingencies in a post-conditioning recognition test. Experiment 2 found that such a conditioned increase in odor sweetness occurred whether training solutions were sipped from a cup or sucked through a straw. Using a frequency test designed to provide a sensitive assay of contingency awareness, there was still no indication that this affected conditioning. It was concluded that such modification of the taste-properties of odors results from implicit simultaneous associative learning and provides an example of learned synesthesia.

Key Words: taste; odor; implicit learning; synesthesia; awareness; simultaneous conditioning.

It is commonly observed that certain odors smell sweet (Dravnieks, 1984; Harper, Land, Griffiths, & Bate-Smith, 1968). This is easily verified by smelling vanilla or strawberry essence, for example. Such sweet-smelling odors have the ability, when mixed with sucrose in solution, to make the mixture appear sweeter than sucrose alone, even though they possess no taste

The authors thank Amber Carver, Scott Gazzard, Dominic Dwyer, Mary-Ellen Harrod, Judi Single and Jason Rolles, for collecting the data in both experiments, Quest International for kindly supplying the odors, and Henry Potts for suggesting the straw condition. This research was supported in part by the University of Sydney/CSIRO Collaborative Grants scheme.

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0023-9690/98 $25.00

themselves (Frank & Byram, 1988; Cliff & Nobel, 1990; Clark & Lawless, 1994). This effect, termed sweetness enhancement, is lawfully related to the degree to which an odor smells sweet (Stevenson, Prescott, & Boakes, submitted). Odor sweetness appears not to have a physiological basis, in that the nose contains no sweetness receptors, unlike the mouth (Miller & Bartoshuk, 1991), nor do such odorants typically have the molecular structure necessary to activate sweetness receptors. The possibility that odor sweetness arises from learned associations between odors and sweet tastes is explored in the present study.

Evidence for the effect of associative learning on the taste-properties of odors was reported by Stevenson, Prescott, and Boakes (1995). These experiments employed the following procedure to obtain odor-sweetness conditioning. A pretest on Day 1 and a posttest on Day 5 included subjects' ratings of the sweetness and sourness, when sniffed, of two target odors, lychee and water chestnut. These had been selected from a set of odors assessed in a preliminary experiment as being relatively unfamiliar, of moderate sweetness and only slightly sour. With the conditioning procedure employed on Days 2–4, subjects sampled a total of nine sucrose solutions, to which one target odor had been added as a flavorant, and nine samples of a citric acid solution, to which a second target odor had been added. These pairings were embedded in a masking task designed to camouflage the conditioning procedure. In both experiments the posttest revealed an increase in perceived sweetness of the sucrose-paired odor and an increase in the sourness of the citric acid-paired odor.

An important issue that was not fully addressed in the earlier paper (Stevenson *et al.*, 1995) concerned the use of an appropriate control for nonassociative exposure effects. The possibility that mere exposure may have accounted for *either* the sucrose-paired *or* the citric acid-paired effect is important for two reasons. First, Shanks and Dickinson (1990) have identified stimulus exposure as a potential problem in evaluative conditioning research (e.g., Levey & Martin, 1975; Martin & Levey, 1978). In view of the procedural similarities between such research and the two conditioning experiments reported by Stevenson *et al.* (1995), changes arising from mere exposure alone could have been present in the latter experiments, since no water paired control, that is a stimulus exposure-only condition, was included. Second, though the differential conditioning procedure employed in Stevenson *et al.* (1995) may in itself make interpretation in terms of exposure effects unlikely, the unwieldy nature of this procedure when more complex manipulations are required (as in Experiment 2 here) makes demonstrating the associative nature of the basic conditioning effect a necessity. This is addressed in Experiment 1.

A different kind of issue is raised by evidence suggesting that the odor-sweetness learning found previously was implicit. In the previous experiments (Stevenson *et al.* 1995) no difference in the magnitude of the conditioning effect was found between subjects classified as Aware or Unaware by a postconditioning recognition test. This finding is in marked contrast to the results from other approaches to the study of implicit learning (see Shanks & St. John, 1994) or of human conditioning (e.g., Boakes, 1989; Dawson & Schell, 1987), where large differences in performance are generally found between Aware and Unaware subjects (but see Baeyens, Eelen, & van den Bergh, 1990).

The issue of awareness may be related to the nature of the association formed between the odor and the taste. One possibility is that in Stevenson *et al.* (1995) a successive association was formed between the smell, i.e., orthonasal odor, of a solution as it approached the lips and its subsequent taste. Alternatively, what was learned might have been a simultaneous association (Rescorla, 1980) between the retronasal odor, i.e., flavor, and the taste, with such a compound experienced as a single configural stimulus. Such configural learning might be more favorable to the occurrence of learning without awareness, simply because it makes it more difficult for subjects to verbalize or identify the component elements, the CS and US.

The configural account is lent some weight by the observation that perception of a taste/odor mixture in the mouth is usually a unitary experience (Lawless, 1995). Mixtures of tastes and smells are highly confusable (Rozin, 1982) and the sensations generated by such mixtures are perceived as being located ''in the mouth'' rather than, correctly, in the mouth and nose (Deems, Doty, Settle, Moore-Gillon, Shaman, Mester, Kimmelman, Brightman, & Snow, 1991). Thus, retronasal odors and tastes are perceived as located in the same place at the same time. However, the experiments reported by Stevenson *et al.* (1995) did not exclude the possibility that subjects were inadvertently smelling the odor before placing the odor-sucrose mixture into their mouths. Experiment 2 addressed this problem by including a condition in which the only experience of the target odor during conditioning sessions could be retronasal.

EXPERIMENT 1

The main aim of this experiment was to compare the effects of odor–sucrose pairings with that of an odor–water control under more rigorous conditions than those employed by Stevenson *et al.* (1995), namely using blind testing, so that experimenters never knew what condition a particular subject was in. The experiment also addressed whether knowledge, as detected by a sensitive postconditioning recognition test (Dawson & Reardon, 1973), could predict performance on the conditioning task.

Method

Subjects

Thirty-eight University of Sydney first-year undergraduates, none suffering from colds or other respiratory infections, took part in the experiment as part of their course requirements. The study was advertised as a ''flavor judgment experiment.''

TABLE 1
Diagrammatic Summary of the Procedure for Experiment 1

Day 1	Day 2	Day 3	Day 4	Day 5
Pretest	Conditioning days			Posttest
(1) Smell LY, WC, TR, & PE odors and rate them.	(1) On each day the same task is repeated. Subjects sample 18 solutions, 3 of which are flavor (WC or LY) plus sucrose and 3 the other flavor (WC or LY) plus water.			(1) Smell LY, WC, TR, & PE odors and rate them. (2) Contingency awareness test and debrief.

Stimuli

Selection of the odor stimuli was based on previously obtained ratings (Stevenson *et al.*, 1995). The odors to be paired with sucrose or water were lychee (LY; 0.05 g/lt in distilled water; Quest) and water chestnut (WC; 0.03 g/lt in distilled water; Quest). The same concentrations were used when the odors were mixed with taste stimuli and presented as flavors. Two other odor stimuli were used as distractors: Taro (TR; 0.17 g/lt in distilled water; Quest) and Pearade (PE; 1.0 g/lt in distilled water; Quest). All odor/flavor stimuli were commercially prepared flavorants. LY and WC were typically described as smelling moderately sweet, mildly sour, and somewhat ‘‘fruit’’ like. They were fairly unfamiliar odors to most subjects. TR was described as smelling like ‘‘rotting carpet’’ or ‘‘dried cat-food’’ and PE as ‘‘pear-drops’’ or ‘‘plastic’’. All odorants used in the study were matched for intensity.

The taste stimuli were 0.3 *M* (10.3% w/v) sucrose and 0.043 *M* (0.25% w/v) sodium chloride (Univar) in distilled water. Pearade was also used during the conditioning sessions at the concentration described above. Odor stimuli were presented in new plastic polypropylene 250-ml wash bottles, each containing 50 ml of odorant in solution. All bottles had contained their odorant for at least 1 week prior to testing and odors were replenished on the morning preceding every test day. Bottles were sealed after use. All taste stimuli were presented in aliquots of 10 ml, contained in 22-ml translucent disposable plastic cups, which were filled on the morning of the experimental session. Only solutions containing sucrose were refrigerated. All stimuli were presented at room temperature in an air-conditioned room.

Procedure

The procedure followed closely that used by Stevenson *et al.* (1995) and is summarized in Table 1. Each subject attended five sessions: pretest, three conditioning sessions, and posttest. The pretest involved smelling and rating four odors: the two targets (LY and WC) and the two distractors (TR and PE). Subjects were first handed written instructions which briefly described the pretest and outlined the use of the rating scales. A blank rating scale was attached to the bottom of the instruction sheet.

Subjects were then briefed on the use of the scales and on how to smell the odors. This involved placing the 3-cm plastic spout of the bottle (opening diameter 0.4 cm) approximately 4 cm below the nose and vigorously squeezing the plastic bottle while sniffing. Subjects were told to take as long as they wanted to smell the odor as they would not be able to smell it again once they were handed the rating sheet. This is because extra sniffing beyond the first sniff provides the subject with little further information, merely confirmation (Laing, 1983). Subjects were then presented with the first test odor in the series of four. The order of presentation was determined by Williams square so that every odor had an equal probability of being followed by any other odor.

After smelling the odor, the subject was given the first rating sheet. This contained four 15.3-cm visual analogue scales (VAS) in the following order: Liking/Disliking (anchors: Dislike extremely, Like extremely; plus a central marker, Indifference), Overall intensity, Sourness, and Sweetness (anchors: None, Extremely strong). Following this subjects were asked ‘‘Before today, had you EVER smelt a SIMILAR odor to this before?’’, available responses: Yes, Unsure, No (termed, ‘‘broad familiarity question’’). They were then asked ‘‘Before today, had you EVER smelt THIS odor before?’’, available responses: Yes, Unsure, No (termed, ‘‘narrow familiarity question’’). On completion of the rating sheet the same procedure was followed for the second, third, and fourth odors.

Subjects were not given specific definitions of what ‘‘sweet’’ or ‘‘sour’’ might mean in the context of judging odors rather than tastes. However, if a subject did ask, they were given previously agreed definitions which were for sweetness, ‘‘A sweet smell similar to that of freshly baked cakes’’; and for sourness, ‘‘A sour smell similar to that of vinegar’’. Subjects appeared to have little difficulty in applying sweet or sour ratings to the odors.

At least 1 day after the pretest, subjects returned for the first of three conditioning sessions which were separated by a minimum of 24 h. Each conditioning session contained six trials, each consisting of three solutions (i.e., 18 solutions per session). Of the six trials on any conditioning session, one was the conditioning trial, consisting of a target odor paired with sucrose *in all three solutions*, and a second was the control trial, in which the other target odor was paired with water, also in all three solutions. Subjects were assigned by order of arrival for Session 1 to one of the two counterbalanced training conditions, LY–sucrose, WC–water vs LY–water, WC–sucrose. The four ‘‘dummy’’ trials comprised the masking task and always contained one trial each of the following: saline, saline, water; water, water, saline; PE in water, PE in water, water; and water, water, PE in water. Trial order was determined by Williams square, while the position of the odd stimulus in the masking trials was varied randomly. All stimuli were visually identical.

Before the three solutions of the first trial were tasted, the experimenter repeated the instructions. Subjects were then given a rating sheet and asked to sample and expectorate the solutions, one at a time, from left to right and to select which solution was different out of the three (the Triangle or Oddity test). Subjects were informed that they should expect the discrimination required by the Triangle tests to vary in difficulty from very hard to fairly hard (note that the conditioning trial in fact involved sampling three *identical* sucrose-flavor solutions). The subject then marked down on a rating sheet the code of the solution perceived as the odd one out. Subjects were then instructed to rinse their mouths with mineral water, which concluded the trial. The next trial began with a new rating sheet repeating the procedure described above. A conditioning session contained six such trials and subjects attended for three conditioning sessions. The only change in the second and third sessions was the order of presentation of the six trials, which was varied by Williams square.

At least 24 h after completing the last conditioning session subjects returned for the posttest. The first part of the posttest was identical to the pretest. Importantly the order in which the four odors—the two targets and two distractors—were presented to a given subject was kept the same as in the pretest so as to maintain the same rating context. After subjects had completed this task they were given the contingency awareness test. They were presented with the four odors used in the posttest in the same order. After smelling each odor, they were handed a multiple choice rating sheet and asked ‘‘Which out of the following tastes, if any, can you recall being most frequently associated with this odor during this experiment?’’. Five response options were offered: No taste at all, Salty, Sweet, Sour, and Unsure. The position of the Salty, Sweet, and Sour response options was varied randomly between subjects, but the No taste at all and Unsure options always came first and last respectively. Subjects were then asked to rate, on a scale of 1 (Very certain) to 4 (Very uncertain, Guessed, No idea) how sure they were of their response. The procedure was repeated for the second, third and fourth odor.

Analysis

Subjects’ VAS scores were converted into percentages. Familiarity ratings were converted into ordinal numeric scores, so that No = 1, Unsure = 2 and Yes = 3. All reported statistical comparisons used 1-tailed probabilities and the 5% significance level, unless otherwise stated. These conventions are employed for both experiments.

Results

Four subjects failed to complete the experiment and a further 4 were excluded from the analysis due to various mistakes made in the execution of

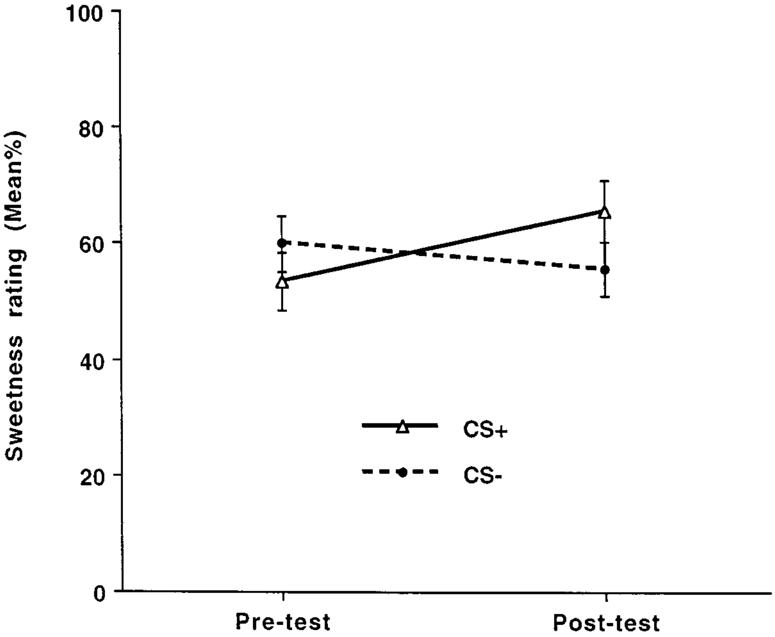


FIG. 1. Changes in odor sweetness ratings, pretest to posttest, for the odor paired with sucrose (CS+) and for the odor paired with water (CS−). All values are means, expressed as percentages, plus SEs.

the experimental protocol. The data from the remaining 30 subjects was then screened to eliminate any subject who appeared to be unable to smell either of the target odors (LY or WC). This was done using the following criteria. Means and standard deviations for overall intensity ratings on pre- and post-test were calculated separately for LY and WC. A ''no-smell'' criterion was set, in which any subject whose overall intensity rating fell below the mean by more than 1.96 standard deviations for either LY or WC on either pretest or posttest was excluded. On this basis, the data from two subjects were removed from further analysis, leaving 28 subjects.

Odor Ratings

As shown in Fig. 1, ratings for sweetness between pre- and posttest increased significantly for the odor paired with sucrose, mean = 12.2%, $t(27) = 2.31$, and somewhat decreased, but not significantly, for the odor paired with water, mean = −4.1%, $t < 1$. The overall difference between the changes in the sucrose-paired and water-paired odors was also significant, mean = 16.3%, $t(27) = 2.13$. As in Stevenson *et al.* (1995), in the pretest lychee was rated sweeter than water chestnut, LY mean = 63.3%; WC mean = 50.2%, but the sweetness change scores for the two odors did not differ. Sourness ratings did not change either for the odor paired with sucrose or for that paired with water, nor did they differ between WC and LY on pretest, nor when sourness change scores were compared between odors (all ts < 1).

Intensity ratings and liking were also examined by testing differences between pre- and posttest ratings. Intensity increased between pre- and posttest for the odor paired with sucrose, mean = 14.0%, $t(27) = 2.45$, but not for the odor paired with water (mean = 7.5%). There was no difference between intensity ratings of WC and LY on pretest, nor in their change scores. Liking for the sucrose-paired odor did not change from pre- to posttest (mean = 1.5%) nor did liking for the water-paired odor (mean = 0.2%). There was no difference in liking for LY and WC on pretest nor did the odors differ when compared on change scores.

For odor familiarity (broad familiarity question), subjects reported that the target odors were more familiar on posttest than they had been on pretest; Wilcoxon signed rank test; sucrose-paired odor, $T(10) = 8.5$; water-paired odor, $T(8) = 4.0$. On the second, narrow familiarity question, subjects also reported being more familiar with the odors on posttest, Wilcoxon signed rank test; sucrose-paired odor, $T(19) = 47.0$; water-paired odor, $T(19) = 34.0$. Odors did not differ in initial familiarity on either of the two questions.

Contingency Awareness

The criterion set to describe a subject as aware of the contingencies was as follows. Subjects were classified as aware if they correctly identified Sweet as the solution with which the sucrose-paired odor had been paired and either (a) identified another solution as being paired with the water-paired odor or (b) identified Sweet as also being paired with the water-paired odor, but were less certain about this judgment than about the odor that was paired with sucrose. On this basis 16 subjects were classed as unaware and 12 as aware. The odor-sweetness change data were then reanalyzed with subjects split into groups depending on their awareness classification. There was no difference between groups in odor sweetness ratings, for either the sucrose-paired odor (aware mean = 12.0%; unaware mean = 12.4%), the water-paired odor (aware mean = −5.2%; unaware mean = −3.1%) or the difference between the two.

Discussion

These results confirm our previous finding that an odor paired with sucrose subsequently smells sweeter (Stevenson *et al.*, 1995). This occurs even under conditions where the experiment was administered by five different experimenters under blind conditions. More importantly, the change in sweetness ratings on which this conclusion is based cannot result from some form of stimulus exposure effect, since no such change was observed for the water-paired control odor which received equal exposure.

With regard to the issue of awareness, the results replicated the finding reported by Stevenson *et al.* (1995) that subjects classified as aware did not perform differently from those categorized as unaware. However, the recognition test used in Experiment 1 is open to the criticisms that it might lack sensitivity and that the testing conditions differed from those where learning took place (see Shanks & St. John, 1994). These were some of the points addressed by Experiment 2.

EXPERIMENT 2

The recognition test for explicit knowledge of the training contingencies used in Experiment 2 was one that required subjects to make frequency estimates. Event frequency information can be acquired automatically (Hasher & Zacks, 1979) and may form the basis for performance in a learning task (Estes & Hopkins, 1961). In general, subjects' frequency estimates are consistently related to the actual frequency with which events have occurred (Zacks, Hasher, & Sanft, 1982). Though frequency estimates have not been previously employed as measures of awareness they may offer a useful insight, because if a subject can correctly express the frequency with which a stimulus has been experienced relative to other stimuli, this might form the basis for a subject's explicit knowledge about the contingencies and thus performance on the smelling task. Therefore the presence of frequency information may not inform directly about the presence or absence of explicit knowledge, but, if frequency information is present, then an account of learning based on this knowledge being used explicitly cannot be excluded.

To minimize the difference between test and training conditions, this test involved presenting an odor–taste combination to subjects. In Experiment 1 the odor stimuli were sniffed rather than tasted and subjects were given written labels for the tastes they were asked to select. In the present experiment subjects were asked to estimate the frequency with which the tasted mixture had occurred in the preceding sessions. This allowed knowledge of the contingencies to be measured in terms of the frequency estimates for mixtures which had been tasted during the training relative to those for mixtures which had not.

In Experiment 1, the time interval between the final conditioning session and the test was at least 24 h. It could be argued that this delay might facilitate the observation of no contingency awareness, simply because subjects could forget. To establish whether delayed testing had any impact on responses, subjects completed a posttest either immediately after the final conditioning session or at least 24 h later.

A final question addressed by Experiment 2 concerned the nature of what is learned during the conditioning sessions. As noted in the introduction, the procedure used by Stevenson *et al.* (1995), which was repeated in Experiment 1 above, allows what is inherent in normal eating and drinking, the opportunity for subjects to perceive an odor on a training trial both orthonasally, by sniffing it as they raise the cup to their lips, and retronasally, after the solution has entered the mouth. In the present experiment this condition was compared to one in which orthonasal perception was prevented, using a within-subject design whereby one target solution was sipped from a cup and another sucked through a straw.

In summary, the aims of Experiment 2 were to assess the use of frequency estimates as a potentially more sensitive test of knowledge of contingencies, to evaluate the possible effect of delay in testing and to determine the relative contributions of successive (orthonasal) and simultaneous (retronasal) learning. The experiment also included modifications to the procedure which were intended to increase effect size. These were: (1) screening out subjects who could not discriminate between the two target odors in the pretest; (2) presenting subjects with very sweet smelling and non-sweet smelling odors before they judged the two target odors, to minimize ceiling effects, and (3) using 0.45 *M* sucrose solution on conditioning trials rather than 0.3 *M* as in previous studies, on the basis that if this learning is akin to that observed in animals, conditioning should be enhanced by increasing US magnitude (Hilgard & Marquis, 1961). Finally, so as to simplify the procedure, Experiment 2 did not use a water-paired control odor, as Experiment 1 had already demonstrated the associative nature of the phenomenon.

Method

Subjects

Thirty-five University of Sydney first-year undergraduates, none suffering from colds or other respiratory infections, volunteered for the experiment as part of their course requirements. The study was advertised as a ‘‘flavor judgment experiment’’. No subject who had taken part in Experiment 1 was in any way involved. Only 29 subjects continued beyond the initial screening described below.

Stimuli

As in Experiment 1, WC and LY were used as the target odors, at the concentrations previously described. The set of ‘‘training’’ odors consisted of taro (TR; as in Experiment 1), snow milk (SM; 2.0 g/lt; a sweet smelling odor akin to vanilla; Quest), caramel, (CR; 2.5 g/lt; Quest) and soy sauce (SS; 50% dilution of Goats & Wall brand commercial soy sauce). The tasted solutions were saline (0.25% w/v; as in Experiment 1), red bean odor in distilled water (RB; 0.05 g/lt; a sweet/savory odor; Quest), SM as described above and SM, WC, and LY in 0.45 *M* sucrose (15% w/v). Stimulus presentation was as described for Experiment 1, except that on conditioning sessions and in the frequency test, certain solutions were presented in sealed cups with a straw and small pressure equalizing hole.

Procedure

Subjects had first to pass a simple odor discrimination test intended to screen out subjects who could not tell the difference between WC and LY.

TABLE 2
Diagrammatic Summary of the Procedure for Experiment 2

Day 1	Day 2 Day 3 Day 4	Day 4—Gp. Immediate Day 5—Gp. Delay
Pretest	Conditioning days	Posttest
(1) Subject selection by discrimination test between WC and LY, the two target odors. (2) Smell TR, SS, CR, and SM. Then smell and rate these odors again, followed by the two target odors.	(1) Subject receives on each day: three solutions of Target Odor 1 plus sucrose through a straw and three solutions of Target Odor 2 plus sucrose, directly by mouth. Subjects also receive four further sets of three masking solutions, half with straws, half directly by mouth.	(1) Smell TR, SS, CR, and SM. Then smell and rate these odors again, followed by the two target odors. (2) Subjects complete frequency judgment task for target flavours and SM, in water, in sucrose, with straw and directly by mouth.

They were instructed how to use the odor bottles, and were then asked to sniff, in order, from left to right, three bottles containing either LY, LY, WC or WC, WC, LY. The ordering within each set of three odors was varied randomly. Subjects were asked to identify the odd one out. This test was then repeated with the other set of odors. Subjects had to identify the odd odor on both tests to take part in the study. Subjects who passed were not aware that this formed a screening test. Only those who were dismissed (6/35) were so informed.

Table 2 provides a summary of the procedure. Subjects completed a pretest, three conditioning sessions, and a posttest. For half the subjects, assigned by uptake to the experiment, the posttest was completed immediately after the third conditioning session (group Immediate), while for the other half it was completed at least 24 h later (group Delay). For both groups all sessions were completed at least 24 h apart.

In the pretest, subjects were asked to read a set of instructions which asked them to smell an odor and to think, while sniffing, about the qualities of liking, intensity, sourness, and sweetness. They were then presented with the training set: TR, SS, CR, and SM. The order was identical for all subjects so as to provide a standard judgmental context. A second set of instructions was then presented which explained use of the odor rating scales. The visual analogue scales were the same as in Experiment 1, but this time no familiarity questions were included, as they were not considered useful. Subjects then smelled and rated, TR, SS, CR, SM and then the two target odors, WC and LY. For half the subjects, WC preceded LY and for the other half LY preceded WC. The order in which a subject received the target odors in the pretest was kept the same in the posttest.

As in Experiment 1, each of the three conditioning sessions contained six trials, each of which consisted of tasting three solutions from left to right and picking the odd one. Instructions for this task and the procedure were similar to Experiment 1, except that half of the trials in each conditioning session involved sucking the solutions through straws, while the other half involved tasting directly by mouth. Hereafter these are referred to as the ''straw'' and ''mouth'' conditions. Crucially, each subject was assigned to either WC in sucrose by straw and LY in sucrose by mouth, or the converse, so that in each conditioning session subjects were given one trial of WC and sucrose, consistently by straw or mouth, and one trial of LY and sucrose, consistently by mouth or straw. Of the other four trials, two were saline, saline, water and water, water, saline, of which one trial was presented by straw and the other by mouth, and two were RB in water, RB in water, water and water, water, RB in water, where again one trial was presented by straw and the other by mouth. The order of trials within a conditioning session was determined by Williams square and the position of the odd sample was randomly varied. Thus, subjects sampled overall a total of nine solutions of LY in sucrose and nine of WC in sucrose, one of which was consistently sampled through a straw and the other by mouth.

The posttest, completed immediately after the third conditioning session by group Immediate and at least 24 h later by group Delay, was divided into two parts. The first was identical to the pretest and involved smelling the four training odors, and then smelling and rating them again along with the two target odors. The second part of the posttest was the frequency judgment task. This involved sampling two identical sets of six solutions, one presented by straw and the other by mouth. The two sets were intermingled and the order of presentation was determined by Williams square. Each set consisted of WC, LY, and SM in 0.45 *M* sucrose and in water. After tasting and expectorating a solution, subjects were asked ''Over the previous three sessions you were given a total of 54 solutions to taste. Do your best to guess how many of them were the same as the solution you just tasted, by writing down one number between 0 and 54 in the circle below.'' Subjects then rated their judgment for certainty using the scale used in Experiment 1 and then rinsed their mouth with mineral water. This procedure was repeated until all the solutions had been sampled and rated.

Results

Of the 29 subjects who passed the initial screening test, two failed to complete the experiment and a further four were removed from the analysis on the basis of the ''cannot smell it'' criterion used in Experiment 1.

Odor Ratings

As shown in Fig. 2, the changes in odor sweetness ratings from pre- to posttest were very similar in the straw and mouth conditions. Single sample t tests ($\mu = 0$) conducted on the sweetness change scores for the odor given

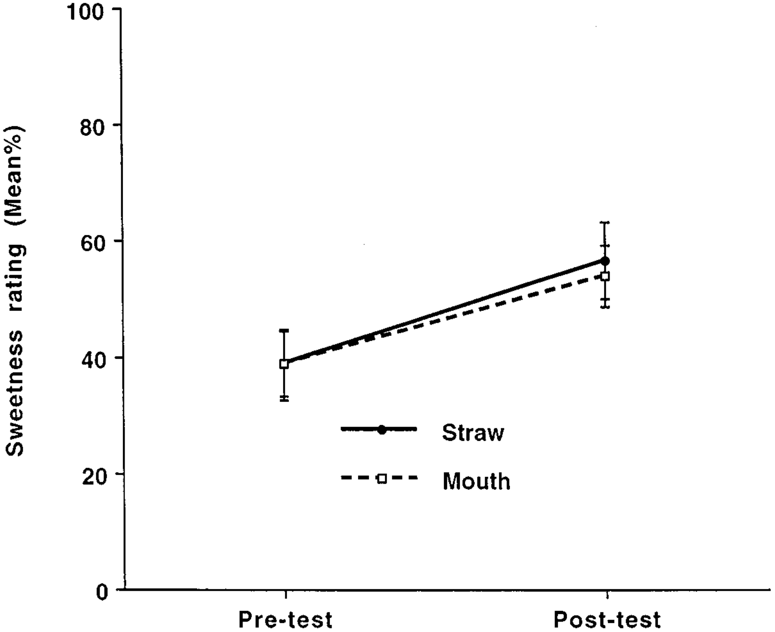


FIG. 2. Changes in odor sweetness ratings, pretest to posttest, for the odor paired with sucrose and sucked through a straw during conditioning sessions (Straw) and for the odor paired with sucrose, but experienced directly by mouth during conditioning sessions (Mouth). All values are means, expressed as percentages, plus SEs.

via the straw revealed a significant increase in ratings of odor sweetness, mean = 18.0%, $t(22) = 3.38$, as did analysis of the sweetness ratings for the mouth odor, mean = 15.3%, $t(22) = 3.98$. The difference between these scores was not significant ($t < 1$). Changes in sweetness for the straw condition were significantly correlated with changes in sweetness for the mouth condition, Pearson's $r = 0.52$. To check that WC or LY were not changing differentially, independent t tests were conducted on subjects who had WC–straw versus LY–straw and WC–mouth versus LY–mouth. There was no significant effect of odor type (all ts < 1). Stability of ratings for the non-paired distractor odors was examined by comparing their change in rated sweetness from pre- to posttest. This did not differ significantly from zero for either SM, mean = 1.2%, $t < 1$, or for CM, mean = −3.2%, $t(22) = 1.01$.

To investigate possible differences in sweetness change between subjects who completed their posttest immediately after the final conditioning session (group Immediate) and those who completed it at least 24 h later (group Delay), a three-way repeated measures ANOVA was conducted. Group (Immediate vs Delay) was entered as a between factor and Condition (straw vs mouth) and Time of rating (pretest vs posttest) as within factors. Although there was a main effect of Time of rating, $F(1, 21) = 18.86$, the main effect and interactions involving Group (Immediate vs Delay) were all nonsignificant. However, there was a tendency for the increase in sweetness from pre- to posttest to be larger in group Delay than in group Immediate in both straw and mouth conditions.

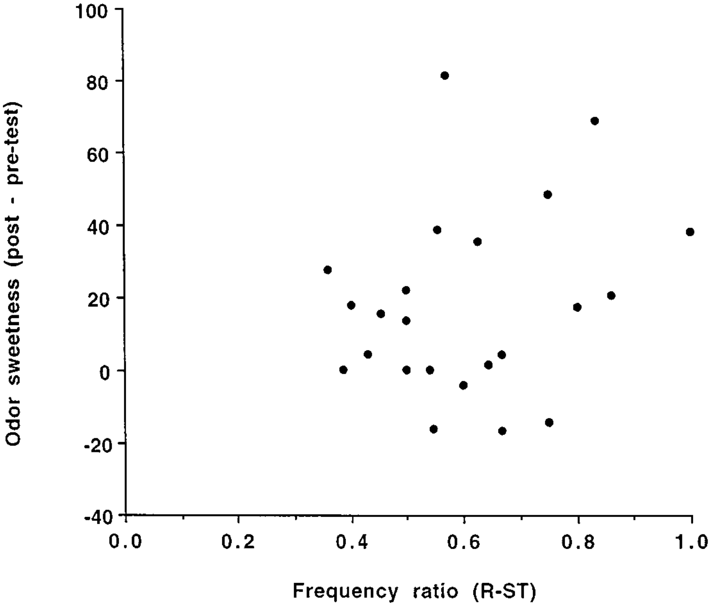
Intensity ratings also increased significantly from pre- to posttest for both the straw, mean = 7.9%, $t(22) = 2.44$, and mouth conditions, mean = 10.7%, $t(22) = 2.73$. The difference between these scores was not significant. There were no significant changes in liking or sourness for either straw or mouth condition, nor any difference between these conditions on these two ratings.

Frequency Judgments

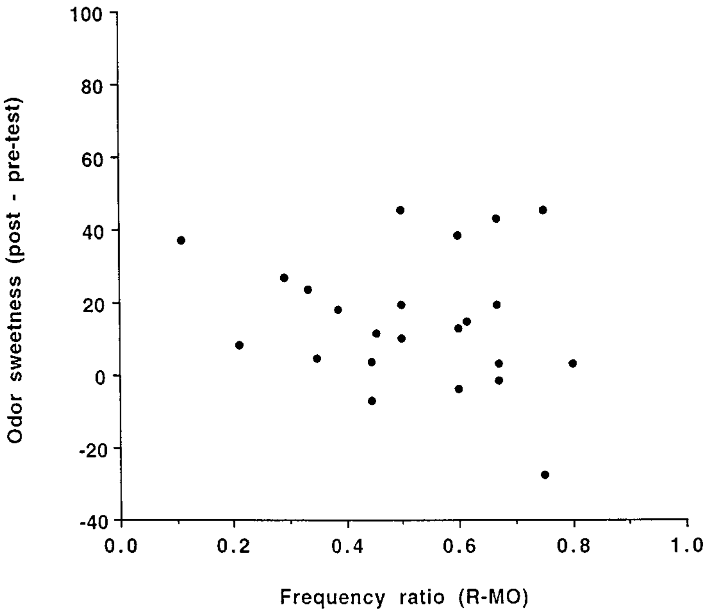
Two measures were derived from the frequency judgment test. The most relevant to the issue of awareness was subjects' frequency estimate for the odor paired with sucrose sampled in sucrose divided by this number plus the frequency estimate for the odor paired with sucrose but sampled in water, i.e., N(odor in suc)/N(odor in suc) + N(odor in water). If a subject believed that the sucrose-paired odor was never presented in water, this ratio should be 1.0. A ratio of 0.5 indicates that the subject believed the sucrose-paired odor occurred with equal frequency in water and in sucrose, and a ratio of 0 indicates that the subject believed they never sampled the sucrose-paired odor in sucrose solution. This ratio for the straw condition was termed R–ST and that for the mouth condition, R–MO.

As indicated by the scattergrams shown in Figs. 3a and 3b, accurate frequency estimates (possibly indicating awareness) were not obviously related to changes in odor sweetness ratings (post- minus pretest). Thus, although in the straw condition (see Fig. 3a) 15 subjects gave relative estimates for the sucrose-paired odor greater than 0.5 and so indicated some knowledge that the odor had occurred more often in a sweet solution than in water, another 5 subjects gave relative estimates less than 0.5. The comparable figures for the mouth condition were 11 subjects with estimates greater than 0.5 and 9 subjects less than 0.5. These ratios were significantly different from the chance level of 0.5 in the straw condition, $t(22) = 3.04$, but not in the mouth condition, $t < 1$. The difference between these two approached significance ($t(22) = 1.65$, $p < 0.06$). The crucial question addressed by these data was whether contingency knowledge, as measured by relative fre-

FIG. 3. (A) Frequency ratios, R–ST, for the Straw condition, where a score of 1.0 indicates accurate relative frequency judgments and a score of 0.0, inaccurate judgments. The vertical axis indicates changes in odor sweetness for the Straw condition odor between pretest and posttest. (B) As above for the Mouth condition.



Odor sweetness (post - pre-test)
100
80
60
40
20
0
-20
-40
0.0
0.2
0.4
0.6
0.8
1.0
Frequency ratio (R-ST)



Odor sweetness (post - pre-test)
100
80
60
40
20
0
-20
-40
0.0
0.2
0.4
0.6
0.8
1.0
Frequency ratio (R-MO)

quency estimates, was related to the conditioned change in sweetness. No significant correlations were found, $r = 0.25$, straw; $r = -0.18$, mouth; with a 5% 1-tailed critical value of r set at 0.35. In view of the finding reported earlier that changes in odor sweetness in the straw and mouth conditions were significantly correlated, if frequency estimates and changes in odor sweetness were related, it might be expected that the R–ST and R–MO ratios would also correlate with each other. However, they did not, $r = -0.09$. No difference in frequency judgments for sucrose-paired odors was found between the Immediate and Delay conditions, all ts < 1. Finally, to check the sensitivity of the frequency judgments subjects' responses were examined for SM. These revealed that subjects reliably judged the conditioned odors (straw and mouth) to have occurred more frequently than SM ($t(22) = 4.75$ for the straw condition—with $\mu = 0.5$—and $t(22) = 3.33$ for the mouth condition using frequency of target odor in sucrose/frequency of target odor in sucrose plus SM frequency rating in sucrose).

Discussion

Experiment 2 produced three main findings. First, simultaneous presentation through a straw, to prevent detection of an odor prior to ingestion, yielded significant changes in odor sweetness of similar magnitude to that for presentation by mouth. Second, frequency judgments bore no significant relationship to changes in odor sweetness. Third, a delay in testing by 24 h or more had no detectable effect on either odor sweetness or awareness.

It is difficult to conceive of a more sensitive procedure for detecting subjects' explicit knowledge of the experimental contingencies than that used in Experiment 2. In the Immediate condition subjects were tested shortly after their final conditioning trials with only the few odor-sniffing trials of the posttest intervening. Furthermore, the ''awareness'' test stimuli included solutions identical to those used during conditioning which were presented in exactly the same way. These frequency tests provide a sensitive form of recognition test, as confirmed by the finding that subjects could use these judgments to reveal that they knew they had not tasted snow milk as frequently as the two target odors. Nonetheless the frequency data revealed limited indication of explicit knowledge that lychee and water chestnut had been sampled only in sucrose solution and never in water alone. Most importantly there was still no sign of any relationship between awareness as measured by this test and changes in odor sweetness.

The straw and mouth conditions yielded almost identical results. This may suggest that the association underlying changes in odor sweetness is between retronasal perception of the odor and the tasted sweetness of the sucrose solution. As discussed earlier, such odor–taste combinations are commonly reported as a unitary sensation. Taken together with the results from Experiment 2, this supports the notion that odor–taste learning is based on the formation of a within-compound association which is experienced as a configural stimulus and which can be viewed as an example of learned synesthesia (see, Howells, 1944; Holland, 1990).

Reber (1985) defined synesthesia as ‘‘The condition in which a sensory experience normally associated with one modality occurs when another modality is stimulated,’’ a description that might be said to characterize the experience of sweetness when an odor previously paired with sucrose is smelled at some later point in time. A more concise set of criteria has been suggested by Cytowic (1989) and it is instructive to see how odor-sweetness matches up to them. Criterion (1), that *synesthesia is involuntary, but elicited:* this criterion is met, in that certain odors, elicit spontaneously the impression of sweetness. Contrast this with vision, where the sight of strawberries or cake may elicit salivation, but not the sensation of sweetness. Criterion (2), that *synesthesia is projected:* this criterion is met, in that the percept of sweetness appears as a part of the odor, but also has properties that parallel those of sweet tastes, suggesting that it is not just imagined. For example, there is evidence that sweet odors can act to suppress sour tastes, just as sucrose can (Stevenson *et al.,* submitted) and that odor sweetness can also act to enhance sweet tastes, as detected by a sweetness matching task (van der Klauuw & Frank, 1994). Criterion (3), that *synesthetic percepts are durable and discrete:* this criterion is met, in that certain odors reliably and repeatedly generate the impression of sweetness, and that odor sweetness can be quantified. Furthermore, odor sweetness ratings account for 60% of the variance of tasted sweetness ratings, when those same odors are added and rated in sucrose (Stevenson *et al.,* submitted). Criterion (4), that *synesthesia is memorable:* this criterion is met in that ‘‘sweet’’ represented a meaningful descriptor of odor quality to over 80% of respondents in Harper *et al.*’s (1968) study, where subjects were asked to rate 69 words for their meaningfulness in describing odor quality, in the *absence* of odor stimuli. Criterion (5), that *synesthesia is emotional:* this criterion is met in that the quality of odor sweetness is highly correlated with liking (see Stevenson *et al.*, submitted) and that we have yet to encounter an odor described by subjects as smelling sweet that is not also highly liked.

If, as suggested, the presence of sweetness in an odor represents a synesthetic percept which is acquired, how does this bear upon the nature of the association between odor and taste and the issue of awareness? Marks (1975) suggests that synesthesia may represent a ‘‘. . . cross modal manifestation of connotative meaning in a pure sensory form . . .’’ and that ‘‘. . . its inflexibility (compared to language) makes synesthesia less significant in adulthood than in childhood.’’ It is well known that olfaction is a linguistically impoverished sense (Engen, 1982). This conclusion is at least partly based on: (1) subjects’ poor ability to name familiar odors (Lawless & Engen, 1977), (2) the complete absence of any widely accepted scheme of olfactory classification (Moncrieff, 1951), (3) the general absence of abstract terms in describing odor qualities; for example, of Dravnieks (1984) 146 attributes, only 6 are abstract, and (4) that olfaction is generally regarded as a modality in which cognitive operations are not performed (e.g., Hvastja & Zanuttini, 1989). Therefore it may not be surprising that this sense might be capable of associations in a ‘‘pure sensory form.’’

This suggestion strongly bears upon the issue of awareness. Rabin (1988) demonstrated that attaching verbal labels to olfactory stimuli significantly improved subjects’ ability to discriminate those odors. Similar effects can also be seen with the sweetness enhancement effect. Trained panelists do not show sweetness enhancement when maltol—a sweet smelling odor—is added to a sucrose solution (Bingham, Birch, de Graaf, Behan, & Perring, 1990). Thus, following training, subjects may be considerably more aware of the components of their taste/olfactory sensorium than untrained subjects. They may also be better able to attach consistent verbal labels to those components, just as expert wine tasters can better communicate wine characteristics to fellow experts, than to novices (Solomon, 1988). It is but a further short step to suggest that conditioning of the sort observed here may not occur with such trained individuals, unless they are aware of the experimental contingencies, as the odor CS and the taste US would be experienced as separate verbalizable elements, rather than as a configuration which is difficult to describe.

In summary, the results from these two experiments demonstrate that conditioned changes in odor sweetness are robust in the face of controls for experimenter bias and mere exposure effects. They occur even when orthonasal contact with the odor, i.e., sniffing, is prevented when a subject samples a training solution. This form of conditioning takes place when awareness of the experimental contingencies is at best very limited and appears unrelated to the size of the change reported by a subject. Such changes are also relatively long lived, in that no sign of a decrease was obtained as a result of delaying testing for 24 h or more. In the context of previous research on odor–taste combinations the present study appears to provide a rare example of an experimental demonstration of learned synesthesia.

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Received August 12, 1997
Revised November 15, 1997