Perceptual learning with odors: Implications for psychological accounts of odor quality perception

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After two odors have been experienced in a mixture, the pair are subsequently rated as sharing more qualities and smelling more alike than equally exposed controls. These effects may result from the retrieval of a common mixture memory when either component is sniffed alone. If correct, odor pairs experienced together in a mixture should also be less discriminable than those experienced an equal number of times but in different mixtures. This was tested here by exposing participants to two odor mixtures (either AX, BY or AY, BX) and then testing their ability to discriminate between the components. As predicted, odors previously experienced together as a mixture were less discriminable than controls. These and related findings noted above suggest that learning and memory play an important role in odor quality perception.

Experiencing a mixture of two odors, both of which are discernible, can subsequently alter one's perception of the mixture components (Stevenson, 2001a, 2001b). For example, if cherry odor is sniffed as a mixture with the smoky smelling odor guaiacol, cherry is rated as smelling smokier and guaiacol as more cherry-like, postexposure. An additional and related finding from such experiments is that odors experienced together in a mixture are also rated as smelling more alike than equally exposed controls. One implication from these findings is that after an odor mixture has been experienced, sniffing either component may cause the memory of the original mixture to be retrieved (Stevenson, Boakes, & Prescott, 1998; Stevenson, Boakes, & Wilson, 2000b). Accordingly, activation of this common mixture memory might then account for the acquisition of odor qualities and the rated similarity between such odors. One prediction that can be derived from this account is that pairs of odors previously experienced as a mixture should be less discriminable on test than pairs experienced an equal number of times, but in different mixtures. This prediction was tested in the experiment reported here.

Several lines of evidence suggest that experience can alter the perception of odors. In a series of experiments (Stevenson et al., 1998; Stevenson, Boakes, & Wilson, 2000a; Stevenson, Prescott, & Boakes, 1995), we have shown that odors can acquire taste properties such as sweetness and sourness. In these experiments, participants sipped and spat mixtures of flavored sucrose and flavored

citric acid. Our consistent finding from these studies was that sucrose-paired odors came to smell sweeter and citric acid-paired odors sourer. These findings and those from sweetness enhancement studies, which show that smelled odor sweetness can be confused with the tasted sweetness of sucrose (Frank & Byram, 1988; Stevenson, Prescott, & Boakes, 1999), have led us and others to suggest that odor qualities may be acquired. The generality of these types of learning effects has been explored in a more recent set of experiments, where instead of mixtures of odors and tastes, participants sniffed mixtures of odors. These experiments, described above, have produced substantially similar results, indicating that odors can acquire the qualities of other odors with which they have been mixed (Stevenson, 2001a, 2001b).

Such findings do not stand in isolation. A considerable body of work on another learning phenomenon, perceptual learning (Epstein, 1967; Goldstone, 1998), has also revealed changes in discriminability resulting from experience. It has been shown repeatedly that familiar odors are more discriminable than unfamiliar odors (see, e.g., Jehl, Royet, & Holley, 1995; Rabin, 1988), although the mechanisms responsible for such effects still remain the subject of debate (e.g., McLaren & Mackintosh, 2000). Not only can experience facilitate discrimination, it can impair it. Several decades of experimental research in humans and animals, albeit not with odors, have shown that if two cues have a common outcome, they become less discriminable than two cues with a unique outcome (e.g., Honey & Hall, 1989; Katz, 1963). This has been termed the *acquired equivalence* and *distinctiveness* of cues (Hall, 1991). Similarly, if two odors have been experienced in a mixture (akin to a common outcome), they too might be expected to be less discriminable than a pair of odors experienced in different mixtures (akin to a unique outcome; see Honey, 1990, for a conceptually similar design). Interestingly, the predicted effects of odor mixture pairings can be derived

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from studies of both odor quality acquisition and perceptual learning.

The design of the present experiment was based on the previous odor quality acquisition studies, in which participants repeatedly sniffed two odor mixtures (AX, BY or AY, BX; Stevenson, 2001a, 2001b). The prediction here is that for participants receiving training with AX, BY, for example, comparisons involving A versus X and B versus Y will be found less discriminable than A versus Y and B versus X. Note, however, that this design does not allow us to tell the direction in which any changes in discriminability are occurring. In addition to assessments of discriminability, similarity ratings were obtained. It was expected that these would show substantially similar effects and provide a link to the odor quality experiments described earlier.

METHOD

Participants

Forty-two Macquarie University first-year psychology students and members of the university community (26 women and 16 men) participated either for course credit or for \$10 cash (mean age = 23.9; range, 19–51; 2 participants failed to report their age). No participant had an upper respiratory tract infection, and none had taken part in a related study.

Stimuli

The odorants were champignon (mushroom-like smell; Dragoco, 3/919621; 0.077g/L) and *p*-anisaldehyde (musty smell; Sigma; 0.250g/L), which most participants find unfamiliar and difficult to identify, and citral (lemon-like smell; Dragoco, 3/920565; 0.018g/L) and cherry (Quest, DC12790; 1.0g/L), which are more familiar and identifiable. All stimuli were dissolved via propylene glycol into water. All of these odors had been successfully employed in earlier odor mixture studies (Stevenson, 2001a, 2001b). The mixtures were made by physically combining the water-dissolved constituents just before each experimental session, using the following proportions: 3 parts champignon to 7 parts citral; 6 parts champignon to 4 parts cherry; 3 parts *p*-anisaldehyde to 7 parts citral; 4 parts *p*-anisaldehyde to 6 parts cherry. The mixture proportions were based on pilot work intended to ensure that the mixture constituents could be detected.

For the tests involving the presentation of single odorants, champignon and citral were diluted with water in the ratio of 3 parts odorant to 7 parts water, *p*-anisaldehyde in the ratio of 1 part odorant to 9 parts water, and cherry in the ratio of 2 parts odorant to 8 parts water. Thus they matched the perceived magnitude of their components in the training mixtures, and this was expected to facilitate retrieval based on perceptual similarity. All posttests and training sessions involved presentation of 20-ml aliquots of the odorants in 100-ml plastic bottles.

Procedure

The participants attended two sessions separated by at least 1 week. In the first session, the participants received 12 exposures to each of two odor mixtures, with an exposure consisting of a sniff of about 3-sec duration. A week later, the participants returned and received a further 6 exposures to the same two odor mixtures. The training task in both sessions involved the rating of liking for each sample. Following the end of training, the test phase began. The first posttest was a discrimination procedure comprising triangle tests (e.g., A vs. A vs. B) followed by similarity ratings. The participants then assessed various attributes of the unmixed odorants and the mixtures in two further posttests.

The participants were assigned by order of arrival to the experiment to one of two training conditions: (1) champignon–cherry and

p-anisaldehyde–citral ($n = 23$) or (2) champignon–citral and *p*-anisaldehyde–cherry ($n = 19$). The training procedure involved the smelling of each sample and then the rating of liking/disliking on a 7-point category scale. The ratings gave some overt purpose to the training procedure, as well as ensured that the participants attended to the stimuli. The first session involved two training episodes. In the first training episode, 24 samples were smelled, and as in all parts of the experiment, progression through the stimuli was self-paced. The 24 samples included 6 exposures to each mixture and 12 water blanks. Following a 5-min break, the second training episode began. This involved the sniffing of 24 more samples, again composed of 6 exposures to each mixture and 12 water blanks. Although the order of presentation of the odor mixtures was counterbalanced, each mixture was always followed by a water blank. This concluded the first session.

The participants returned approximately 1 week later to complete the second session of the experiment. This commenced with a further training episode in which they received 6 more exposures to each mixture and 12 water blanks. After a 5-min break, the participants started the first posttest. This involved completing four blocks of triangle tests. Each block was composed of five triangle tests, of which one compared champignon with citral, one champignon with cherry, one *p*-anisaldehyde with citral, one *p*-anisaldehyde with cherry, and one water with water. The latter test was always given as the third triangle test of any block. Presentation order and type of stimuli within each triangle test (e.g., cherry vs. cherry vs. *p*-anisaldehyde) was counterbalanced, as was the order of triangle tests within each block (excepting the water-only test). The participants received a 5-min break after completing Block 2 and a further 5-min break after completing Block 4.

For each triangle test, the participants were asked to smell the odors one at a time, from left to right. Although they were allowed to smell each odor for as long as they wished, they were explicitly instructed not to go back and smell an odor again. Once they had smelled all three odors, the participants were asked to complete two tasks: first, to pick the “odd sample out,” even if they had to guess, and second, to rate on a 7-point category scale from *identical* to *very different* how similar the “odd sample out” was to the other two in the set.

Following the 5-min break at the end of the triangle tests, the second posttest began. This involved the smelling of each of the four unmixed odorants, presented in counterbalanced order. Using 7-point category scales, the participants were asked to rate how strong the odors smelled (*not at all* to *very*), how much they liked or disliked them (*like* to *neutral* to *dislike*), and how often they had smelled the odor outside of the laboratory (*never* to *all the time*). These data were collected because all three factors—intensity, liking, and familiarity—might affect discriminability. The participants were then asked to write down (free recall) what the odor smelled like.

The third posttest involved the smelling of the four odor mixtures used in the experiment. The participants were asked to smell the mixture and then rate how often they had smelled it during the study, using a 7-point category scale (*never* to *all the time*). All the tests reported in the Results section were significant at the 5% level, unless otherwise stated.

RESULTS

Posttest 1

In total, each participant received 16 triangle tests, excluding the 4 water only tests. Correct triangle test responses were scored 1 and incorrect responses 0. The scores were then sorted into four totals for each participant. The first total was composed of the 4 triangle tests of *p*-anisaldehyde versus cherry (or citral) and the second, the 4 triangle tests of champignon versus citral (or cherry). In both of these cases, *all* the triangle tests involved com-

parisons of odors that had been experienced by the participant together as a mixture during training (termed *mixture* tests). The third total was composed of the 4 triangle tests of *p*-anisaldehyde versus citral (or cherry), and the fourth, the 4 triangle tests of champignol versus cherry (or citral). In both of these cases, *all* the triangle tests involved comparisons of odors that had been experienced by the participant in different mixtures during training (termed *nonmixture* tests).

These scores were then analyzed with a three-way analysis of variance (ANOVA), with two within-subjects factors, treatment (mixture vs. nonmixture triangle tests) and test odor (triangle tests involving *p*-anisaldehyde vs. champignol), and one between-subjects factor, contaminant (which contaminant [citral or cherry] was contrasted with which test odor in the mixture and nonmixture triangle tests). The latter two factors, test odor and contaminant, were included to see whether they would interact with factor treatment. Such interactions would indicate whether any treatment effect was stimulus specific.

The ANOVA revealed two significant effects. The first was a main effect of treatment [$F(1,40) = 8.19$, $MS_e = 0.76$]. As predicted, odors that had been experienced together as a mixture during training were not discriminated as well (mean correct = 6.2) as odors that had not been experienced together as a mixture during training (mean correct = 7.0). The second finding was a main effect of contaminant [$F(1,40) = 7.60$, $MS_e = 0.53$]. This unexpected effect showed merely that training groups differed in their discriminative abilities, because the group that received *p*-anisaldehyde–citral and champignol–cherry was worse at *all* discriminations (mean correct = 6.3) than the group that received *p*-anisaldehyde–cherry and champignol–citral (mean correct = 6.9). There were no other significant main effects or interactions.

As with the triangle tests, there were 16 similarity ratings in total. These were sorted into four separate mean scores for each participant in the same way as the triangle test scores were partitioned. These scores were then analyzed with a three-way ANOVA, with two within-subjects factors, treatment (mixture vs. nonmixture tests) and test odor (tests involving *p*-anisaldehyde vs. champignol) and one between-subjects factor, contaminant (which contaminant [citral or cherry] was contrasted with which test odor in the mixture and nonmixture tests). The ANOVA revealed just one main effect, that of treatment [$F(1,40) = 39.41$, $MS_e = 1.29$]. As expected, odors that had been experienced together as a mixture were rated as more alike (mean similarity = 4.0) than odors experienced before, but not together as a mixture (mean similarity = 5.1). There were no other significant main effects or interactions.

To establish whether the similarity and discrimination scores were associated, the difference between the nonmixture and mixture triangle test scores and the difference between the nonmixture and mixture mean similarity scores were correlated using Pearson's *r*. If these two measures are related, participants who rate mixture odors as more alike than nonmixture odors should also make more errors on the triangle tests involving mixture odors

than on those involving nonmixture odors. This was the case, with a significant correlation between the two scores [$r(41) = 0.59$].

The testing over four blocks allowed a further hypothesis to be explored—namely, whether odor mixture memories were resistant to retroactive interference in the same way as were odor–taste memories (Stevenson et al., 2000a). If interference can occur over relatively few trials, it might be expected that presentation of single odorants over the four test blocks would disrupt prior learning and so affect the degree to which mixture odors were judged alike and discriminated. Thus a comparison was made between the first two and the last two blocks of triangle tests. This was done by taking the difference between mixture and nonmixture similarity ratings on the first two blocks and comparing this score by means of a paired *t* test with that from the last two blocks. There was no significant difference. The same result emerged when this procedure was repeated, using the triangle test scores. This is consistent with the view that once established, odor memories are resistant to retroactive interference.

Posttest 2

Intensity ratings of the pure odorants were compared in a two-way ANOVA with one between-subjects factor, training condition (i.e., champignol–cherry and *p*-anisaldehyde–citral or champignol–citral and *p*-anisaldehyde–cherry) and one within-subjects factor, odor type (champignol, cherry, *p*-anisaldehyde, and citral). The participants were found to have rated the odors as significantly different in intensity, with cherry as the strongest ($M = 5.2$), followed by citral (4.6), champignol (4.3), and *p*-anisaldehyde [4.0; $F(3,120) = 6.36$, $MS_e = 1.73$]. There were no other significant effects. The larger intensity ratings for cherry may have made it more discriminable, but this did not affect the main hypothesis under test, as it would equally have altered the hit rates on both mixture and nonmixture triangle tests.

Liking ratings of the pure odorants were compared in the same way as were intensity ratings. Liking ratings differed between odors, with cherry as the most preferred ($M = 3.3$), followed by citral (3.5), *p*-anisaldehyde (4.3), and champignol [4.3; $F(3,120) = 4.70$, $MS_e = 2.46$]. There were no effects involving training condition. As with the intensity ratings, these differences did not affect the main hypothesis under test.

The participants were also asked how frequently they had encountered these odors outside of the laboratory. In the same ANOVA design, frequency ratings significantly differed between odors, with citral rated as the most frequently encountered ($M = 4.2$), followed by cherry (3.8), champignol (2.7), and *p*-anisaldehyde [2.6; $F(3,117) = 15.64$, $MS_e = 1.58$; 1 participant's data was excluded, owing to missing values]. There were no significant effects involving condition. For the reasons described above, these differences also did not affect the discrimination findings.

After making these ratings, the participants were asked what the odors reminded them of. These responses were then blind coded, so that the number of appropriate attrib-

utes for each odor was evaluated. The keywords were as follows for cherry: *berry fruit, rose-like, cherry, sweet, or perfumefragrance*; for lemon, *citrus fruit, orange, lemon, sour, or cleaning agent*; for mushroom, *stale, earthy, moldy, mushroom, or damp*; and for *p*-anisaldehyde, *almond-like, floral/flower-like, licorice, aniseed, musty*. Where identification is defined as naming at least one appropriate attribute for each odor, 6/42 participants identified *p*-anisaldehyde; 16/42, mushroom; 29/42, lemon; and 34/42, cherry. A sum total identification score for each participant was then calculated. This score could vary from 0 (*not named any odor with appropriate attributes*) to 20 (*identified the five appropriate attributes for each odor*). This naming score was then correlated with the total number of correct triangle tests (maximum 16), the rationale being that better identification should be associated with better discriminability. This was observed [$r(41) = .35$].

Posttest 3

In this test, the participants were presented with the odor mixtures and were asked to estimate the frequency with which they had encountered each one in the experiment. Frequency ratings were analyzed with a two-way ANOVA, with training condition (stimuli received during training) as a between-groups factor and mixture (each of the four odor mixtures used in the experiment) as a within-subjects factor. The only significant effect was an interaction between training condition and mixture, which showed that the participants correctly rated mixtures experienced during training as having occurred more frequently than those not experienced during training [$F(3,120) = 12.07$, $MS_e = 1.9$]. Apart from indicating that the participants generally knew which mixtures they had experienced before, this test also indicated that the mixtures were discriminable from each other.

DISCUSSION

This experiment was performed as a test of whether or not experiencing an odor mixture would affect the subsequent discriminability of its components. The results indicate that odors previously experienced together in a mixture are less discriminable and are rated as more alike than control odors experienced an equal number of times, but in different mixtures. In addition, these two findings were related. The experiment also addressed a further question, that of the resistance of odor memory to retroactive interference. Presentation of the odors alone during the first part of the discrimination test did not affect discriminability or similarity ratings on the second part of the test. This suggests, as have our earlier studies (Stevenson et al., 2000a, 2000b) and those of others (e.g., Engen & Ross, 1973; Lawless, 1978), that once established, odor memories may be resistant to such interference. Finally, and consistent with previous findings (e.g., Rabin, 1988), a relationship was observed between participants' ability to identify the odors and their ability to discriminate them.

If experience affects discriminative ability as these results suggest, then memory probably has a role in this. At

least two discrete forms of memory may be involved. The first is *odor sensory memory* (hereafter, *odor memory*), which refers to the store of sensory experience gained primarily during inhaling, sniffing, eating, and drinking. The second is the combined activity of episodic and semantic memory (Cain & Potts, 1996). Odor memory effects, discussed in the introduction, would appear to occur primarily through mere exposure. Episodic and semantic memory effects, on the other hand, are a consequence (ultimately) of effortful association of names with odors (de Wijk & Cain, 1994; Rabin, 1988). Either episodic and semantic memory or odor memory alone may account for the results in this experiment. For example, in a triangle test of odor A versus X versus X, if odor A and X both evoke the name *mint*, participants may be more apt to confuse A and X, through comparing the remembered name of A, *mint*, with odor X. Alternatively, if A evokes an AX odor memory and X also evokes an AX odor memory, A and X may be perceived as more alike and thus be less discriminable. This experiment cannot provide a definite answer regarding the type of memory involved, but two observations favor odor memory. First, it is unlikely that participants would go to the effort of generating and learning names for the mixtures when there is no demand to do so (see Lyman & McDaniel, 1986, for a similar argument). Second, if name generation and learning were taking place, then such verbally coded information should be sensitive to interference (e.g., Underwood, 1957); yet no evidence of this was obtained here or in past studies of related effects (Stevenson et al., 2000a, 2000b).

A further issue is raised by the apparent resistance of odor memory to interference. If an odor is familiar, as cherry and citral were here, it should not be possible to alter their smell or discriminability; yet this appears to have occurred. This may suggest that resistance to interference may obtain only under conditions when an odor has an absolute match in memory (e.g., smell A, A in memory). The conditions here, however, favored partial matches, such as between a mixture, AB, and its previously stored and hence familiar components, A, B. This would allow some encoding of the AB percept and hence interference.

The results from this experiment also have implications for models of odor quality perception. Odor quality is generally regarded as a correlate of some aspect of the chemical structure of the odorant (see, e.g., Amoore, 1982; Beets, 1982; Boelens, 1974; Chastrette, Elmouaffek, & Sauvegrain, 1988). This approach is not without its problems, because chemicals that have diverse structures can share identical odor qualities (Richardson & Zucco, 1989; Stevenson et al., 1999) or come to acquire them (Stevenson et al., 1998; Stevenson et al., 1995). One way to address this problem is to include a role for learning and memory in such models. Stevenson (2001a, 2001b) has suggested one way in which this might be achieved. When an odor is sniffed in the absence of other cues, the output pattern from the receptors is automatically compared with odor memory, and similar memories are retrieved. The retrieved memories constitute our conscious experience of smell (see Haberly & Bower, 1989, for a similar notion).

The importance of odor memory in this process is illustrated clearly by the observation that disorders of memory (e.g., Korsakoff's, Alzheimer's, damage to the thalamus and temporal lobes) are typically accompanied by a loss of odor quality, but not quantity perception (Mair, Harrison, & Flint, 1995). This memory-based approach to odor quality perception can account for structurally different chemicals' sharing qualities. If, for example, two structurally different chemicals have both been experienced with a third (e.g., AX and BX), each may retrieve the memory of the mixture (e.g., A or B can retrieve memories containing "X"). In this respect, the retrieved odor memory containing "X" is then an odor quality common to A and B. Importantly, this approach encompasses structure quality models, because similar receptor output (i.e. similar structure) should retrieve similar odor memories, and hence similar quality.

In conclusion, this experiment demonstrates that odors experienced the same number of times can significantly differ in discriminability by virtue of their history of co-occurrence with other odors. This finding adds to the growing body of evidence that learning and memory play a central role in odor quality perception.

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