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Effect of endogenous attention on detection of weak gustatory and olfactory flavors

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The effect of endogenous attention on the detectability of weak flavorants was examined in an absolute detection (two-alternative forced-choice) task. Attention to sucrose improved the detectability of sucrose, a gustation-based flavorant, both when the alternative was water and when it was vanillin. But attention to vanillin did not improve the detectability of vanillin, an olfaction-based flavorant, either when the alternative was water or when it was sucrose. Nor did attention improve the detectability of vanillin when the alternative was citric acid, a tastant that is qualitatively less similar to vanillin than is sucrose. Attention had no positive effect on the detection of either sucrose or vanillin when it was mixed with the other substance. These findings suggest that although it is possible to attend selectively to gustatory flavors, it may be more difficult to attend selectively to olfactory flavors—perhaps because attention to flavors, which are taken in the mouth, is directed spatially toward the tongue, where gustatory, but not olfactory, receptors are located.

Voluntarily allocated attention, also called endogenous attention, is a fundamental process in perception. Studied extensively in several modalities, such as vision (Posner, 1978; Posner, Snyder, & Davidson, 1980; see also Pashler, 1998, for a review), hearing (Schröger & Eimer, 1997; Spence & Driver, 1994), touch (Evans & Craig, 1991; Whang, Burton, & Shulman, 1991), and pain (Eccleston, 1994; Miron, Duncan, & Bushnell, 1989), as well as crossmodally (Spence & Driver, 1996; Spence, Pavani, & Driver, 2000), endogenous attention enables us to extract relevant information from a rich and complex stimulus environment. That is, stimuli are better processed, in terms of response time and accuracy, when they are anticipated.

A widely used tool in the study of endogenous attention is Posner's (1978) cuing paradigm. In a typical experiment in visual attention, a participant fixates at the center of a screen, where an informative cue is expected (e.g., an arrow pointing to a certain location or a number indicating a spatial position). After presentation of the cue, a target stimulus appears, and the participant's task is to respond as quickly as possible to its onset. To evaluate the effect of attention, on a fraction of the trials the target stimulus is presented at a location different from the cued location. A well-documented finding is the enhanced detectability of (faster response to) stimuli at the attended location, as compared with stimuli at unattended locations (Abrams & Law, 2000; Briand & Klein, 1987; Posner et al., 1980; Theeuwes, 1991). Similar effects of spatial attention are found with auditory stimuli (Spence & Driver, 1994), tactile stimuli (Evans & Craig, 1991), and hand movements (Lee, 1999). Attention may be allocated along other dimensions besides space. For instance, cuing an acoustic signal's frequency can affect the detectability of an auditory target (Green & McKeown, 2001). Despite the substantial research on attention, however, only a small number of studies have heretofore investigated the role of endogenous attention in the chemical senses.

Marks and Wheeler (1998) were the first, to the best of our knowledge, to test explicitly the effect of cued attention on the detection of weak taste stimuli. These investigators determined how attention modifies the detectability of sucrose and citric acid, using an adaptive forced-choice method, the *transformed up–down procedure*. Attention was manipulated by three procedural maneuvers. First, participants were told at the beginning of each session to expect a certain tastant (either sucrose or citric acid). Second, a cue, consisting of the attended tastant at a weak suprathreshold concentration, was delivered to the participants after every eight trials. Instructions and cue served to focus attention on one tastant or another throughout the session. Finally, the attended tastant was presented on 75% of the trials, and the other, unattended tastant on 25% of the trials. This made it possible to measure sensitivity to both the attended and the unattended stimuli within a single test session. Thresholds for both sucrose and citric acid were lower in the attended sessions than in the unattended ones, indicating the existence of a mechanism for endogenous selective attention in taste.

The findings of Marks and Wheeler (1998) indicate that the gustatory system permits attentional selection, but they do not establish the mechanism of gustatory selection. One model suggests that attention affects the relative sen-

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sitivity of detectors or channels (presumably, in the central nervous system) that are specialized for processing information about different classes of stimuli; presumably, attention augments sensitivity in the channels used to detect attended stimuli, attenuates sensitivity in the channels used to detect unattended stimuli, or both. Support for this hypothesis can be found in studies on the role of attention in the detectability of auditory stimuli varying in sound frequency. A robust finding is that sensitivity declines significantly when the frequency of the target stimulus deviates from that of the cue (Botte, 1995; Greenberg & Larkin, 1968; Scharf, Quigley, Aoki, Peachey, & Reeves, 1987), suggesting the existence of auditory *attention bands* in the frequency domain. Especially notable is the similarity between these attention bands and critical bands in hearing, which are related to the tuning characteristics of auditory neurons (Hafter, Schlauch, & Tang, 1993; Hübner & Hafter, 1995; Moore, 1997). Attention bands could reflect either elevated sensitivity of detectors primarily processing signals in the cued channel or attenuated sensitivity of detectors primarily processing signals in the uncued channel. In either case, detection would reflect the relative sensitivity of detectors processing signals in the cued channel. In trying to account for their results, Marks and Wheeler (1998) hypothesized that directing attention to sucrose may, relatively speaking, enhance information from neurons most sensitive to sweet stimuli, as compared with information from neurons most responsive to sour ones, and that directing attention to citric acid may, relatively speaking, enhance information from neurons most responsive to sour stimuli, as compared with information from neurons most responsive to sweet.

A somewhat different model proposes that selective attention operates on the basis of higher neural representations of perceptual similarity. For instance, several studies have shown that visual attention may be directed toward stimulus objects rather than locations in the visual field (Bundesen, 1990; Duncan, 1984; Duncan & Humphreys, 1989; Egly, Driver, & Rafal, 1994). For such a mechanism to operate, the visual system must first segment the visual field into objects, perhaps according to Gestalt principles. Subsequently, attention may selectively enhance or attenuate performance on the basis of similarity of features. Objects sharing features with the attended objects (test objects similar to attended objects) will be processed more effectively than objects not sharing features (test objects dissimilar to attended objects). A similarity-based model, therefore, predicts that unattended stimuli will be less well detected than attended stimuli if the unattended and the attended stimuli are perceptually dissimilar. In the gustatory system, sucrose and citric acid are perceived to be dissimilar (Rankin & Marks, 2000), so consequently, an attentional mechanism that operates on the basis of similarity could also explain the findings of Marks and Wheeler (1998).

In the present study, we sought to decide between the two models just described. To do this, we capitalized on the well-known evidence that flavor perception depends on inputs from the olfactory, as well as the gustatory, system (Bartoshuk & Beauchamp, 1994; Chifala & Polzella, 1995; Hornung & Enns, 1986; Rozin, 1982). In principle, then, by measuring detection performance with gustatory-based and olfactory-based flavorants that are perceived as similar to each other, one can determine whether endogenous attention is better described (1) in terms of amplification and/or attenuation of detectors within modality-specific channels or (2) in terms of qualitative similarity and dissimilarity of features. Consider, in this regard, two stimuli processed through different neural channels that are nevertheless perceived as similar, as is the case with sucrose and vanillin. If directing attention to sucrose or vanillin improves the detectability of that stimulus, but not of the other one, the results would support a channel detector model of attention. If, on the other hand, attending to either sucrose or vanillin improves the detectability of both stimuli, the results would support a similarity model of chemosensory attention.

EXPERIMENT 1

The aim of the first experiment was to answer two questions. First, we asked whether endogenous attention can affect the detectability of both gustatory and olfactory flavorants. To answer this question, we used sucrose and vanillin as target stimuli. We chose sucrose as a gustatory flavorant because the olfactory system lacks receptors responsive to it (Dravnieks, 1985; Harper, Land, Griffiths, & Bate-Smith, 1968). And we chose vanillin as an olfactory flavorant because, at low concentrations, (1) vanillin cannot be perceived by anosmics (Doty et al., 1978; Kobal & Hummel, 1991), indicating that it does not activate nonolfactory (e.g., trigeminal) receptors in the nose, and (2) when dissolved in water and sipped, vanillin is readily perceived by normosmics when the nose is open, but not when the nose is pinched closed, as is the case with olfactory stimuli (Cain, 1976; Murphy, Cain, & Bartoshuk, 1977), indicating that it does not activate gustatory receptors. Thus, we can be confident that solutions containing weak sucrose and vanillin selectively activate only the gustatory and olfactory systems, respectively. Because, at higher concentrations, vanillin may produce a bitter taste or activate trigeminal receptors in the nose, it is critical to use relatively low stimulus concentrations. Thus, a detection task, such as that of Marks and Wheeler (1998), is especially well suited to the present investigation.

Second, assuming that attention would affect the detectability of gustatory and olfactory flavorants, we sought to determine whether attention operates on the basis of neural channels or perceptual similarity. To accomplish this, we capitalized on the evidence that sucrose and vanillin, although processed through different modalities, are judged to be relatively similar perceptually (Rankin & Marks, 2000). We tested the two models by asking how attention to each of these substances affects the detectability of that substance in a two-alternative forced-choice (2AFC) detection paradigm.

In this design, on each trial, the participant receives in succession two stimulus solutions, only one of which contains a target stimulus. In the baseline phase, the target can be sucrose or vanillin, and the alternative is always water. The task is simply to identify which solution contains a flavorant. In the test phase, attention is directed throughout a block of trials to a particular substance (e.g., sucrose). The alternative can be either water or the other flavorant (i.e., vanillin). This time, the task is to identify which solution contains the attended flavorant.

If attention improves the detectability of a given flavorant, relative to baseline, we may infer that attention affects relative sensitivity in the relevant modality (gustatory or olfactory for sucrose or vanillin, respectively). If detectability improves regardless of the nontarget (i.e., both when the nontarget is the other flavorant and when it is water), we would conclude that attention operates within modality-specific neural channels. If, on the other hand, attention produces greater improvement in the detectability of the attended stimulus when the nontarget is water, we would infer that attention operates by means of perceived similarity.

Method

Participants

Thirteen participants, all nonsmokers, started the experiment, but 3 had to be excluded because they were insensitive to changes in either vanillin or sucrose concentrations. The remaining 10 participants consisted of 7 women (19–30 years old) and 3 men (19–35 years old). Each served in six sessions and was paid $10 per hour to participate.

Stimuli

The flavorants were sucrose and vanillin. In the baseline phase, each flavorant was dissolved in deionized water to create a series of six concentrations. The sucrose concentrations ranged from 0.05 to 0.00156 M in steps of 0.3 log units, and the vanillin concentrations ranged from 0.02 to 0.0000195 M in steps of 0.6 log units.

In the test phase, a series of six concentrations was formed for each flavorant as follows. First, for each participant, a baseline psychometric function was calculated for each flavorant. As will be noted in the Design section below, the baseline phase actually contained three sessions: one with sucrose trials, another with vanillin trials, and a third with sucrose and vanillin trials intermixed. Because, for each flavorant, the blocked and the unmixed baselines were essentially the same (see Figure 1), the results for the blocked and the intermixed trials were pooled to give a single psychometric function. Next, a regression line was fitted to each participant's pooled baseline psychometric function, excluding the lowest and/or the highest concentrations if they represented asymptotic performance (50% and 100% correct, respectively). Finally, the regression line was used to calculate six concentrations that would give forced-choice detectabilities of 55%–95% in steps of 8%.

In this and in subsequent experiments, solutions were prepared every 5 days, stored in a refrigerator, and brought to room temperature (~21ºC) before each session. The stimuli on each trial consisted of 5 ml of each solution or deionized water.

Design

All of the experiments used a 2AFC method. On each trial, the participants sipped two solutions in succession, rinsing their mouths before and after each, and then indicated which solution contained a target stimulus.

Baseline phase. Experimental sessions will be designated $X_{T,N}$, where T and N refer to the target and the nontarget, respectively, on each trial in the session. The baseline phase consisted of three sessions, with sucrose serving as the target stimulus in one session ($B_{S,W}$), vanillin in another ($B_{V,W}$), and both sucrose and vanillin in the third ($B_{S \text{ or } V,W}$). In all three sessions, deionized water served as the nontarget on every trial. Each $B_{S,W}$ and $B_{V,W}$ session contained 120 test trials: 6 target concentrations × 2 orders (target first or second) × 10 repetitions. Each session was divided into two blocks of 60 randomly ordered test trials. In addition, 6 practice trials were given be-

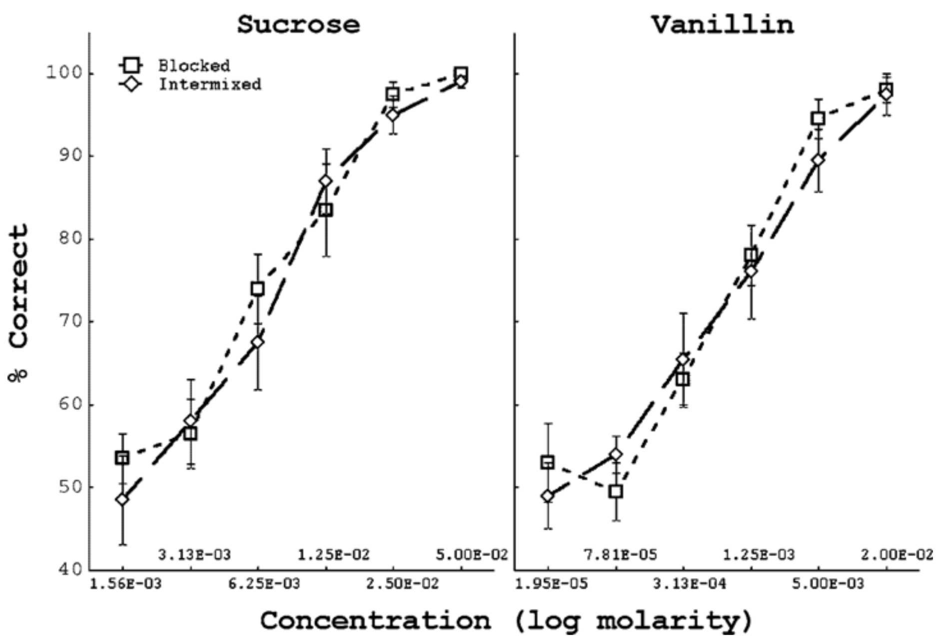

Figure 1. Mean percentages of detectability and standard errors of the means for sucrose (left panel) and vanillin (right panel) in two baselines: when each flavorant was blocked over trials and when trials containing the two flavorants were intermixed.

fore each block, in which each of the six concentrations was presented once. The $B_{S\ or\ V, W}$ session contained 240 test trials: 2 target flavorants × 6 concentrations × 2 orders × 10 repetitions. This session was divided into four blocks of 60 test trials. In this case, each block contained five repetitions of every concentration of sucrose and vanillin. In the first and third blocks, each sucrose concentration preceded water on three of the five repetitions, and each vanillin concentration preceded water on two of the five repetitions. In the second and fourth blocks, these proportions were reversed. Within each block, order of presentation of target and water was randomized. Again, 6 practice trials were presented before each block, 3 with sucrose and 3 with vanillin.

Five participants started with the $B_{S\ or\ V, W}$ session, 3 of whom continued with the $B_{V, W}$ session and then the $B_{S, W}$ session; the other 2 continued with $B_{S, W}$ and then $B_{V, W}$. Of the remaining 5 participants, 3 started with $B_{S, W}$ and then continued with $B_{V, W}$, and 2 started with $B_{V, W}$ and then continued with $B_{S, W}$. All 5 finished with $B_{S\ or\ V, W}$.

Test phase. The test phase also contained three sessions per participant. In one session, the participants attended to sucrose, which was the target, whereas the nontarget could be either water or vanillin ($T_{S, V\ or\ W}$). In another, analogous session, the participants attended to vanillin, which was the target, whereas the nontarget could be either water or sucrose ($T_{V, S\ or\ W}$). Finally, a third session, $C_{S\ or\ V, W}$, served as control and was identical to the baseline $B_{S\ or\ V, W}$ session, except for the concentration levels, which were tailored to each participant. When a flavorant served as the nontarget, its concentration was set to produce the same baseline probability of detection as that of the target. The $T_{S, V\ or\ W}$ and $T_{V, S\ or\ W}$ sessions contained 240 test trials: 2 nontargets × 6 target concentrations × 2 orders × 10 repetitions. These were divided into four blocks of 60 test trials, each block containing five repetitions of every concentration of the target sucrose (or vanillin). On the first and third blocks, each target stimulus preceded water on three of the five repetitions and preceded the nontarget stimulus (vanillin when the target was sucrose, sucrose when the target was vanillin) on two of the five repetitions. On the second and fourth blocks, the proportions were reversed. Within each block, the order of presentation of the target and the nontarget was randomized. Six practice trials were given before each block, 3 with water and 3 with the other flavorant as the nontarget. As has been mentioned, the $C_{S\ or\ V, W}$ session was identical to the $B_{S\ or\ V, W}$ session, save for the concentrations. Five participants started with $T_{S, V\ or\ W}$, continued with $T_{V, S\ or\ W}$, and ended with $C_{S\ or\ V, W}$, whereas the other 5 started with $T_{V, S\ or\ W}$, continued with $T_{S, V\ or\ W}$, and ended with $C_{S\ or\ V, W}$.

Procedure

On each trial, the participants sipped two solutions in succession, rinsing their mouths before the first, between the first and the second, and after the second. Before sipping each solution (whether sucrose, vanillin, or water), the participants pinched their noses and released them only when the solution was in their mouths. Pinching the nose prevented the participants from smelling the vanillin before "tasting" it.

In baseline sessions, the participants were told that they would sip two solutions, one containing a flavorant and the other water, and that their task was to indicate which of the two solutions contained the flavorant. The session began with the practice trials, the test trials following without delay. The instructions were repeated before each block. In the test sessions, the procedure was identical, except that the participants were told that one solution on each trial would contain a particular target stimulus and the other would not and that their task was to indicate which solution contained the target. Because the $C_{S\ or\ V, W}$ session mimicked the $B_{S\ or\ V, W}$ session, the participants were told that one solution in each trial contained a flavorant and that their task was to indicate which. Finally, on the test sessions, a cuing solution, containing the target flavorant at a suprathreshold concentration, was delivered to the participants at the beginning of each block and after every 20 test trials.

Results

Baseline Phase

Figure 1 shows the psychometric functions (average detectability as a function of concentration) for sucrose (left panel) and for vanillin (right panel) in each of the two baseline sessions: The session in which trials for that flavorant were blocked and the session in which trials containing the two flavorants were intermixed. Detectability was entered into a two-way analysis of variance (ANOVA), using as independent variables the six concentrations and the two baseline sessions (blocked vs. intermixed) for each flavorant separately. As was expected, session had no effect on the detectability of either sucrose or vanillin [$F(1,9) < 1$, for both]. Thus, the six concentrations used in the test phase for each flavorant were based on the data pooled over the two baseline sessions.

Test Phase

Figure 2 shows the psychometric functions (average detectability as a function of concentration) for sucrose (left panel) and for vanillin (right panel) in each of the three experimental sessions: control, attention with the alternative being water, and attention with the alternative being the other flavorant. For sucrose, the control function gives the percentage of times that sucrose was detected in the $C_{S\ or\ V, W}$ session, and for vanillin, the control function gives the percentage of times that vanillin was detected in the same session. The results in the left panel show that when sucrose was the target in the $T_{S, V\ or\ W}$ session, it did not matter whether the foil (nontarget) was vanillin or water. These results also show that sucrose was better detected when it was the only target ($T_{S, V\ or\ W}$ session) than when it was one of two targets ($C_{S\ or\ V, W}$ session). The comparable results in the right panel do not show a comparable effect for vanillin. Indeed, vanillin was better detected in the control session than it was in the test session when the foil was water or sucrose.

Effect of attention on detectability of sucrose. Detectability was entered into a two-way ANOVA, using as independent variables the six concentrations and the three experimental sessions (sucrose vs. water, sucrose vs. vanillin, and no attention to sucrose). As was expected, concentration exerted a substantial effect, consistent with the monotonically increasing psychometric functions [$F(5,45) = 76.28$, $MS_e = 0.009$, $p < .001$]. (Note that here and subsequently, all values of p hold when assessed for possible nonsphericity, using both Huynh–Feldt and Greenhouse–Geisser corrections.) The effect of experimental session was also significant [$F(2,18) = 7.5$, $MS_e = 0.013$, $p < .005$], indicating a role of attention. That the two-way interaction was not significant [$F(10,90) = 1.18$] suggests that the effect of attention was independent of concentration.

We also compared each attention session (sucrose vs. water and sucrose vs. vanillin) separately with the control session. Detectability of sucrose was significantly greater both when water served as the nontarget [$F(1,9) = 13.81$, $MS_e = 0.008$, $p < .005$] and when vanillin served as the nontarget [$F(1,9) = 9.13$, $MS_e = 0.018$, $p < .05$]. Performance in the two attentional sessions did not differ [$F(1,9) < 1$], in-

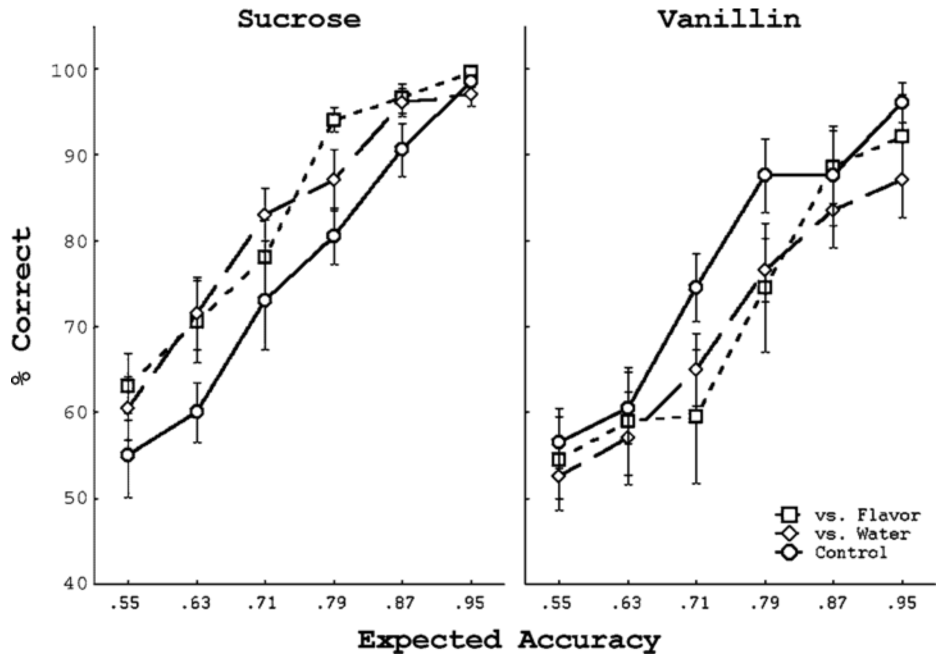

Figure 2. Mean percentages of detectability and standard errors of the means for sucrose (left panel) and vanillin (right panel) in three kinds of trials: attended with water as nontarget, attended with the other flavorant as nontarget, and control.

dicating that attention improved performance to a similar degree when the alternative stimulus was water and when it was vanillin.

Effect of attention on detectability of vanillin. As with sucrose, concentration significantly affected the detectability of vanillin [$F(5,45) = 55.74$, $MS_e = 0.013$, $p < .001$], again consistent with the monotonic psychometric functions. With vanillin, however, the effect of experimental (attentional) session was not reliable [$F(2,18) = 1.57$]. As with sucrose, the interaction between concentration and session was not significant [$F(10,90) = 1.25$], suggesting independence between the effect (in this case, the lack of effect) of attention and the effect of concentration.

Direct comparison of each attentional session with control showed that the detectability of vanillin was marginally worse when water served as the nontarget [$F(1,9) = 7.99$, $MS_e = 0.018$, $p < .05$] but was not reliably different when sucrose served as the nontarget [$F(1,9) = 1.24$]. Finally, there was no difference in detectability between the two attentional sessions [$F(1,9) < 1$].

Remember that the controls were different for sucrose and vanillin; the control for sucrose were those trials in the $C_{S \text{ or } V, W}$ session in which sucrose served as the target, and the control for vanillin were those trials in the $C_{S \text{ or } V, W}$ session in which vanillin served as the target. Hence, prior to concluding that attention affected the detectability of sucrose but not vanillin, it is important to compare the controls themselves. This is necessary in order to exclude the possibility that, perhaps fortuitously, the detectability of vanillin in its control trials was greater than the detectability of sucrose in its control trials. Detection rates in the control trials for sucrose and vanillin were entered into a two-way ANOVA with six concentrations and two flavorants as independent variables. Detectability of the two flavorants did not differ [$F(1,9) < 1$], nor was there a significant interaction between flavorant and concentration [$F(5,45) < 1$]. Thus, it is reasonable to infer from the results that attention to sucrose did improve the detectability of sucrose but attention to vanillin did not improve the detectability of vanillin.

Discussion

The results of the first experiment suggest that endogenous attention improves the detectability of the gustatory flavorant sucrose but not the olfactory flavorant vanillin. Although one might argue that presenting a suprathreshold cue improves performance by making available a better template of the to-be-detected stimulus, the detectability of vanillin did not improve, contrary to this hypothesis. One might also argue that attention failed to show an effect on the detectability of vanillin because the control session followed the attention session and control performance may have improved through practice. Under comparable circumstances, however, attention did improve the detectability of sucrose, making unlikely the explanation in terms of practice.

Why did endogenous attention improve the detectability of the gustatory flavorant but not the olfactory flavorant? Two possible explanations come to mind.

Perhaps the olfactory system cannot capitalize on selective attention when stimuli are delivered retronasally, in the mouth, because attention implicitly engages processes of spatial localization. If attention to stimuli presented in the mouth entails attending to signals emanating physically from the mouth, attention might improve gustatory sensitivity because gustatory receptors are located in the mouth but fail to improve olfactory sensitivity because olfactory receptors are located in the nose. The localization of olfactory flavors in the mouth is actually a mislocalization, an *illusion*, probably produced by the concomitant mechanical stimulation in the mouth. For such an illusion to occur, one must assume a multisensory response for olfactory stimulation and mechanical stimulation of the oral cavity. Such a pattern was found in the gustatory cortex of rats for gustatory and mechanical stimulation (Katz, Nicolelis, & Simon, 2002). It is reasonable to assume a similar pattern for olfactory and mechanical stimulation, since olfactory and gustatory stimulation have been found to converge in the secondary taste cortex in the orbitofrontal cortex (Rolls & Baylis, 1994).

Alternatively, the failure of attention to improve the detectability of vanillin might reflect the perceived similarity between vanillin and sucrose. Given that vanillin at low concentrations is perceived to be similar to sucrose (Rankin & Marks, 2000), it is possible that people tend to *label* vanillin and sucrose in a similar fashion; this labeling could, of course, be implicit. In Experiment 3, we will explore this possibility in greater detail.

In addition to testing whether the gustatory and the olfactory systems permit attentional selection, in Experiment 1, we attempted to identify the characteristics of such selection. Two models were considered: attention based on neural channels, or attention bands for specific flavorants, and attention based on perceptual similarity. The detectability of sucrose improved relative to baseline to a comparable extent when water served as the nontarget and when vanillin served as the nontarget. Given that Rankin and Marks (2000) showed sucrose and vanillin to be perceived as relatively similar, the present results support the first hypothesis, at least with regard to gustatory flavors: that attention is guided by modality-specific neural channels. To be sure, the present experiment tested only a single gustatory flavorant, sucrose. Marks and Wheeler (1998), however, found evidence for selective attention to two gustatory flavorants, sucrose and citric acid. Thus, taken together, the present Experiment 1 and Marks and Wheeler's experiment indicate that attention to the gustatory system can differentiate, on the one hand, between gustatory and olfactory flavorants and, on the other, between different gustatory flavorants. These findings support the notion that attention to gustatory flavorants is, or at least can be, directed toward specific stimulus channels in the gustatory system.

Note that Experiment 1 measured detectability in a limited condition—namely, one in which each solution contained at most a single flavorant. In everyday life, one is much more likely to encounter complex flavors containing many constituents than a single pure substance. Thus, the first experiment provides no answer to the question, "Is it possible to attend selectively to the component of a complex flavor?" Experiment 2 addressed this issue.

EXPERIMENT 2

In Experiment 2, we asked whether attention can improve the detectability of a single flavorant when it is presented in a mixture with another flavorant. Specifically, we asked whether people can attend selectively to the individual flavorants sucrose and vanillin when they are mixed. Just to ask this question, however, in turn raises other questions regarding the perceptual interactions between and among flavorants. Do flavorants, when combined, simply add their effects linearly? Or do flavorants interact nonlinearly, mutually suppressing, or perhaps enhancing, one another?

Mixtures of flavorants may conveniently be classified as either intramodal (gustatory–gustatory or olfactory–olfactory) or intermodal (gustatory–olfactory). Whereas earlier studies of interactions in mixtures had focused mainly on gustatory flavors (Kamen, Pilgrim, Gutman, & Kroll, 1961; Kuznicki & Ashbaugh, 1979; Kuznicki, Hayward, & Schultz, 1983; Pangborn, 1961; Schifferstein & Frijters, 1990; Stevens & Traverzo, 1997), the concern here was with interactions that may arise with intermodal, gustatory–olfactory stimulus combinations.

The perceived intensity of suprathreshold mixtures of gustatory and olfactory flavors is, at least approximately, additive. For instance, using a magnitude estimation method, Murphy et al. (1977) showed that the perceived intensity of mixtures of saccharin and ethyl butyrate equaled almost exactly the sum of the perceived intensities of the unmixed components. Such a pattern suggests that at suprathreshold levels, gustation and olfaction act independently (Murphy & Cain, 1980).

Findings with mixtures of weak stimuli are less conclusive. Dalton, Doolittle, Nagata, and Breslin (2000) reported an increase in sensitivity to a just-below-threshold olfactory stimulus (benzaldehyde) in the presence of a just-below-threshold gustatory stimulus (saccharin). This outcome led the authors to suggest the "existence of a central point of intermodal convergence containing neurons responsive to the combined inputs" (p. 432). Burdach, Kroeze, and Köster (1984) reported a different result when presenting their participants with weak odorants. When odorants were presented retronasally (in the mouth), their detectability declined when sucrose was added, implying intermodal suppression. Direct comparison of the two results is made difficult, however, by procedural differences: Dalton et al. introduced benzaldehyde nasally, whereas Burdach et al. added sucrose to the odors at a fixed, moderately high concentration.

In Experiment 2, we asked whether participants can attend selectively to individual components of mixtures of weak gustatory and olfactory flavorants. Again, the flavorants were sucrose and vanillin.

Method

Participants

Ten nonsmokers, 8 women (19–30 years old) and 2 men (27–35 years old), participated. Each served in six sessions and was paid \$10 per hour. Of the 10 participants, 9 had taken part in Experiment 1, from which their baseline measures were taken.

Stimuli

There were three sets of stimuli, each consisting of a series of six concentrations: sucrose alone, vanillin alone, and sucrose–vanillin mixtures. For each participant, the series of pure sucrose and pure vanillin were identical to the two series used in the test phase of Experiment 1 (except for the single participant who had not served in Experiment 1 and who, consequently, began this experiment with an analogous set of baseline measures). The series of sucrose–vanillin mixtures was created from the baseline measures (Experiment 1 for 9 participants and Experiment 2 for the 10th) by combining concentrations of the two flavorants calculated to produce equivalent levels of detectability (from 55% to 95% in steps of 8%). The stimuli on each trial consisted of 5 ml of each solution or deionized water. Note that these mixtures involved the addition of solutes. Thus, a concentration for a mixture calculated at 71% contained an amount of sucrose sufficient to produce 71% detection at baseline, when sucrose was presented alone, plus an amount of vanillin sufficient to produce 71% detection at baseline, when vanillin was presented alone.

Design and Procedure

The baseline procedure used with the single new participant was identical to that in Experiment 1. The test phase also followed the design in Experiment 1, except for the stimuli constituting each forced-choice pair. In the $S_{S+V, V \text{ or } W}$ session, the participants were asked to detect the sucrose that was presented in a mixture with vanillin, whereas the nontarget could be either water or vanillin. In the complementary $V_{S+V, S \text{ or } W}$ session, vanillin served as the target, presented in a mixture with sucrose, whereas the nontarget could be either water or sucrose. Finally, the $C_{S+V, W}$ session served as a control, in which a sucrose–vanillin mixture was presented on each trial versus water, and the participant could detect either substance.

Results

Figure 3 shows the psychometric functions for sucrose (left panel) and vanillin (right panel). In each case, the functions increase with concentration, except for session $S_{S+V, W \text{ or } V}$, in which water served as the nontarget. In that session, the detectability of sucrose declined at high concentrations. But most strikingly, performance was better in the control task, which was simply to detect a flavorant versus water ($C_{S+V, V \text{ or } W}$) than it was when the task was to detect sucrose versus either water or vanillin ($S_{S+V, V \text{ or } W}$).

Effect of attention on detectability of sucrose. A two-way ANOVA, using the six concentrations and three experimental sessions as independent variables, revealed significant effects of both main variables [concentration, $F(5,45) = 23.45$, $MS_e = 0.018$, $p < .001$; session, $F(2,18) = 9.27$, $MS_e = 0.023$, $p < .005$]. The interaction between concentration and session was not significant [$F(10,90) = 1.92$].

Although the effect of session was significant, it was opposite in direction from that in Experiment 1. In Experiment 1, attention improved the detectability of sucrose, relative to control, both when water and when vanillin served as the nontargets. In Experiment 2, on the other hand, the detectability of sucrose, now mixed with vanillin, was worse when the participants attended to sucrose, both when water served as the nontarget [$F(1,9) = 11.98$, $MS_e = 0.034$, $p < .01$] and when vanillin served as the nontarget [$F(1,9) = 9.85$, $MS_e = 0.02$, $p < .05$]. In addition, when water served as the nontarget, there was a significant interaction between session and concentration [$F(5,45) = 2.56$, $MS_e = 0.02$, $p < .05$], reflecting a disparity between detectability in the control and attentional sessions that grew as concentration increased. No significant difference was found between the two attentional sessions [$F(1,9) = 2.51$], suggesting a comparable decrease in detectability of sucrose regardless of the nontarget.

Effect of attention on detectability of vanillin. Overall, the detectability of vanillin followed that of sucrose, with a positive monotonic relation to concentration [$F(5,45) = 56.33$, $MS_e = 0.011$, $p < .001$], a significant effect of experimental session [$F(2,18) = 6.65$, $MS_e = 0.017$, $p < .01$], and no significant interaction between concentration and session [$F(10,90) = 1.45$]. As with sucrose, detectability of vanillin was worse when it was attended, relative to control, but only when sucrose served as the nontarget [$F(1,9) = 9.4$, $MS_e = 0.021$, $p < .05$]. When water served as the nontarget, attention had no effect [$F(1,9) < 1$]. The detectability of vanillin was significantly better when water, rather than sucrose, served as the nontarget [$F(1,9) = 8.16$, $MS_e = 0.017$, $p < .05$].

Although the results of Experiments 1 and 2 suggest that attention affects the detectability of sucrose only when the sucrose is presented in isolation, and not when it is mixed with vanillin, there is an alternative explanation, based on the detectability of gustatory–olfactory mixtures. Recall previous studies suggesting that gustatory and olfactory stimuli combine additively (independently) in suprathreshold mixtures (Murphy & Cain, 1980; Murphy et al., 1977). Even if weak sucrose and vanillin were to be detected by independent decisions, in the control session, in which the participants could respond correctly on a given trial by detecting either component, we would predict probabilistic summation. That is, in control sessions, the detectability of mixtures should surpass the detectability of the individual components. Consequently, when participants try to attend selectively to one component of a mixture, any attentional gain in sensitivity to that component might be offset by the cost associated with not detecting the other component, relative to overall performance with the mixture in the control session, in which it is possible to capitalize on probabilistic summation. Thus, for example, attending to sucrose in the mixture might increase its detectability, but not sufficiently to surpass the combined detectability of sucrose and vanillin in the control session.

In accord with this interpretation, the sucrose–vanillin mixture was better detected in the control session of Experiment 2 than pure sucrose was in the control session of Experiment 1 [$F(1,8) = 8.97$, $MS_e = 0.01$, $p < .05$]. This difference in performance might help account for the effects of attention on the detectability of sucrose: better detectability when presented alone but poorer detectability when presented in the mixture. But this explanation cannot suffice. For when we compare performance with attention across the two experiments (in the 9 individuals who participated in both experiments)—that is, performance when the participants attended isolated substances and when they attended components of mixtures—the detectability of sucrose was greater when it was presented in

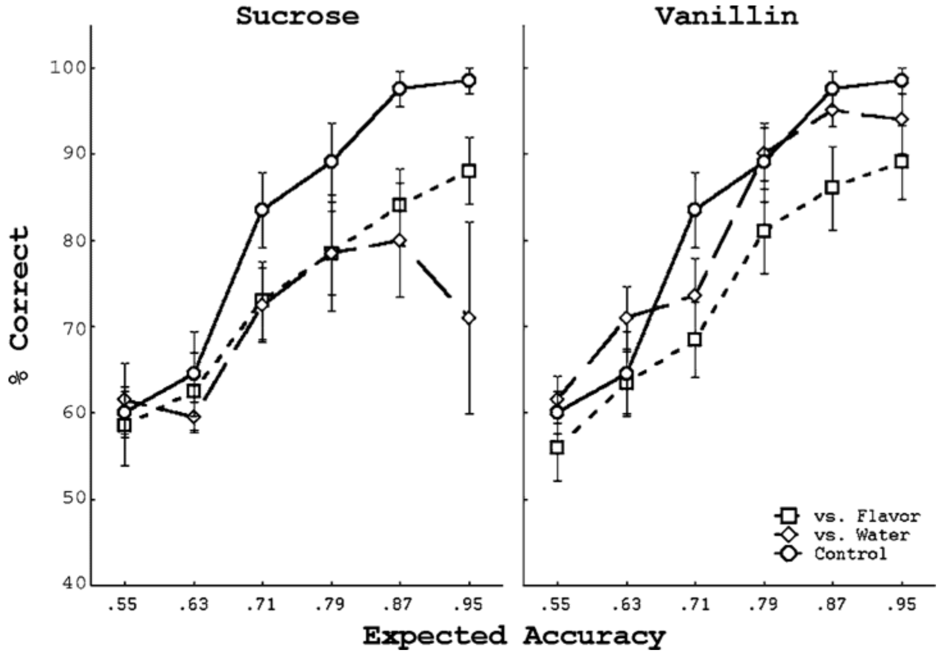

Figure 3. Mean percentages of detectability and standard errors of the means for sucrose (left panel) and vanillin (right panel) in a mixture with each other in three kinds of trials: attended with water as nontarget, attended with the other flavorant as nontarget, and control.

isolation than when presented in a mixture with vanillin. This was true both when water served as the nontarget [$F(1,8) = 15.69$, $MS_e = 0.029$, $p < .005$] and when vanillin served as the nontarget [$F(1,8) = 11.93$, $MS_e = 0.026$, $p < .01$]. Thus, the difference in detectability in the two control sessions (pure sucrose and sucrose–vanillin mixture) cannot account for the difference between the effects of attention in the two experiments. Instead, it appears that attention per se effected an increase in the detectability of sucrose when sucrose was presented alone, but not when sucrose was mixed with vanillin.

Discussion

In this experiment, we presented the participants with bimodal mixtures composed of sucrose and vanillin, asking whether attention would improve the detectability of a single component. Unlike the results in Experiment 1, in which attention improved the detectability of sucrose, in Experiment 2 detectability got worse. The participants also did poorly at attending to vanillin when it was mixed with sucrose, but this outcome mimicked the results of Experiment 1.

Although single components and mixtures were compared within participants, the single components and mixtures were given in different blocks of trials on different days. This design raises the question: Might the differences in the effects of attention on the detectability of sucrose presented alone and in mixtures reflect differences in decisional strategies? For instance, the fact that the target in the mixture session contains both flavorants might lead participants to use an elimination strategy (Tversky, 1972), basing their judgments on the detection of the irrelevant component (i.e., vanillin) rather than on the detection of the relevant component (i.e., sucrose) of the target. In this case, detecting the irrelevant component would lead participants to choose the nontarget interval as the one containing the target. It is important to clarify that using vanillin as a cue does not necessarily require identifying it as vanillin per se. If this were the case, the detectability of vanillin should have been higher when it was attended. Participants might base their elimination on detection of a flavor other than sucrose, without specifying the flavor as vanillin.

Whatever strategy the participants used in the second experiment, note that in Experiment 1, the psychometric function was monotonic for the detection of sucrose when attended, where water was the nontarget. If the nonmonotonic function in Experiment 2 resulted from the participants' strategy, when it is possible that the participants used different strategies in the two experiments.

In order to test this hypothesis, we recalled 3 of the participants and had them serve in a single session in which sucrose was attended. The session was similar in design to session $S_{S+V, W \text{ or } V}$, with two exceptions. First, only three concentrations were presented (representing 2AFC detectabilities of 63%, 71%, and 79%). Second, each sucrose concentration was presented either in isolation or in a mixture with vanillin, at a matching concentration. All the stimuli were randomly intermixed, thereby preventing the participants from adopting different decisional strategies for pure sucrose and for mixtures. When water served as the nontarget, detectability of sucrose, with increasing concentration, was 65%, 75%, and 95% (with $SE = 10\%$, 8%, and 10%) when presented alone and 60%, 60%, and

57% (with SE = 20%, 15%, and 22%) when mixed with vanillin. When vanillin served as the nontarget, the corresponding detectability of sucrose was 63%, 82%, and 85% (with SE = 7%, 9%, and 8%) presented alone and 73%, 67%, and 67% (with SE = 7%, 14%, and 11%) when mixed with vanillin. In both cases, sucrose was more detectable when presented alone than in a mixture with vanillin, implying that the difference between the results of Experiments 1 and 2 was not the outcome of differences in decisional strategy.

A consideration regarding Experiment 2, already alluded to, concerns the way detectabilities of individual flavorants combine in a mixture. Models of probability summation for 2AFC can be used to predict the detectability of mixtures on the basis of the detectability of the components. Such models have been offered in vision (Tyler & Chen, 2000; Usher, Bonneh, Sagi, & Herrmann, 1999). Probability summation, according to these models, depends on several factors. One is the pattern of noise in the system (whether independent, specific to each target stimulus, or globally affecting all stimuli). Another factor is uncertainty, defined as the ratio between the number of channels monitored by the observer and the number of stimulated channels. The present study presents an even more complex situation, because these factors may vary between modalities. That is, the noise distribution, as well as the uncertainty ratio, might differ in the gustatory and the olfactory systems. The aforementioned models predict shallow functions for probability summation, shallower than the widely use fourth-root power law. The data from the present experiment hint at such a weak summation. Average detectability of sucrose alone was 54%, 60%, 73%, 81%, 91%, and 98% for the lowest to the highest concentrations, respectively. Average detectability of vanillin alone was 57%, 61%, 76%, 90%, 93%, and 98%. Finally, average detectability of the mixture was 60%, 64%, 83%, 89%, 97%, and 98%. Additional data are needed in order to determine the exact rule underlying detection of gustatory–olfactory mixtures, a goal beyond the scope of the present study.

Finally, as was considered in the Discussion section for Experiment 1, it is possible that attending simply does not benefit the detection of vanillin, either when presented by itself or in a mixture with sucrose, perhaps because of the ways in which vanillin and sucrose are implicitly labeled. Although participants may detect vanillin, they may fail to label or identify it as such. Experiment 3 tested this possibility directly.

EXPERIMENT 3

Rankin and Marks (2000) showed that participants perceive sucrose and vanillin to be qualitatively similar, raising the possibility that the failure to detect vanillin in the present study was the result of mislabeling. The participants might have detected the vanillin but falsely identified it as sucrose. This might have arisen from the fact that the olfactory flavorant, vanillin, was delivered retronasally, through the mouth. As a result, the participants might have misidentified vanillin as a gustatory stimulus, rather than an olfactory one. This kind of smell–taste confusion has been shown to occur with other olfactory flavorants, such as ethyl butyrate (Murphy & Cain, 1980; Murphy et al., 1977). That sucrose was not mislabeled as vanillin can be explained by the same token. That is, because flavors are perceived to be aroused in the mouth and because sucrose receptors are located in the mouth, there is little chance that participants will confuse sucrose with an odorant.

To test this hypothesis, in Experiment 3 we asked the participants again to detect vanillin, but this time citric acid served as a nontarget. Because citric acid and vanillin were found to be perceptually dissimilar (Rankin & Marks, 2000), mislabeling should not occur; consequently, if mislabeling was responsible for the results of Experiment 1, the present experiment should reveal positive effects of attention on the detectability of vanillin. Results similar to those in Experiment 1, however, would require another explanation for the failure of retronasal olfaction to evidence gains from selective attention.

Method

Participants

Five nonsmokers (4 women and 1 man; age range, 18–31 years) participated. Each served in five sessions and was paid $10 per hour to participate.

Stimuli

The flavorants were sucrose, vanillin, and citric acid. In the baseline phase, each flavorant was dissolved in deionized water to create a series of four concentrations, as follows: for sucrose, from 0.025 M to 0.003125 M in steps of 0.3 log units; for vanillin, from 0.005 M to 0.0000781 M in steps of 0.6 log units; and for citric acid, from 0.0000547 M to 0.0000068 M in steps of 0.3 log units. In the test phase, a series of three concentrations, representing forced-choice detectabilities of 60%, 70%, and 80%, was formed for each flavorant, following the same method as that used in the previous experiments.

Design and Procedure

Baseline phase. The baseline phase contained two identical sessions, both designated as $B_{S \text{ or } V \text{ or } C,W}$, where S refers to sucrose trials, V to vanillin trials, and C to citric acid trials, all of which were intermixed. Thus, in both sessions, all three flavorants served as targets and deionized water as the nontarget. Each session contained 192 test trials: 3 target flavorants × 4 concentrations × 2 orders × 8 repetitions. The session was divided into four identical blocks of 48 test trials, where order of presentation of target and water was randomized. Six practice trials were presented before each block, 2 with each flavorant.

Test phase. The test phase contained three sessions, in two of which the participants attended to vanillin. In one session ($T_{V,C \text{ or } W}$), citric acid and water served as the nontargets, and in the other ($T_{V,C \text{ or } S \text{ or } W}$), citric acid, sucrose, and water served as the nontargets. Whenever a flavorant served as a nontarget, its concentration was set to produce the same baseline probability of detection as that of the target. The third session, $C_{S \text{ or } V \text{ or } C,W}$, served as control.

The $T_{V,C \text{ or } W}$ session contained 120 test trials: 2 nontargets × 3 target concentrations × 2 orders × 10 repetitions. These were divided into two identical blocks of 60 test trials. Within each block, order of presentation of target and nontarget was randomized. Six practice trials were given before each block, 3 with water and 3 with citric acid as the nontarget.

The $T_{V,C \text{ or } S \text{ or } W}$ session contained 180 test trials: 3 nontargets × 3 target concentrations × 2 orders × 10 repetitions. These were di-

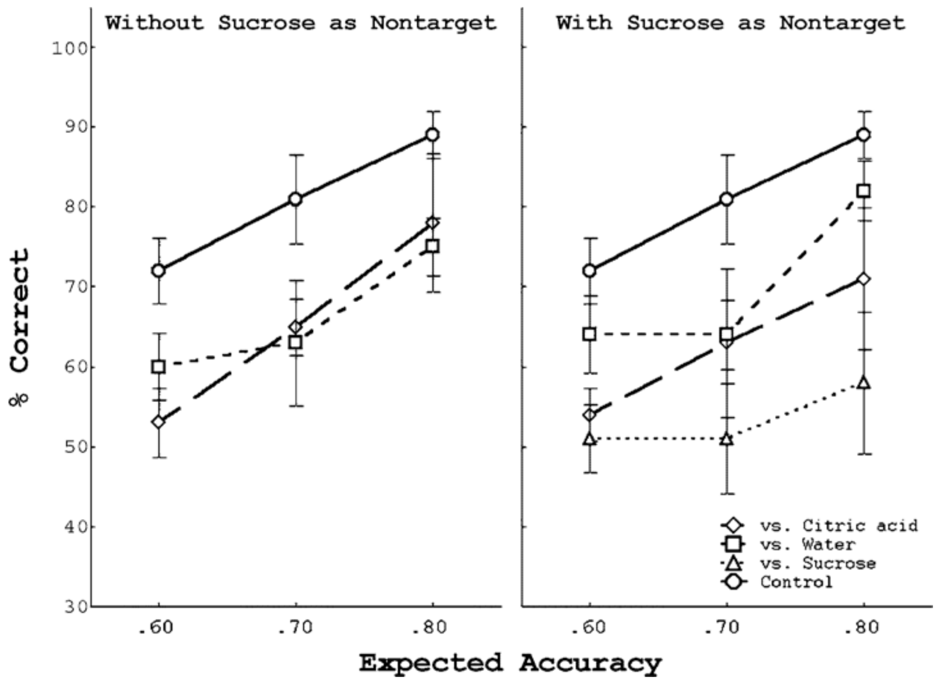

Figure 4. Mean percentages of detectability and standard errors of the means for vanillin with only citric acid and water as nontargets on attended trials (left panel) and with citric acid, water, and sucrose as nontargets on attended trials (right panel). Each panel presents three kinds of trials: attended with water as nontarget, attended with the other flavorant(s) as nontarget, and con-

vided into four blocks of 45 test trials. In the first and third blocks, vanillin preceded sucrose and citric acid on two of the five repetitions for the extreme concentrations and three of five repetitions for the middle concentration. Vanillin also preceded water on three of five repetitions for the extreme concentrations and on two of five repetitions for the middle concentration. In the second and fourth blocks, these proportions were reversed. Within each block, order of presentation of target and nontarget was randomized. Nine practice trials were given before each block, 3 with each nontarget.

The $C_{\text{S or V or C,W}}$ session, which served as the control, was analogous to the baseline session $B_{\text{S or V or C, W}}$, except for the concentration levels, which were tailored to each participant. Because Experiment 3 tested vanillin detectability, only vanillin trials from the $C_{\text{S or V or C,W}}$ session served as the control. The control session contained 180 test trials: 3 targets × 3 target concentrations × 2 orders × 10 repetitions, divided into four blocks of 45 test trials. In the first and third blocks, water preceded sucrose and citric acid on two of the five repetitions for the extreme concentrations and three of five repetitions for the middle concentration. Water also preceded vanillin on three of five repetitions for the extreme concentrations and on two of five repetitions for the middle concentration. In the second and fourth blocks, these proportions were reversed. Within each block, order of presentation was randomized. Nine practice trials were given before each block, 3 with each flavorant. All 5 participants started with $T_{\text{V, C or W}}$, continued with $T_{\text{V, C or S or W}}$, and ended with $C_{\text{S or V or C,W}}$.

Results and Discussion

Figure 4 shows the percentages of correct detection of vanillin, when the alternatives were water and citric acid (left panel) and when the alternatives were water, citric acid, and sucrose (right panel). As in Experiment 1, the detectability of vanillin was worse under attention, as compared with control. This was the case with both sets of alternative stimuli.

Attention to vanillin versus water/citric acid ($T_{\text{V, C or W}}$). Detectability was entered into an ANOVA, using as independent variables the three concentrations and three experimental sessions (vanillin vs. water, vanillin vs. citric acid, and no attention to vanillin [control]). Again, there was the ubiquitous effect of concentration [$F(2,8) = 11.19$, $MS_e = 0.012$, $p < .005$], together with a significant effect of session [$F(2,8) = 6.67$, $MS_e = 0.017$, $p < .05$] but a nonsignificant interaction [$F(4,16) < 1$]. A comparison of each attentional session with the control session showed detection to be worse when vanillin was attended, both when water served as the nontarget [$F(1,4) = 9.75$, $MS_e = 0.017$, $p < .05$] and when citric acid served as the nontarget [$F(1,4) = 39.55$, $MS_e = 0.004$, $p < .005$]. The two attentional sessions did not themselves differ [$F(1,4) < 1$], suggesting that the effect of attention on detectability of vanillin did not depend on the nontarget.

Attention to vanillin versus water/citric acid/sucrose ($T_{\text{V, C or S or W}}$). We again performed a two-way ANOVA, using as independent variables the three concentrations and four experimental sessions (vanillin vs. water, vanillin vs. citric acid, vanillin vs. sucrose, and no attention to vanillin). Again, detectability depended significantly on both concentration [$F(2,8) = 6.94$, $MS_e = 0.016$, $p < .05$] and session [$F(3,12) = 7.7$, $MS_e = 0.026$, $p < .005$], without a significant interaction [$F(6,24) < 1$]. Detectability of vanillin when attended was worse than control when the alternatives were water [$F(1,4) = 6.87$,

$MS_e = 0.012, p < .06$], citric acid [$F(1,4) = 15.07, MS_e = 0.016, p < .05$], and sucrose [$F(1,4) = 16.44, MS_e = 0.034, p < .05$]. Pairwise comparisons of the three attentional sessions revealed no significant difference.

In Experiment 1, attention to sucrose improved performance, whereas attention to vanillin did not. Because sucrose and vanillin are perceived to be similar (Rankin & Marks, 2000), it was conceivable that the participants did detect vanillin when attending to it but implicitly mislabeled it as sucrose. Experiment 3 tested this hypothesis by adding to the alternatives citric acid, a flavorant that is perceived to be qualitatively different from vanillin. Detectability of vanillin was not helped by attention—indeed, was reduced—when citric acid was the alternative, thereby suggesting that similarity and misidentification were not responsible for the failure of attention to improve performance in detecting vanillin.

GENERAL DISCUSSION

The present study was designed to test whether directing attention to a flavorant increases its detectability. Marks and Wheeler (1998) previously showed that participants can benefit from attending selectively to one gustatory stimulus or another (sucrose vs. citric acid), and Experiment 1 extended these findings by showing that attending to sucrose can benefit its detectability, relative to control. Attending to vanillin, however, did not improve its detectability; in fact, detectability was even worse when the participants attended to vanillin, as compared with control. This outcome is not likely to reflect effects of implicit labeling, resulting from the perceptual similarity between vanillin and sucrose, because attention to vanillin also failed to improve performance when the alternative stimulus was the dissimilar-tasting citric acid.

Although sucrose reaped gains from attention, it did so only when the sucrose was presented in isolation. Attending to sucrose did not improve its detectability when the sucrose was mixed with vanillin, nor did attending to vanillin improve its detectability when mixed with sucrose.

Marks and Wheeler (1998) offered two possible models to account for attention-based improvements in gustatory detection, and the same models may be considered with regard to the present results. One model proposes that attention results from selective monitoring of neurons maximally responsive to the attended stimuli; improvements in performance could arise from amplification of signals in attended channels, from attenuation of noise in unattended channels, or from both. The second model proposes that attention is directed toward common stimulus objects on the basis of similarity of features. When applied to gustatory and olfactory flavorants, the first model predicts that attention to either flavorant will selectively improve the detectability of that flavorant but not of the other. The second model predicts that attending to either will improve the detectability of both, to the extent that sucrose and vanillin are perceived as similar (Rankin & Marks, 2000). That attention improved the detectability of sucrose both when the nontarget was water and when it was vanillin is consistent with the first model, postulating stimulus-specific neural channels. The failure to find improvements in detectability resulting from attention to vanillin, however, suggests that the model does not apply in blanket fashion to all chemosensory stimuli.

Several possible explanations for this limitation come to mind. First, we presented the olfactory stimulus, vanillin, retronasally, through the mouth, and other evidence suggests that both identification (Pierce & Halpern, 1996) and detectability (Voirol & Daget, 1986) of odorants are poorer when they are presented retronasally rather than orthonasally. Although the odorants in these studies were presented only in their vapor phase, it is reasonable to assume similar behavior when odorants are presented retronasally in liquid solution, as in the present study. Thus, our finding that attention did not improve the detectability of vanillin may be the result of the retronasal pathway by which vanillin molecules reach the nose. In this regard, it would be important to know whether attention can improve the detectability of vanillin presented orthonasally.

It would be especially informative, for example, to run an experiment analogous to Experiment 1, substituting orthonasally for retronasally presented vanillin. In the main experimental trials, participants would attend either to sucrose when the nontarget was vanillin or water + pure air or to vanillin when the nontarget was sucrose or water + pure air. Unfortunately, such an experiment faces the great technical difficulty of simultaneously presenting an orthonasal stimulus (vanillin or pure air to the nose) and an oral stimulus (sucrose or water to the mouth). Fewer technical difficulties would arise in a study of orthonasal olfactory attention—that is, a study whose purpose was to determine whether people may benefit from attending to one olfactory stimulus versus another. But studies of olfactory attention, as important as they may be, would necessarily not shed light on the matter of intermodal attention to flavorants. If the olfactory system contains multiple channels, it is not yet clear what stimuli might activate different channels; and it is conceivable, of course, that the entire olfactory system operates as a single channel at threshold.

Second, because both gustatory and olfactory stimuli were presented orally, it is conceivable that attention was directed spatially to the mouth. If so, one would expect attention to improve the detectability of sucrose, because sucrose activates receptors located in the mouth. Because vanillin, on the other hand, activates receptors located in the nose, attention directed to the mouth should not improve detectability of vanillin and might even decrease it.

Third, it has previously been shown that the discrimination of odor quality is poor. For instance, Livermore and Laing (1996) showed that, regardless of training, participants succeed in discriminating and identifying up to only three or four components of odor mixtures. In four-component mixtures, all the odorants were identified, with no false alarms, on only 10% of the trials, and with five-component mixtures, performance dropped to 3% (see also Laing & Francis, 1989). This poor quality discrimination may reflect the way odors are processed in the olfactory system. It is increasingly clear that a single odorant receptor can respond to multiple odorants and a single odorant can stimulate multiple odorant receptors (Fried, Fuss, & Korsching, 2002; Malnic, Hirono, Sato, & Buck, 1999). As a result, odors recognition is presumably based on information gathered from several receptors. Although most studies have looked at responses to suprathreshold stimuli, there is no reason not to assume similar processes operating also at low levels of stimulation in vertebrates (W. S. Cain, personal communication, October 4, 2002). Assuming that different odorants generate overlapping patterns of activation near threshold, we would expect poor quality discrimination. Consequently, attending selectively to a particular odorant, such as vanillin, might not improve detection, due to the difficulty in discriminating vanillin from other, qualitatively similar stimuli, and therefore, in identifying the odorant as vanillin.

Several investigators have suggested that gustatory mixtures are substantially "synthetic" —to wit, that the result of mixing stimuli is a unique taste and not a simple combination of the components (Kuznicki & Ashbaugh, 1979; Kuznicki et al., 1983; Rozin, 1982; Schiffman & Erickson, 1971, 1980). In this regard, gustatory mixtures may be functionally similar to metameric color mixtures, which represent "true" synthesis. To the extent that gustatory–olfactory mixtures are also synthetic (as has been suggested by Dalton et al., 2000, and by Laing, Link, Jinks, & Hutchinson, 2002), "synthesis" may account for the failure to find any evidence of selective attention to either gustatory or olfactory components of sucrose–vanillin mixtures. It is important to note that synthetic integration is not expected with every combination of gustatory and olfactory stimuli. Indeed, Dalton et al. found evidence for perceptual mergence of benzaldehyde with saccharin, but not with L-glutamic acid monosodium salt (MSG). The difference may reflect the congruence in the flavors of the first pair, where saccharin, like benzaldehye, is perceived as sweet, but the dissonance between the flavors of second pair, where MSG is perceived as savory. Because vanillin and sucrose are perceived to be similar (Rankin & Marks, 2000), the failure of attention to improve their detectability, when mixed with each other, might result from their integration into a unique flavor.

Finally, it is conceivable that the olfactory system is intrinsically limited in its capacity to reap gains of focal attention, perhaps because of its particular neural organization. Whereas neural signals from all other senses project to the cortex through the thalamus, olfactory inputs bypass the thalamus (Greer, 1991; Price, 1990). This may be of particular importance given the evidence that the thalamic reticular nucleus (TRN) acts an as informational gate between the thalamus and the cortex (Guillery, Feig, & Lozsádi, 1998; McAlonan, Brown, & Bowman, 2000). This finding, in turn, has led to speculation that the TRN may serve as an attentional gate (Crick, 1984). In addition to the anatomical evidence, several behavioral experiments, with both monkeys (Peterson, Robinson, & Morris, 1987) and rats (Montero, 2000; Weese, Phillips, & Brown, 1999), also have suggested that the TRN may play a role in selective attention. It is possible, for instance, that olfactory stimuli are already fully processed before attention is directed toward them, reducing the functional consequence of attention. If so, then perhaps the failure of attention to improve the detection of vanillin reflects the absence of a neural mechanism comparable to the attentional mechanisms operating relatively early in processing in other modalities. This suggestion is, of course, speculative, and it leaves open two questions. First, why does olfaction lack such a mechanism? And second, even if olfaction does lack an attentional mechanism that would improve the detection of weak stimuli, might olfaction have available attentional mechanisms with other functional properties—for example, attentional mechanisms that enhance performance in response to suprathreshold stimuli?

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