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The Addition of CO_2 to Traditional Taste Solutions Alters Taste Quality

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Abstract

Previous studies of the effect of carbonation on taste perception have suggested that it may be negligible, manifesting primarily in increases in the perceived intensity of weak salt and sour stimuli. Assuming CO_2 solutions in the mouth stimulate only trigeminal nerve endings, this result is not altogether surprising; however, there are neurophysiological data indicating that CO_2 stimulates gustatory as well as trigeminal fibers. In that case, carbonation might alter the quality profile of a stimulus without producing substantial changes in overall taste intensity—much as occurs when qualitatively different taste stimuli are mixed. To address this possibility, subjects were asked to rate the total taste intensity of moderate concentrations of stimuli representing each of the basic tastes and their binary combinations, with and without added carbonation. They then subdivided total taste intensity into the proportions of sweetness, saltiness, sourness, bitterness and 'other taste qualities' they perceived. The addition of carbonation produced only small increases in ratings of total taste intensity. However, rather dramatic alterations in the quality profiles of stimuli were observed, particularly for sweet and salty tastes. The nature of the interaction is consistent with a direct effect of carbonation/CO_2 on the gustatory system, although the possibility that at least some of the observed effects reflect trigeminal–gustatory interactions cannot be ruled out.

Introduction

Everyday experience suggests that carbonation (CO_2) impacts taste perception. For example, the taste of a 'flat' soda is commonly reported to be sweeter than that of a freshly opened one. Nonetheless, the two principal parametric studies of interactions between carbonation and taste have found carbonation to have little or no effect on the rated intensity of sweet, salty, sour or bitter stimuli.

Cometto-Muñiz *et al.* (1987) and Yau and McDaniel (1992) systematically varied both the concentration of tastants in aqueous solution and the level of added carbonation, and asked subjects to rate the taste intensities of the resulting stimulus mixtures. Both reported significant enhancement of the sourness of acid stimuli in the presence of carbonation, although this was limited to relatively weak acids. Neither observed any substantial change in ratings of sweetness. Yau and McDaniel did report a marginal decline in intensity ratings of aspartame (but not sucrose); however, the significance of even that finding depended on the way their data were analyzed. Cometto-Muñiz *et al.* also looked at the effects of carbonation on the tastes of salt and bitter solutions. As was the case with sour, some enhancement of saltiness was observed, but this held true only at the lowest concentration of NaCl presented (0.086 M). The effects of carbonation on the bitterness of quinine were mixed and dependent on tastant concentration, although not systematically related to the level of carbonation, and thus difficult to interpret. Overall, then, in neither study did there appear to be much effect of carbonation on taste, and both groups of authors tended to dismiss those effects they observed as primarily reflecting confusion on the part of subjects between gustatory sensations produced by salt and acids and the trigeminal sensations elicited by CO_2.

In both of these studies, subjects were ostensibly rating the intensity of the sweetness, saltiness, sourness or bitterness of stimuli. However, in any given session, they received only one type of taste, and they were told the quality they were to rate without being given the option of rating any other aspect of their taste experience. There is now a small body of literature (Frank and Byram, 1988; Frank *et al.*, 1993; Clark and Lawless, 1994; Ossebaard *et al.*, 1997) demonstrating what has been called the 'dumping' effect, i.e. the tendency of subjects to assign sensations to an inappropriate category in the absence of an appropriate one. Thus, the ratings obtained by Cometto-Muñiz *et al.* (1987) and by Yau and McDaniel (1992) may not have reflected simply the sweetness, saltiness, sourness or bitterness of stimuli, but rather their total taste intensity. If CO_2 were to alter the quality profile of a taste stimulus without substantially impacting total taste intensity (much as the addition of one taste to another can), that effect could have been obscured.

The results of an early study by McLellan *et al.* (1984) are, in fact, consistent with this possibility. These authors asked subjects to rate both the sweetness and the sourness, as well as a few other sensory attributes, of uncarbonated apple juice and juice that had been carbonated at two different levels. In contrast to the findings of Cometto-Muñiz *et al.* (1987) and Yau and McDaniel (1992), they observed not only a significant linear increase in sourness with increasing carbonation, but also a significant linear decline in sweetness. Participants in this study were limited to a small group of trained panelists, and the results are presented in a way that makes it difficult to judge the size of the effects. Nonetheless, this report does suggest that it may be important not just to ask subjects how strong a taste is when CO_2 is added, but also to ask what it tastes like.

Materials and methods

Subjects

Fifteen subjects (seven females, eight males) were paid to participate in the experiment. Subjects included employees of the Monell Center and students from the University of Pennsylvania; their median age was 24 years.

Stimuli

Ten stock taste solutions were prepared using deionized water (dH_2O) as the solvent. These included 1.28 M sucrose, 0.70 M sodium chloride (NaCl), 22.4 mM citric acid (CA) and 224 μM quinine sulfate (QS), and each of the six binary combinations of these concentrations of tastants. The stock solutions were stored refrigerated for up to 2 weeks.

Uncarbonated taste stimuli for each subject were prepared by diluting 15 ml of each stock with 45 ml dH_2O in 60 ml bottles, resulting in effective concentrations of 0.32 M sucrose, 0.18 M NaCl, 5.6 mM CA, 56 μM QS and the binary combinations of these stimuli. The final concentrations of the simple tastes were selected on the basis of pilot studies to elicit approximately equivalent, moderately strong taste sensations.

Carbonated stimuli for each subject were prepared by diluting 15 ml of each stock with 45 ml of carbonated dH_2O in 60 ml bottles. Prior to use, a thin layer of melted Crisco® shortening was applied to the lips of these bottles; pilot testing indicated that this added no noticeable odor or taste, but improved the seal, reducing loss of CO_2. The final stimulus samples of both carbonated and uncarbonated tastes were stored refrigerated for no more than 1 week.

Carbonation was achieved using a Zahm Pilot Plant carbonating unit. Carbonated water was dispensed at 4°C under pressure via an airtight nozzle inserted into the previously chilled bottles. The pressure in the carbonating unit was adjusted to deliver a nominal concentration of ~6400 p.p.m. (w/w), producing a target carbonation level of ~4800 p.p.m. or ~2.4 vol. This falls within the range of carbonation encountered in carbonated soft drinks.

During the preparation of each series of carbonated stimuli, an additional 10 bottles containing 15 ml of dH_2O were carbonated to provide a measure of actual CO_2 concentration. The day after the last day of testing with stimuli from each bottling run, carbonation levels in the extra bottles were measured using a Corning 965D CO_2 analyzer. These bottles were first brought to 28–30°C in a water bath and ~20 ml aliquots were poured in medicine cups, simulating testing conditions (see below). Each cup contained 0.4 ml NaOH to preserve CO_2 content by raising the pH, converting CO_2 to CO_3^{2-}. Following dilution with dH_2O, a sample was pipetted into the reaction chamber of the analyzer, which contained a small amount of an acidic CO_2 releasing agent (lactic acid). Released CO_2 concentration was then measured by means of a thermal conductivity detector. The mean measured level of CO_2 across all bottling runs was 4720.6 p.p.m., with standard deviations within runs ranging between 1 and 6%.

Procedure

All subjects participated in two test sessions beginning at 8:30 a.m. and separated by 1–7 days. The Labeled Magnitude Scale (LMS) (Green *et al.*, 1993), presented on a computer screen, was used to obtain ratings of the intensity of sensations of tingling/irritation and of taste (the purpose of the former ratings was to reduce the likelihood that this aspect of the sensory experience of carbonated solutions would be confounded with or added to taste). Detailed instructions on the use of the scale, which emphasized that both types of sensation were to be rated in the context of all oral sensations, were provided in the first session (see Green *et al.*, 1993, 1996). These included asking subjects to rate the imagined intensities of a set of 10 hypothetical oral stimuli to provide practice with the scale and the computer mouse used to mark it. The instructions were reviewed at the beginning of the second session.

Immediately following their ratings of the irritation and taste intensities of each stimulus, subjects were asked to identify the taste or tastes they perceived in the solution and to estimate the relative strengths of each. The labels 'Sweet', 'Salty', 'Sour', 'Bitter' and 'Other' appeared on the computer screen, and subjects were required to indicate the percentage of each (0–100%) that characterized the taste they had experienced.

Approximately 45 min prior to each test session, stimulus bottles were submerged in a circulated, constant-temperature water bath and maintained at a temperature of 28–30°C. Stimuli were dispensed as 10 ml aliquots into 30 ml plastic medicine cups. Within each session, subjects received each stimulus twice in random order (with the constraint that all were presented before any were repeated), yielding four replicates per subject. To minimize loss of CO_2, only a single aliquot was poured from each carbonated bottle. Subjects rinsed with dH_2O prior to receiving each stimulus and were instructed to close their eyes to avoid their being biased by the sight of the bubbles associated with carbonation. They then held the stimulus in their mouths for 3–5 s, spit it into a sink and provided their ratings.

Data analysis

Data were first averaged over replicate and session. Because intensity ratings from the LMS tend to be distributed log-normally across subjects (Green *et al.*, 1993), these were subjected to log transformation prior to parametric analysis. Ratings of irritation and taste intensity were analyzed separately in 2 (carbonation) × 10 (taste stimulus) repeated measures ANOVAs. Carbonation × taste stimulus interactions were explored by pairwise *t*-tests comparing the rating of each uncarbonated stimulus with that of its carbonated counterpart.

Quality profile data (percent sweetness, saltiness, sourness, bitterness or other) were analyzed separately for each type of taste stimulus. Ratings of the four dominant qualities (based on means) were included in each analysis. For stimuli containing sucrose, these were sweetness, saltiness, sourness and bitterness; for all other stimuli, the dominant qualities were saltiness, sourness, bitterness and other. In each analysis, the profile of the uncarbonated version of a taste was contrasted with that of the carbonated version, resulting in 2 (carbonation) × 4 (quality) repeated measures ANOVAs. The large number of 0% ratings in this data set precluded arcsin transformation prior to parametric analysis. Thus, across-quality ANOVAs were used as guides to identify stimuli whose mean quality profiles were substantially altered by the addition of carbonation. Significant carbonation × quality interactions ($P \leq 0.05$) were then followed by two-tailed Sign tests of the ratings of each quality in the absence and presence of carbonation to assess median differences in the relative contribution of each to the tastes of uncarbonated versus carbonated stimuli. As described below, the results of these analyses suggested that the effect of carbonating some taste stimuli was similar to that of adding a traditional, sour taste stimulus. Thus, comparable analyses were performed contrasting the taste quality profiles of carbonated sucrose, NaCl and QS with those of the uncarbonated binary mixtures of each of those tastants with CA.

In all ANOVA results involving factors with more than two levels, *P* values are those associated with a Greenhouse–Geisser correction, although the uncorrected degrees of freedom are reported.

Results

Intensity ratings

As expected, carbonation produced significant increases in tingling/irritation ratings [$F_{1,14} = 15.7$, $P = 0.001$], but there was also a significant main effect of taste stimulus [$F_{9,126} = 3.5$, $P = 0.001$], and a significant interaction between carbonation and taste stimulus [$F_{9,126} = 5.3$, $P < 0.001$]. Among the uncarbonated tastes, binary mixtures tended to be rated as more irritating than the simple taste stimuli, and of the simple tastes, QS and CA received the highest ratings of irritation. Post hoc paired *t*-tests indicated that although mean irritation increased with carbonation in each case, the increase was not statistically significant for the three binary mixtures that included QS [sucrose–QS: $t(14) = -1.5$, $P = 0.16$; NaCl–QS: $t(14) = -1.6$, $P = 0.13$; CA–QS: $t(14) = -1.8$, $P = 0.09$].

There was no main effect of either carbonation [$F(1,14) = 2.8$, $P = 0.119$] or taste stimulus [$F(9,126) = 1.7$, $P = 0.186$] on ratings of total taste intensity, nor did the interaction between these two factors attain traditional statistical significance, although a marginal interaction was observed [$F(9,126) = 2.4$, $P = 0.051$]. As can be seen in Figure 1, slight increases in taste intensity ratings were observed with carbonation for most, but not all, tastes. Notably, binary mixtures of tastes also elicited only modestly higher ratings of taste intensity than did their unitary components.

Quality ratings

As expected, in none of the repeated measures ANOVAs of quality profile data was there a significant main effect for carbonation, and the main effect for quality was significant in all cases.

Among the simple tastes, carbonation × quality interactions suggested that the quality profiles of sucrose and NaCl were markedly altered by the addition of carbonation [sucrose: $F(3,42) = 15.0$, $P < 0.001$; NaCl: $F(3,42) = 10.6$, $P < 0.002$], and that the profile of CA was somewhat altered [$F(3,42) = 3.7$, $P < 0.05$]. No significant carbonation × quality interaction was observed for QS [$F(3,42) = 1.4$, $P = 0.260$]. These data are depicted in Figure 2.

For all 15 subjects, the relative (to other taste qualities) sweetness of sucrose was reduced by carbonation (Sign test, $P < 0.001$), with a median decline in sweetness of 23.75%. On the other hand, the relative sourness of the sucrose solution increased with carbonation for 12 subjects (three showed no change; Sign test, $P < 0.001$); relative saltiness and bitterness were not consistently affected.

Similarly, the relative saltiness of NaCl was reduced by carbonation for all but one subject (Sign test, $P = 0.001$), with a median decline of 32.5%. The carbonated NaCl solution was also perceived as relatively more sour than the uncarbonated solution by 13 subjects (for one subject sourness declined and one showed no change; Sign test, $P = 0.002$), with no consistent change in rated bitterness or 'other' taste.

No significant change, by Sign test, in ratings of any specific taste quality was observed as a function of carbonation of the CA stimulus. However, there was a tendency for subjects to assign *lower* proportional ratings of sourness to the carbonated stimulus (11 subjects, with three reporting an increase in relative sourness and one showing no change; Sign test, $P = 0.057$).

Quality profiles of the carbonated sucrose, NaCl and QS

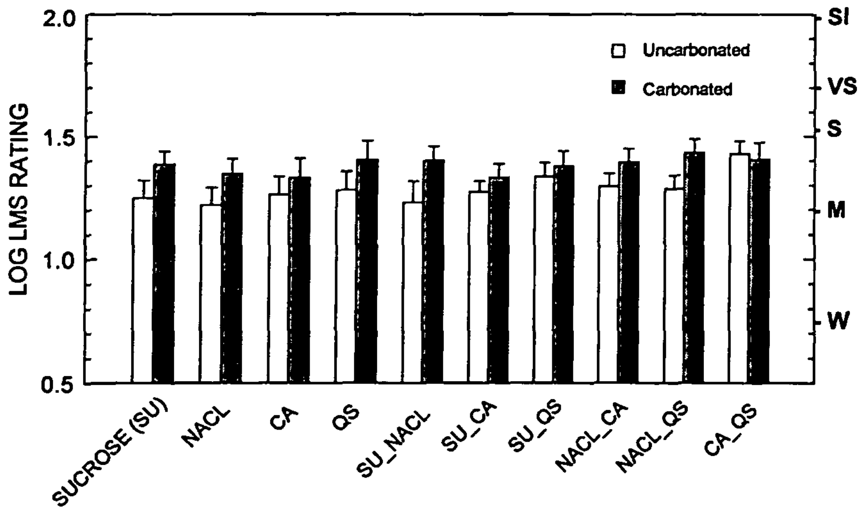

Figure 1 Mean total taste intensity ratings (± SE) of each of the 10 taste stimuli with and without added carbonation. The letters on the right y-axis represent verbal labels of the LMS: W = weak, M = moderate, S = strong, VS = very strong, SI = strongest imaginable (the label 'barely detectable' was omitted here because it falls below 0.5). See the text for abbreviations used for taste compounds.

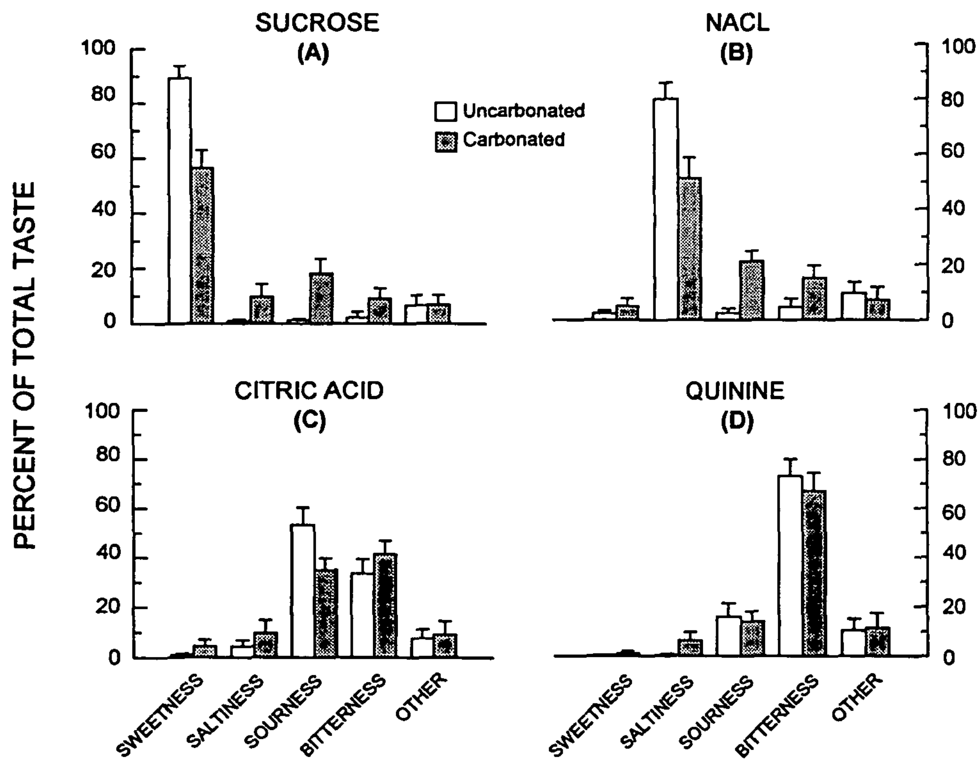

Figure 2 Quality profile ratings of uncarbonated and carbonated taste solutions (mean relative strengths of each of five quality categories ± SE). **(A)** Sucrose, **(B)** NaCl, **(C)** citric acid, **(D)** quinine sulfate.

were also contrasted with those of corresponding mixtures of each of these tastants with CA to determine whether the addition of CO_2 produced stimuli qualitatively equivalent to those produced by the addition of a traditional sour tastant. In repeated measures ANOVAs, no interaction between mixture type (CO_2 versus CA) and quality was observed for either sucrose or NaCl ($P > 0.5$ in both cases). The carbonated QS was, however, qualitatively different than QS + CA [$F(3,42) = 5.9$, $P < 0.01$]. Subsequent Sign tests showed a significant tendency for the QS + CA mixture to be perceived as relatively more sour than the carbonated QS (for 13 subjects, with one reporting the reverse and one no difference; Sign test, $P < 0.002$).

Not surprisingly given their greater complexity, the effects of carbonation on the qualities of binary mixtures of tastants tended to be less sharply defined than those observed with simple tastes. Nonetheless, significant carbonation × quality interactions were observed for three of the six mixtures, and consistent with the results from simple taste stimuli, the most pronounced effect of carbonation on perceived quality occurred with the sucrose–NaCl mixture [$F(3,42) = 10.1$, $P < 0.001$]. Significant carbonation × quality interactions were also observed in analyses of the ratings of the most naturalistic mixture, sucrose–CA [$F(3,42) = 3.3$, $P = 0.05$], and in those of the QS–CA mixture [$F(3,42) = 4.1$, $P < 0.05$].

Post hoc Sign tests indicated that the relative sweetness of sucrose–NaCl was reduced by carbonation (for 14 subjects, with one reporting the reverse; $P = 0.001$), while both its sourness ($P = 0.039$) and bitterness ($P < 0.01$) tended to increase. There was also a tendency for the relative sweetness of sucrose–CA to decline with carbonation, but this did not attain statistical significance ($P = 0.12$); the relative sourness of this solution was unchanged by CO_2, but the carbonated version was perceived to be relatively more bitter ($P < 0.01$). Finally, the QS–CA mixture was perceived to be relatively more sour in its uncarbonated form ($P < 0.05$).

Discussion

These results indicate that carbonation does impact taste perception, but that its impact manifests as a change in the perceived qualities of some taste stimuli, particularly sweet and salty ones, not as a substantial alteration in taste intensity. The failure to observe significant changes in the total taste intensity of moderately strong tastes with the addition of CO_2 is at least superficially consistent with the findings of Cometto-Muñiz *et al.* (1987) and Yau and McDaniel (1992). In the latter studies, however, subjects had been instructed to rate sweetness, saltiness, sourness or bitterness specifically, rather than total taste intensity. Thus, in the absence of significant changes in those ratings with carbonation, it was presumed that none of these specific taste experiences were affected—which is not consistent with the present results.

As indicated earlier, the procedures adopted by Cometto-Muñiz *et al.* (1987) and Yau and McDaniel (1992) did not allow subjects to rate anything other than the single taste quality presumed to be elicited by a given taste compound. This kind of limitation in alternatives can lead subjects to lump together (or 'dump') qualitatively diverse sensations into whatever response category is available to them (Frank and Byram, 1988; Frank *et al.*, 1993; Clark and Lawless, 1994; Ossebaard *et al.*, 1997). The results of the present study, as well as those of McLellan *et al.* (1984), are consistent with the hypothesis that this occurred in the Cometto-Muñiz *et al.* and Yau and McDaniel studies. That is, when subjects were given the opportunity to rate several qualitative aspects of their taste experiences in the absence and presence of carbonation, clear and sometimes striking differences in the nature of those experiences became evident.

A second issue concerns the basis for this effect. Both Cometto-Muñiz *et al.* (1987) and Yau and McDaniel (1992) explicitly assumed CO_2 to be a trigeminally mediated stimulus that is largely (Yau and McDaniel, 1992) or completely (Cometto-Muñiz *et al.*, 1987) tasteless. Thus, both groups of authors presumed they were exploring oral trigeminal–gustatory interactions. In that context, the small effects they observed were not surprising. The one other oral trigeminal stimulus whose interactions with taste have been extensively studied is capsaicin, and its impact on taste perception has been found to be small and inconsistent (Lawless and Stevens, 1984; Lawless *et al.*, 1985) or non-existent (Cowart, 1987). Notably, to the extent that capsaicin affects taste, that effect appears to be entirely inhibitory/suppressive.

The effects of carbonation on taste perception observed here are, in fact, more suggestive of a taste–taste interaction than of a taste–trigeminal interaction. The addition of carbonation did not simply suppress (or enhance) the tastes elicited by traditional gustatory compounds, but in some cases resulted in the addition of new taste qualities (primarily sour and/or bitter). Indeed, carbonating sucrose and NaCl solutions at the level used here produced solutions whose tastes were equivalent to those produced by the addition of a moderately strong CA stimulus (although there were other cases in which the effects of adding CO_2, while still 'taste-like', were different from what was seen or might be expected with the simple addition of CA).

There is no question that CO_2 is a trigeminal stimulant. There are also, however, neurophysiological data from cat, dog and rat indicating that carbonated water, and even CO_2 gas, elicit chorda tympani responses; this has been shown in recordings from both whole nerve (Komai and Bryant, 1992) and single gustatory fibers (Kawamura and Adachi, 1967). In fact, thresholds for chorda responses to CO_2 in rat appear to be lower than those for trigeminal responses (B. Bryant, personal communication). Preliminary data from this laboratory indicate that humans do perceive simple carbonated dH_2O, at ~4800 p.p.m., to have a distinct taste that is predominantly sour, although less intense and more complex (with more pronounced bitter, salty and/or 'other taste' components) than that produced by the traditional sour tastant that was used in the present study (5.6 mM CA). This complexity may underlie the somewhat surprising qualitative shift observed in the taste of CA with the addition of CO_2; it is also possible that what subjects label as non-sour tastes in CO_2 are in fact trigeminal sensations that are not clearly irritating.

It is unclear why aqueous solutions of CO_2 have been presumed to be virtually tasteless [e.g. Cometto-Muñiz *et al.* (1987) do not even reference their statement that CO_2 in water is tasteless (p. 630)], although evidence that gaseous CO_2 is odorless (e.g. Cain and Murphy, 1980) may have contributed to this notion. It is also unclear exactly what the effective taste stimulus in carbonated water might be. The addition of CO_2 to water produces a rapidly equilibrating mixture of carbonate, bicarbonate and CO_2, the relative concentrations of which vary as a function of both the partial pressure of CO_2 and pH. A low, equilibrium concentration of carbonic acid is also present. Dissociated H^+ protons in this dynamic mix might contribute sourness to carbonated water, but because none of these atomic/molecular species can be varied independently in the mixture, it is impossible to study their separate efficacies as taste stimuli. Nonetheless, the present results do seem to confirm anecdotal reports of taste differences between carbonated and flat sodas, and suggest that those differences arise from a direct effect of aqueous solutions of CO_2 on the gustatory system, although trigeminal–gustatory interactions may also contribute to the observed effects.

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