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The Bitter Taste of Confidence: Exploring Audio-Visual Taste Modulation in Immersive Reality

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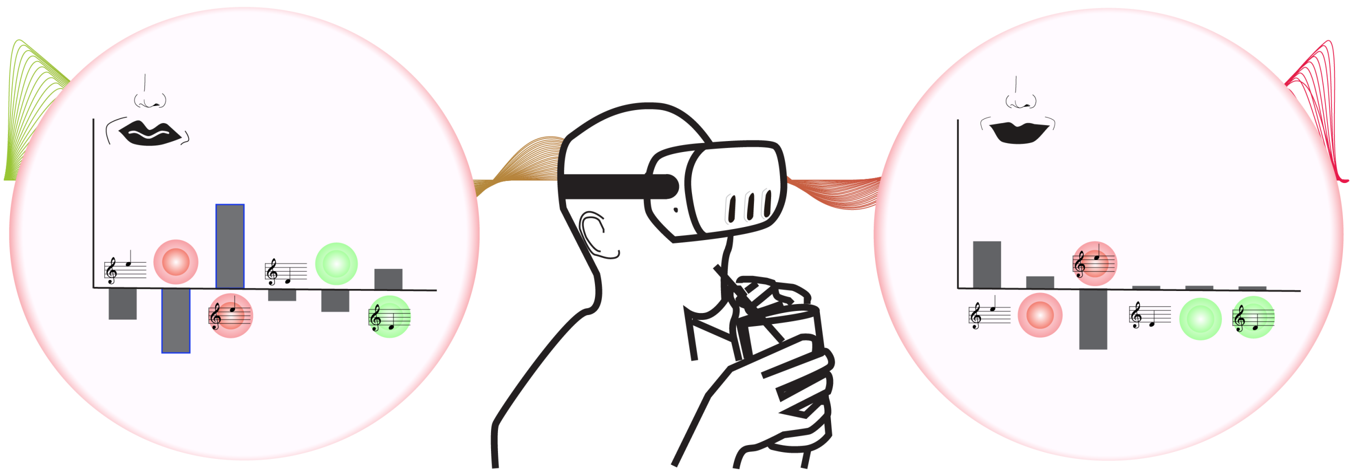

Figure 1: The effects of audio and visual stimuli, and their interaction, on bitterness perception (left) and sweetness perception (right). Significant effects found for bitter taste are outlined in blue.

Abstract

Extended Reality (XR) technologies present innovative ways to augment sensory experiences, including taste perception. In this study, we investigated how augmented reality (AR) visual filters and synchronized audio cues affect gustation through a controlled experiment with 18 participants. Our findings revealed unexpected crossmodal interactions: while pink visual filter typically associated with sweetness reduced perceived bitterness in isolation, it paradoxically enhanced bitterness perception when combined with sweet-associated audio cue. Furthermore, we observed an inverse correlation between participant confidence levels and their perception of taste intensities across multiple dimensions, highlighting confidence as an overlooked factor in sensory experience design. These findings inform the design of nuanced multisensory experiences in immersive media, where subtle crossmodal interactions significantly influence user perception.

*Both authors contributed equally to this research.

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CCS Concepts

• **Human-centered computing → Empirical studies in HCI**.

Keywords

augmented reality, taste perception, multisensory, immersive experiences, interactive media

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1 Introduction

Extended Reality (XR) environments enable studying crossmodal perception and taste experiences in immersive settings [7, 17, 30] while allowing controlled integration of modalities such as haptics [2]. Research shows taste integrates multiple sensory inputs [1, 3, 21, 33], with XR offering controlled multisensory stimulation. Two key research gaps exist: limited study of combined audio-visual effects [26], and inconsistent results in individual sensory studies [16, 23]. XR presents an opportunity to overcome traditional methodological limitations [11] through precise stimulus control.

We explored visual and auditory effects on taste perception in XR (Figure 1). Our AR experiment tested sugar solutions under various visual and audio conditions, with participants rating taste qualities and confidence levels. While broad effects were limited, specific stimulus combinations showed significant influence. A pink visual filter decreased perceived bitterness alone but **increased** it with sweet audio cues. Higher confidence was correlated with lower perception of bitterness. This study contributes: (1) empirical evaluation of combined audio-visual effects on taste using XR [26], beyond separate Audio-Taste [4–6, 9, 14, 15, 21, 28] or Visual-Taste studies [16, 22–24, 27, 32, 34], and (2) confidence-weighted sensory analysis.

2 Related Work

This section reviews the literature on taste perception across sensory modalities, examining two key areas: (1) audio-visual influences on taste and (2) confidence in crossmodal perception.

2.1 Audio-Visual Influences on Taste

Both auditory and visual cues influence taste perception through crossmodal correspondences [14]. Research demonstrates how different types of sounds affect our perception of food. For instance, the sound of biting influences perceived freshness, particularly evident in studies involving potato chips [37]. The pitch of the sound also plays a crucial role, with higher pitches being associated with sweet and sour tastes, while lower pitches connect to bitter tastes [6]. Drawing on these insights, we developed piano-based stimuli that match sweet tastes with high-pitched, smooth sounds and bitter tastes with low-pitched, rough sounds [14].

Visual elements like shape and color also affect taste perception [20]. Round shapes suggest sweetness [31], while colors have specific taste associations: red/pink for sweet, yellow for sour, white for salty, and green/black for bitter [27]. While individual effects are well-studied, research on **combined visual-auditory** influence remains **limited** [26].

2.2 Confidence in Crossmodal Perception

While crossmodal research has advanced our understanding of flavor perception, replication remains challenging [10]. Studies typically use self-reported data through questionnaires [36], but rarely examine participants' confidence in their judgments. To the best of our knowledge, within the field of crossmodal sensory research on taste, only one study has addressed confidence, focusing on predictions of others' responses rather than self-perception [34].

Neuroscience research emphasizes confidence measurements, using both initial judgments (Type 1) and confidence ratings (Type 2). Confidence reflects factors like signal clarity, evidence strength, and context [18]. Recent work shows that expectations influence both perceptions and confidence [29].

Confidence measurement is crucial beyond neuroscience, including AI system trust calibration [38]. Despite this, sensory research often overlooks confidence measures. We argue for including confidence ratings in questionnaires to better weigh and validate perceptual results.

3 Methodology

Our study uses a within-group factorial design to explore the interaction between visual and auditory stimuli on taste perception. First, we investigated how visual and auditory cues influence taste perception in Extended Reality (XR). Second, we examined whether including confidence measurements in crossmodal taste studies could enhance data reliability.

3.1 Study Design

We used a within-group design to study variable interactions while controlling for individual taste differences. We tested three variables: (1) *Sucrose Concentration*, (2) *Auditory Stimulus*, and (3) *Visual Stimulus*.

For *Sucrose Concentration*, we used two solutions (3 g/L and 10 g/L) [8]. For *Auditory Stimulus*, we used three piano-based conditions [14]: a sweet-promoting track (legato G major), a bitter-promoting track (lower pitch, higher roughness), and silence as control. For *Visual Stimulus*, we used pink filter for sweetness, green filter for bitterness [35], and no filter as control.

This created 18 conditions $2 \times 3 \times 3 = 18$. Participants tasted solutions through a straw while wearing an HMD, rating taste intensities and confidence levels (0-100) via VR questionnaire (inVRQ) [19]. we implemented custom inVR questionnaires where participants rated taste intensities and their corresponding confidence for each taste on a continuous 0–100 scale. A brief demographics questionnaire was administered before the experiment.

We randomized conditions using a Latin square design, included neutralization periods between tastings, and scheduled breaks every six conditions.

3.2 Apparatus

The experiment used Unity 6000.0.23f1 and a Meta Quest 3 headset for controlled visual and audio stimuli. Participants were seated in a minimalist room with basic furniture. The interviewer remained out of sight, and participants used glass straws (Figure 2).

3.3 Procedure

Participants sequentially experienced all 18 conditions in a randomized order. For each trial, they donned the HMD, the assigned visual filter and audio were presented, and they sipped the sample through a straw. The visual filters were purely chromatic overlays without additional video or contextual visual content. Simultaneously, auditory stimuli (piano-based soundtracks corresponding to sweetness or bitterness) were precisely synchronized to begin at the exact moment participants began tasting each solution.

They then rated the perceived sweetness, bitterness, sourness, and saltiness of the liquid, and their confidence in each rating on a

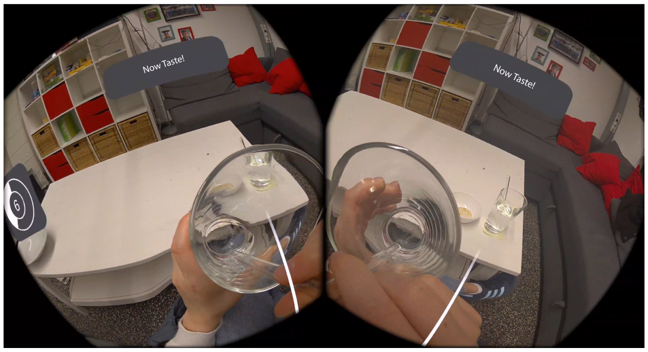

Figure 2: Participant drinking a sugar-water solution during the tasting phase of the experiment

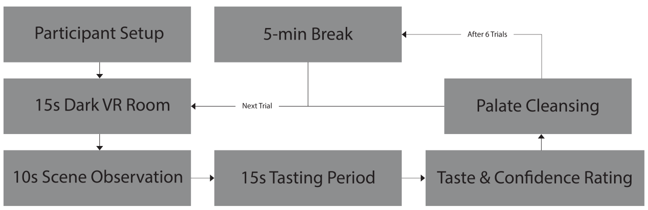

Figure 3: Flowchart depicting the step-by-step experimental procedure.

0–100 scale via a VR questionnaire (inVRQ) [19]. Confidence scores were treated as metacognitive judgments of perceptual certainty and were later used as weights in our statistical models to enhance result reliability.

A palate cleanser (plain cracker and deionized water [12, 13]) was used between samples to avoid taste carryover (Figure 3). Each experimental session lasted approximately $M = 45.7$ min, $SD = 8.02$ per participant, including tasting phases, rating periods, palate cleansing, and scheduled breaks.

3.4 Participants

We recruited 18 participants (8 M, 9 F, and 1 participant identifying as gender-diverse) aged between 18 and 34 ($M = 23.56, SD = 2.22$) via word-of-mouth, with no monetary compensation.

3.5 Data Analysis

We used Linear Mixed-Effects Model (LMM) and Type III ANOVA for analysis. The LMM included sucrose concentration, visual and auditory stimuli as main effects, with participant ID as random effect. Baseline parameters were set to 3 g/L sugar concentration without stimuli. Analysis occurred in two phases: examining effects without confidence scores, then using confidence-weighted taste scores. We also created a model with confidence as a non-interacting independent factor to study taste confidence-perception relationships. For evaluation, we compared weighted and unweighted taste scores via Wilcoxon Signed-Rank test and calculated partial eta-squared (η_p^2) values with residual analysis for effect size and model fit.

4 Results

We found that sweetness was not affected by neither of visual or auditory stimuli. Moreover, all combinations of visual and auditory stimuli had no effect on the perception of sweetness. The only factor that affected the perception sweetness was the sugar level. However, the situation looks different for the perception of bitterness. The sweet-promoting visual stimulus (pink filter) individually reduces bitterness. Moreover, the combination of sweet-promoting visual and auditory stimuli **increases** bitterness. The remaining individual and combined factors had no effect on neither saltiness nor sourness. Lastly, we found that weighing participants' responses with confidence scores leads to robust results.

4.1 Sweetness

Neither visual stimuli (sweet-promoting: $M = 17.1, SD = 20.8$; bitter-promoting: $M = 16.8, SD = 22$; neutral: $M = 16.5, SD = 18.8$; $F(2, 289) = 0.0549, p > 0.05$) nor audio stimuli (sweet-promoting: $M = 18.2, SD = 20.4$; bitter-promoting: $M = 16.1, SD = 21.7$; neutral: $M = 16.1, SD = 19.5$; $F(2, 289) = 0.9047, p > 0.05$) influenced sweetness perception. Combined stimuli also showed no effect ($F(4, 289) = 0.2380, p > 0.05$). Analysis showed no relationship between sweetness perception and confidence as a covariate ($t(302.29) = 1.14, p = 0.254$). While the unweighted model suggested a marginal effect of the pink filter in low sugar conditions ($t(289) = 1.712, p = 0.09$), the weighted model showed no significant interactions.

4.2 Bitterness

Bitterness perception revealed subtle variations across conditions. For visual stimuli, mean bitterness ratings showed minimal differences between sweet-promoting ($M = 2.00$, $SD = 6.02$), bitter-promoting ($M = 2.33$, $SD = 4.41$), and neutral conditions ($M = 2.58$, $SD = 6.83$). Auditory stimuli exhibited similar patterns, with sweet-promoting ($M = 1.57$, $SD = 4.78$), bitter-promoting ($M = 2.86$, $SD = 6.81$), and neutral conditions ($M = 2.48$, $SD = 5.70$) showing limited variation between the levels.

Type III ANOVA results indicated no significant main effects for either visual ($F(2, 289) = 0.30$, $p = 0.739$) or auditory stimuli ($F(2, 289) = 1.57$, $p = 0.209$). The interaction between visual and auditory categories also proved non-significant ($F(4, 289) = 0.38$, $p = 0.823$). However, our linear mixed-effects model revealed that specific stimulus combinations significantly affected perceived bitterness. Notably, the interaction between pink visual filter and sweet audio cues significantly **increased** perceived bitterness ($\beta = 5.23$, $SE = 2.59$, $t(289) = 2.02$, $p = 0.044$) compared to our reference condition (3g/L sugar, neutral visual and audio). This finding highlights how specific sensory combinations can influence perception in ways that broader categorical analyses might overlook. The sweet-promoting pink filter significantly reduced perceived bitterness relative to the reference visual condition ($\beta = -3.70$, $SE = 1.83$, $t(289) = -2.02$, $p = 0.044$). Since the broader visual category showed no significant variance in the Type III ANOVA ($F(2, 289) = 0.30$, $p = 0.739$), this effect is specific to the pink filter (Figure 4).

Both confidence-weighted and unweighted analyses revealed significant intercepts, indicating consistent bitter taste detection in

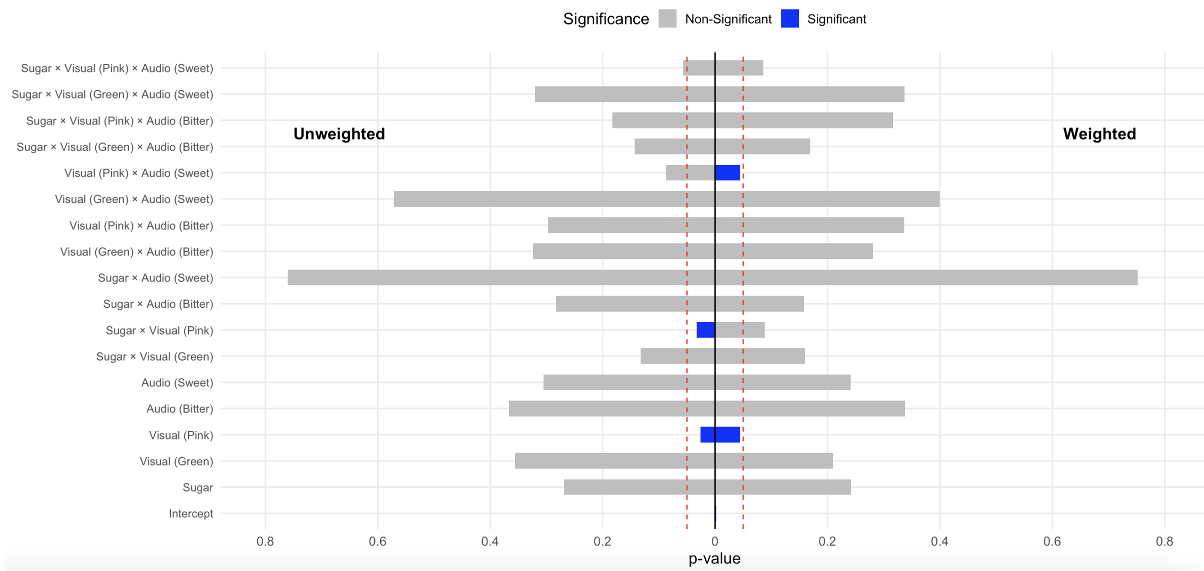

Figure 4: Comparing confidence-weighted and unweighted p-values across different predictor combinations for bitterness perception.

our base scenario. This finding likely stems from our use of 3g/L sugar concentration, which is a level that reaches the detection threshold but remains below the recognition threshold for sweet taste identification. Participants could detect the water's impure state at this concentration but struggled to identify the specific taste modifier. Most notably, our analysis revealed a previously undocumented relationship between confidence and perceived bitterness ($\beta = -0.10211$, $SE = 0.01916$, $t(119.97) = -5.329$, $p < 0.001$). Each unit increase in reported confidence corresponded to a 0.10-unit decrease in perceived bitterness, demonstrating a robust link between confidence and taste perception. Figure 4 visualizes the p-values for different predictor combinations in bitterness perception, comparing the impact of confidence weighting. This highlights how certain interactions become significant and how some lose significance only when confidence is accounted for, illustrating the methodological value of our approach.

4.3 Saltiness and Sourness

As for the saltiness and sourness, our analysis revealed highly significant relationships between taste and confidence for both sour ($\beta = -0.098$, $SE = 0.029$, $t(112.76) = -3.415$, $p < 0.001$) and salty tastes ($\beta = -0.113$, $SE = 0.021$, $t(186.85) = -5.475$, $p < 0.001$). This consistent pattern across multiple tastes highlights the importance of confidence in sensory analysis. Similar to the bitterness interaction, when confidence was not considered, the unweighted analyses revealed seemingly significant interactions that disappeared in the confidence-weighted analysis. Specifically, the unweighted analysis found significant effects for two interactions on saltiness perception: the effect of sweet-promoting audio ($\beta = -4.944$, $SE = 2.273$, $t(289) = -2.175$, $p < 0.05$) and the two-way interaction between sugar concentration and bitter audio ($\beta = 8.222$, $SE = 3.215$, $t(289) = 2.558$, $p < 0.05$). However, the confidence-weighted analysis showed no significant interactions between our independent variables for saltiness or sourness.

4.4 Confidence-Weighted and Unweighted Model's Explanation of Variance

We conducted Wilcoxon signed-rank tests for each taste to compare the confidence-weighted and unweighted taste scores across participants. The results revealed significant differences between weighted and unweighted versions for all tastes (sweet: $V = 20301$, $p < 2.2 \times 10^{-16}$; bitter: $V = 5778$, $p < 2.2 \times 10^{-16}$; salty: $V = 5460$, $p < 2.2 \times 10^{-16}$; sour: $V = 6786$, $p < 2.2 \times 10^{-16}$).The boxplot comparison of weighted and unweighted results demonstrates a smaller interquartile range (IQR), lower median, and higher number of outliers (Figure 5).

Building upon our earlier finding of a significant relationship between non-sweet taste perceptions and their associated confidence ratings, we examined how confidence weighting affects the model's fit and effect sizes through partial eta-squared (η_p^2) and residual analysis. The results revealed an interesting pattern: while unweighted models exhibited larger effect sizes for visual-audio stimuli and their interactions, the weighted model showed stronger effects for sugar concentration (47% vs. 39% in sweet taste) and specific interactions (e.g., Visual:Audio in sour taste, 3% vs. 2%). However, it should be noted that the overall audio and visual effect sizes remained relatively small across all conditions for both models.

In our residual analysis of linear mixed models, we examined the difference between observed and predicted values (residuals), which should ideally be close to 0. Across all taste perceptions, both weighted and unweighted models showed strong central tendency with means near zero ($M \approx 10^{-15}$), indicating no systematic prediction bias. However, the confident-weighted models consistently

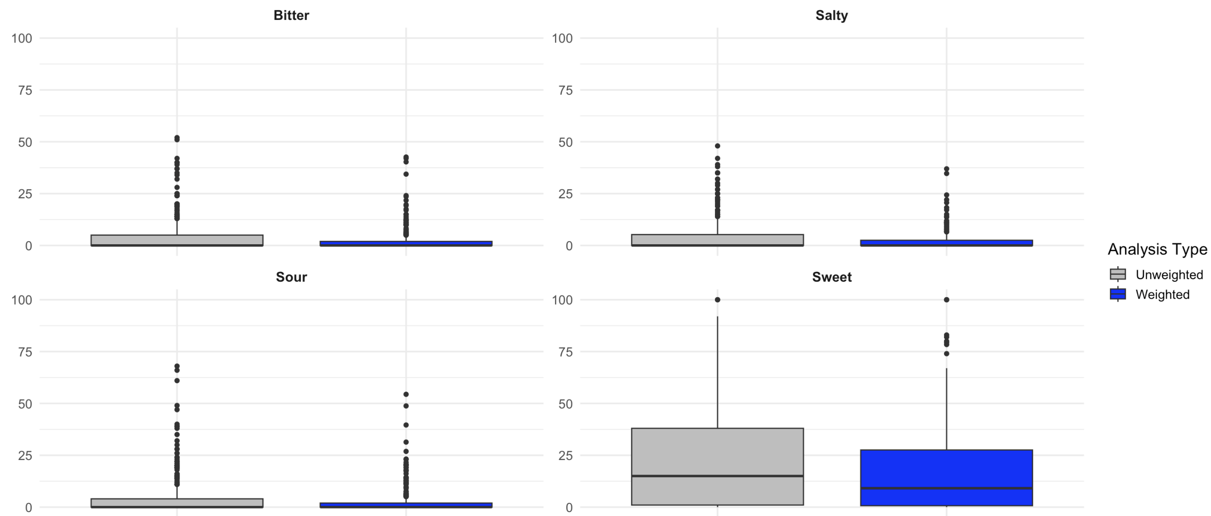

Figure 5: Comparison of Confidence-Weighted vs. Unweighted Scores Across Tastes.

showed lower standard deviations than unweighted models (bitter: SD = 8.31 vs 5.24; sweet: SD = 15.23 vs 12.68; salty: SD = 6.43 vs 3.98). This suggests incorporating confidence weights produces more precise predictions and better model fit.

5 Discussion

While broad visual and auditory stimuli showed no overall significance, our study revealed interesting patterns in taste perception. The sweet-promoting pink filter alone reduced bitterness perception [16], though its combination with sweet-promoting audio surprisingly increased it, supporting Spence's findings on non-visual dominance [26] in taste perception and also finding a non-additive effect between the two seemingly congruent stimuli. This unexpected outcome suggests that combining multiple congruent sensory modalities in immersive environments may not reinforce intended perceptions but instead produce counterintuitive cross-modal effects. A possible explanation relates to sensory expectation violation: when participants received strong congruent sensory cues predicting sweetness, the solution's relatively low sweetness intensity may have heightened their perception of its contrasting bitterness through a "negatively valenced expectation disconfirmation response" [25]. These insights are vital for designers creating multisensory experiences, warning against oversimplified assumptions about sensory modality combinations and highlighting the importance of testing sensory congruency in context.

Using confidence ratings as a covariate uncovered previously undocumented relationships, showing that higher confidence correlated with lower perceived bitterness, sourness, and saltiness, and eliminating several previously significant interactions by reducing noise. This relationship introduces a valuable consideration for future interactive media experiences: user confidence may affect not only the reliability of data but also the overall subjective experience especially when dealing with weak signals. Capturing a metacognitive dimension such as confidence as part of sensory evaluations can thus enhance the robustness of multisensory research outcomes, offering richer insights into user engagement and perceptual reliability. These findings also raise opportunities for designing interactive media that deliberately take user's signal uncertainty as a design element.

6 Limitations & Future Work

Our study employed subtle AR color filters rather than more immersive, spatially extended AR effects such as environmental ambient lighting, which might produce stronger or different perceptual outcomes. Furthermore, the modest sample size (N = 18) and the narrow demographic focus (primarily younger adults) limit generalizability of such a nuanced effect. Future research should explore these crossmodal effects further by employing stronger immersive cues, such as dynamic environmental AR lighting or more complex audio designs. Extending this work to broader demographics and investigating different taste profiles could confirm the robustness and generalizability of these findings. There is also value in further exploring confidence and signal uncertainty as a design parameter.

7 Conclusion

Our research shows that carefully synchronized AR audiovisual stimuli can unexpectedly influence flavor perception. By incorporating confidence measurements, we've gained deeper insights into these immersive sensory experiences and uncovered new links between confidence levels and taste perception. Our findings challenge traditional views about how audio and visual stimuli interact in virtual environments. This clear connection between confidence levels and taste perception opens new possibilities for designers to investigate signal uncertainty and multisensory integration in future applications.

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