Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

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Massively collaborative crowdsourced research on COVID19 and the chemical senses: Insights and outcomes

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ABSTRACT

In March 2020, the Global Consortium of Chemosensory Research (GCCR) was founded by chemosensory researchers to address emerging reports of unusual smell and taste dysfunction arising from the SARS-CoV-2 pandemic. Over the next year, the GCCR used a highly collaborative model, along with contemporary Open Science practices, to produce multiple high impact publications on chemosensation and COVID19. This invited manuscript describes the founding of the GCCR, the tools and approaches it used, and a summary of findings to date. These findings are contextualized within a summary of some of the broader insights about chemosensation (smell, taste, and chemesthesis) and COVID19 gained over the last 18 months, including potential mechanisms of loss. Also, it includes a detailed discussion of some current Open Science approaches and practices used by the GCCR to increase transparency, rigor, and reproducibility.

1. Introduction

On 9 January 2020, the World Health Organization (WHO) announced the existence of a cluster of unexplained pneumonia cases in Wuhan China attributed to a novel coronavirus, as laboratory tests had ruled out known respiratory pathogens such as SARS-CoV, MERS-CoV, influenza, avian influenza, and adenovirus (WHO., 2020). Twelve days later, on 21 January 2020, Chinese scientists confirmed human to human transmission, and the first case of a novel coronavirus infection in the United States was confirmed via Polymerase Chain Reaction (PCR) based testing (CDC, 2020). Over the next year and a half, the world would experience a pandemic of a scale not seen since the H1N1 avian flu of 1918 (e.g., (Beach, Clay, & Saavedra, 2020; Faust, Lin, & Del Rio, 2020)), as the SARS-CoV-2 virus swept around the globe, leaving hundreds of millions affected by COVID19.

In mid-March 2020, social media posts began suggesting COVID19 infections may associate with unusual symptoms not usually seen with prior coronavirus outbreaks like SARS in 2003 or MERS in 2012(Joseph, 2020; Rabin, 2020). For example, on 17 March 2020, actress Rachel Matthews reported a detailed timeline of symptoms on her Instagram story, including losing smell and taste for multiple days (Dicker, 2020), while on 18 March 2020, influencer and blogger Arielle Charnas reported diminished appetite and loss of smell and taste on her Instagram story (Minton, 2020). Similarly, on 22 March, basketball star Rudy Gobert tweeted "loss of smell and taste is definitely one of the symptoms, haven't been able to smell anything from the last 4 days. Anyone experiencing the same thing?" The next day, on 23 March, two British otolaryngologists published an open letter describing a spike in sudden unexplained anosmia in otherwise asymptomatic patients in the United Kingdom (Hopkins & Kumar, 2020). As this information spread across traditional news media (Joseph, 2020; Rabin, 2020; Stone, 2020), and professional email lists, sensory and consumer scientists, chemosensory biologists, and sensory psychologists found themselves immersed in research on the growing viral pandemic. Here we disseminate the

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experiences, insights, and outcomes of engaging in the novel model of consortium research; that is, massively collaborative crowdsourced science supported by Open Science practices.

2. Founding and organization of the Global Consortium of Chemosensory Research (GCCR)

On 24 March 2020, roughly 100 interested individuals, mostly researchers and clinicians, but also patient advocates, students, and others, met on a Zoom call to discuss how we might contribute our unique skills, knowledge and expertise to the then newly emerging pandemic, with an initial goal of gathering quantitative and systematic evidence that anecdotal patient reports of smell and taste loss and a growing number of google searches for 'taste loss' were in fact related to spreading COVID19 infections. Using a multichannel Slack workspace to organize, and daily Zoom calls for the leadership team, a draft survey on COVID19 symptoms, including chemosensory loss, was finalized, along with a broader vision for the Global Consortium of Chemosensory Research (GCCR). Although all authors here were and are active GCCR members, we caution that this paper does not reflect the perspective of all GCCR members. From the outset, the GCCR chose to leverage modern best practices in Open Science and reproducibility (discussed below), along with a mandate to be highly collaborative, inclusive of multiple disciplines, and truly global. By 31 March 2020, 472 members in dozens of countries had joined. The first GCCR survey in English was launched on 7 April 2020; additional languages were deployed as soon as they were translated and programmed in Compusense Cloud. By Spring 2021, the survey had been launched in 35 different languages, with responses from over 50,000 participants around the world (Fig. 1).

3. Summary of some initial findings from the GCCR

While all the GCCR papers to date have resulted in key insights on COVID19 and its effects on all three chemosesenses, the first GCCR paper (Parma et al., 2020) provided especially vital information. This analysis asked a simple question: "did self-assessment of taste, smell, and chemesthesis during illness differ from retrospective assessment of chemosensory function prior to illness?" This was determined by asking participants to rate their smell ability on a 0–100 visual analog scale (VAS) *during* their illness, as well as retrospectively rating their smell ability prior to their illness on the same scale – the difference between these two self-reported ratings was taken as a measure of lost function. Parallel questions were asked for taste and oral chemesthesis. Using data from ~4000 participants collected in 10 languages, Parma et al. found that a majority of COVID19 positive participants reported a significant drop in ability to smell, with a mean drop of almost 80 points relative to their ability to smell prior to their illness. This suggested anosmia was a characteristic symptom of COVID19 (Parma et al., 2020), confirming the anecdotal reports noted above. Taste and oral chemesthesis were also significantly blunted in individuals with COVID19, with mean decreases of ~70 and ~37 points, respectively (Parma et al., 2020). Notably, impairment of chemesthesis was typically accompanied by either taste and/or smell loss, although in other participants, taste and smell loss occurred when normal chemesthesis was preserved. Because the survey was based on self-report of function, rather than assessment with controlled stimuli, reports of taste loss may not actually reflect taste loss (which is very rare with other viral illnesses), but may instead reflect a common taste/smell confusion among the general public (and some clinicians; see (Boltong, Keast, & Aranda, 2011)). However, the survey also asked about alteration of specific taste qualities (i.e., salty, sweet, sour, bitter, and umami/savory) with a check-all-that-apply (CATA) question, and significant deficits were also observed. Changes in specific taste qualities were consistently reported by ~37–45% of participants for sweet, sour, salty and bitter; reports were slightly lower for umami/savory (~25%), but this may reflect lack of familiarity with the concept of umami and/or translation difficulty, rather than any specific robustness of this quality against loss. As noted by Green (Green, 2020), a high endorsement rate of altered function was reported for salty (~45%), a quality that is not commonly attributed to odors (in contrast to sweetness or sourness). Collectively, this suggested that reported taste loss is not merely an artifact arising from a taste/smell confusion, an observation that was subsequently confirmed by multiple studies that assess taste function using various stimuli, rather than relying on self-report. While the quality of these studies is highly variable, on balance, they support the view that some of taste loss reported by those with COVID19 reflects a true disruption of the taste system.

Specifically, over a dozen studies using various stimuli (e.g., strips, homemade solutions) indicate taste loss occurs with COVID19. Although the measures of taste in these studies were often ad hoc (given the urgency of the pandemic), it is still evident that true taste loss (and not merely a semantic taste-flavor confusion) is a characteristic feature of COVID19. Still, validated methods, like those developed as part of the NIH Toolbox (Coldwell et al., 2013) or used for the National Health and Nutrition Examination Survey (NHANES) Chemosensory Exam (Rawal,

Fig. 1. Screenshot of the website landing page for the initial GCCR survey, showing the 35 different languages the survey was translated into by volunteer members of the GCCR. Deployed languages include Arabic, Bengali, Chinese (Traditional and Simplified), Czech, Danish, Dutch, English, Farsi, Finnish, French, German, Greek, Gujarati, Hebrew, Hindi, Italian, Japanese, Kannada, Korean, Malayalam, Marathi, Norwegian, Polish, Portuguese, Punjabi, Russian, Slovenian, Spanish, Swahili, Swedish, Tamil, Turkish, Urdu, and Yoruba.

Hoffman, Honda, Huedo-Medina, & Duffy, 2015), have not been employed to date. This is wholly understandable given the needs of clinicians and researchers to collect data as quickly as possible during early days of the pandemic, often when few resources were available. Moving forward, a prime goal of chemosensory scientists should be to apply rigorous test methods to study COVID19 taste loss, especially in those with post-acute sequelae of COVID19 (PASC). Still, the primary message here is that the preponderance of evidence, even with imperfect measures, indicates taste loss is a verifiable symptom of COVID19.

COVID19 associated anosmia also appears to be distinct from the transient anosmia experienced with respiratory illnesses such as the common cold. With the common cold, smell loss typically co-occurs with a lack of airflow, as a consequence of nasal congestion – that is, volatile odor active molecules cannot reach receptors on the olfactory epithelium at the top of the nasal cavity, as mucus and/or swelling block the nasal passages. In the first GCCR survey, participants were also asked to report apparent congestion, via a rating of perceived nasal blockage, where a higher score indicated more blockage. The mean pre-COVID19 nasal blockage was almost zero, whereas the mean reported blockage during COVID19 was ~22 points higher, suggesting some participants experienced some blockage. However, comparison of the distribution of nasal obstruction ratings before and after COVID19 indicated that many participants had little to no blockage during COVID19 (Parma et al., 2020), and more critically, principal components analysis (PCA) indicated ratings of blockage were independent to ratings of smell and taste loss. This implies acute change in olfactory function for COVID19 positive individuals was not attributable to simple conductive losses. Although mechanisms for changes in taste, smell, and chemesthesis remain to be elucidated, these early data suggested disruption of chemosensory function was a hallmark indicator of COVID19 infection.

After reporting that smell and taste loss were cardinal symptoms of COVID19, the GCCR analyzed a second data tranche from the same survey that included ~15,000 responses in 23 languages collected between 7 April 2020 and 2 July 2020. Besides fully replicating findings from the first study among non-overlapping participants (n = 4825), the new report compared responses in COVID19 positive and negative individuals, all with recent respiratory symptoms (Gerkin et al., 2021). The primary goal was to try to predict COVID19 diagnosis from all reported symptoms, regardless of whether they were chemosensory in nature.

Using both categorical and binary responses, chemosensory symptoms were found to be more strongly associated with COVID19 diagnosis than fever, cough, or any other non-chemosensory symptoms, including difficulty breathing. In fact, self-reported smell ability during illness was the single most predictive factor for COVID19, followed by self-reported taste ability during illness. These results highlight the importance of chemosensory changes during COVID19 infection. As anticipated, smell, taste, and chemesthesis were reported to be greatly reduced for COVID19 positive individuals compared to COVID19 negative individuals. Also, this analysis confirmed that nasal obstruction was not predictive of COVID19. Overall, non-chemosensory symptoms were less specific symptoms than smell loss, allowing those with COVID19 to be distinguished from other respiratory illnesses. In summary, smell loss was quantified as the single best predictor of COVID19, and this specificity was used to create a novel tool, the ODoR-19 (Olfactory Determination Rating Scale in COVID19) scale, for use in rapid screening (Gerkin et al., 2021).

4. Rapid olfactory screening for COVID19

Access to PCR-based tests and antigen-based tests were and continue to be limited in some regions during the COVID19 pandemic. The ODoR-19 is a free, noninvasive tool, which provides immediate identification of a possible infection. Participants are asked to rate their smell ability on an 11-point scale (from 0 to 10) anchored with no sense of smell to excellent sense of smell. Compared to lab tests, which can take up to several days to return results, this tool, while admittedly crude, is immediate. Preliminary modeling suggests that a response of 3 indicates borderline risk of COVID19 positive infection, while a response of 2 or lower is highly predictive of being of COVID19 positive in the absence of any other potential cause of smell loss. This tool may be useful for telemedicine, in person assessment, or for in worksite screening for companies whose employees are returning to offices and/or manufacturing plants, as it is easy to use, non-invasive and inexpensive, with the caveat that subsequent formal clinical validation is still needed (Gerkin et al., 2021). Additionally, many individuals may be unaware of smell loss until specifically asked to perform olfactory tasks, so otherwise asymptomatic individuals are also encouraged to use this tool.

Early in the pandemic, fever was highlighted as a cardinal symptom of COVID19 and was screened for using contactless infrared thermometers. However, fever is only present in ~18–26% of COVID19 cases and is not specific to COVID19, see (Larremore, Toomre, & Parker, 2021). Conversely, olfactory dysfunction may serve as a more reliable predictor of COVID19 (Gerkin et al., 2021; Larremore et al., 2021). Meta-analyses across multiple studies indicate that up to ~75% of COVID19 positive individuals experience loss of smell and taste (Hannum et al., 2020), although other reports suggest only ~15% of people experience anosmia as their first symptom (Klein et al., 2021). Still, as suggested by Parma and colleagues (Parma et al., 2020), sudden smell and taste loss may be early and specific predictors of the virus. Thus, assessing olfactory function may be more effective than assessing fever as an early COVID19 screening method.

5. Brief summary of presumed mechanisms underlying COVID19-associated chemosensory dysfunction

5.1. Smell

Loss of smell, either anosmia (full loss) or hyposmia (partial loss), is associated with many viral upper respiratory infections, such as influenzas or rhinoviruses. But COVID19 induced anosmia (Parma et al., 2020) as well as other rarer forms of post-viral illness (Deems et al., 1991) can persist long after any blockage has been resolved. SARS-CoV-2 infects cells via interactions between the spike protein of the virus and the ACE2 protein (angiotensin converting enzyme II) expressed on the surface of target cells. After cleavage of the spike protein by TMPRSS2 (transmembrane serine protease 2), the receptor binding domain of the virus' spike protein binds to the peptidase domain of ACE2, as ACE2 acts as the main SARS-CoV-2 receptor (Butowt and von Bartheld, 2020). This process occurs throughout the airway, including the nasal cavity and lungs. At the top of the nasal cavity, the olfactory epithelium contains mature olfactory sensory neurons (OSNs) that are responsible for odor detection, as the OSNs express specialized olfactory receptors (ORs) that bind odor active molecules (odorants). Notably, OSNs do not themselves express ACE2 or TMPRSS2 – instead, infection of non-neuronal supporting cells, such as sustentacular cells, may be responsible for disruption of normal smell function. OSN supporting cells, including sustentacular cells, horizonal basal cells, and Bowman's gland cells, have been shown to express ACE2 and TMPRSS2, indicating that support cells may be targeted by SARS-CoV-2 (Brann et al., 2020).

At least three biologically plausible mechanisms have been proposed to explain how COVID19 associated anosmia occurs, and more than one of these may be involved, given the diverse symptoms and differential timing of anosmia occurrence seen across patients. One potential mechanism may originate from infection of support cells via ACE2 and the subsequent inflammation that occurs. Infection of support cells allows for SARS-CoV-2 to invade the olfactory mucosa, causing the local increase of inflammatory cytokines and apoptosis, which might prevent the virus from propagating to the central nervous system (Yazdanpanah, Saghazadeh, & Rezaei, 2020). This inflammation potentially blocks the olfactory clefts and affects OSN function, which may decrease odor perception (Eliezer et al., 2020). Further, attachment of SARS-CoV-2 to

ACE2, triggering inflammatory cytokines may lower expression of odorant receptor genes by OSNs, which can lead to changes in odor perception as well (Cooper et al., 2020; Zazhytska, Kodra, Hoagland, D. A., Fullard, J. F., Shayya, & Omer, 2021). Support cells are responsible for local water and ion balance, so damage here may indirectly diminish OSN signaling to the brain and affect firing rates, affecting odor function (Brann et al., 2020). The recovery of sustentacular cells damaged by SARS-CoV-2 occurs faster than regeneration of OSNs, which must mature and grow new axons through the cribriform plate, potentially explaining why some individuals experience rapid smell recovery and why OSNs are unlikely to be the direct target of SARS-CoV-2 (Butowt & von Bartheld, 2020).

A second general mechanism of loss involving regulating gene expression in the OSNs has been recently proposed. Though a specific mechanism that is still unknown, this infection causes OSNs to shut down gene expression for proteins necessary for signal transduction including olfactory receptors (Zazhytska et al., 2021). There are two types of human olfactory receptors, called Class 1 and Class 2, which are distinguished by their ability to bind hydrophilic versus hydrophobic ligands, respectively (Freitag, Ludwig, Andreini, Rossler, & Breer, 1998). It appears Class 1 receptors are less downregulated with COVID19 than are Class 2 receptors. These observations suggest that olfactory tests might potentially be devised to measure differential smell loss using ligands for Class 1 and Class 2 receptors to gauge whether smell loss is complete for all ligands or only those that bind to Class 2 receptors. It may be that the perception of hydrophilic ligands, like carboxylic acids (e.g., sweaty), would remain in mild cases of COVID19, while hydrophobic odorants, like musk, may be completely lost. This may also explain why recovery tends to start with bad odors – i.e., the re-emergence of full Class 1 receptor function. Evaluating more odorants can help us better understand whether all ligands are affected equally or whether certain odorants, e.g., food flavors, are more affected than others. Hints that some odorants are better than others at distinguishing people with and without COVID19 come from smell tests done at home using a range of uncontrolled odorants (Snitz, Honigstein, Weissgross, Ravia, Mishor, & Perl, 2021).

A third mechanism to explain olfactory loss with COVID19 depends on the enzymes in the nose that metabolize odorants and drugs. Data from a study that included a sample of 69,841 people all with COVID19 show that specific genetic variants in a small cluster of biotransformation enzymes were more common in people reporting smell loss than in those who did not report smell loss (Shelton, J. F., Shastri, A. J., Asli-bekyan, & Auton, 2021). Studies of these biotransformation enzymes in rodents suggest they metabolize drugs and toxins found in the olfactory epithelium and are present in supporting (sustentacular) cells (Heydel et al., 2001). In humans, one of these enzymes is expressed in sustentacular cells in the nasal epithelium, and a gain of function of this enzyme decreases olfactory responses by degrading specific odorants (Neiers, Jarriault, Menetrier, Briand, & Heydel, 2021). Research on COVID19 and biotransformational enzymes is in the early stages but if these enzymes are important for smell loss, the results suggest a biological mechanism that could be targeted for therapeutic potential.

These three mechanisms may not be mutually exclusive, with each potentially playing a part in the sudden loss of smell that comes with COVID19. A recent comparison of brain scans of people before and after being ill with COVID19 suggest that gray matter in brain areas associated with olfaction and taste are reduced (Douaud, Lee, Alfaro-Almagro, Arthofer, Wang, & Lange, 2021), although whether this is a primary cause or a result of lack of input from the periphery is not known. Finally, early media reports from England and South Africa suggested some SARS-Cov-2 variants (Delta, and Omicron, respectively) may cause less smell loss than other variants. If confirmed, this would certainly reduce the utility of sudden smell loss as a screening tool, while also providing a natural experiment to study the mechanism(s) of loss. However, to date, no convincing evidence on differential smell loss with the Delta and Omicron variants has been published.

5.2. Taste

Gustatory dysfunction, manifesting as either ageusia (taste loss) or hypogeusia (reduced taste function), has been highlighted as a strong predictor of being infected with COVID19. Unlike the olfactory sensory neurons, which do not express the ACE2 receptor, at least some taste receptor cells do (Doyle, M. E., Appleton, Liu, Q.-R., Yao, Mazucanti, C. H., & Egan, 2021) and thus, taste loss during SARS-CoV-2 infection may be a direct effect of the virus on taste receptor cells. These cells found in the taste buds of the tongue are of three types that differ in the receptors they contain and the taste qualities they respond to, e.g., bitter, sour, sweet, salty or umami. Studies of a human taste bud indicate that ACE2 is expressed in at least some taste receptor cells, which may have an effect on taste by disrupting the cells directly and also by impairing the ability of the stem cells to repopulate the taste bud (Doyle et al., 2021). Like olfactory receptor neurons, taste receptor cells are continuously replenished in the healthy tongue which leaves taste vulnerable to any type of assault that reduces cell turnover (Barlow, 2015). There is controversy about whether different types of taste cells are differentially affected by SARS-CoV-2 infection and while some studies show quality-specific differences (Adamczyk, Herman, Frączek, Piec, Szykuła-Piec, & Zaczyński, 2020; Altin, Cingi, Uzun, & Bal, 2020; Bidkar et al., 2020; Niklassen et al., 2021; Salcan et al., 2021; Singer-Cornelius, Cornelius, Oberle, Metternich, & Brockmeier, 2021), others do not (Hintschich et al., 2020; Le Bon et al., 2021; Mazzatenta et al., 2020; Petrocelli et al., 2020; Vaira, Deiana, et al., 2020; Vaira, Hopkins, Petrocelli, Lechien, Chiesa-Estomba, et al., 2020; Vaira, Hopkins, Petrocelli, Lechien, Soma, et al., 2020; Vaira, Hopkins, Salzano, et al., 2020; Vaira, Lechien, et al., 2020; Vaira, Salzano, et al., 2020). Thus, it is open question whether sweet or bitter might be more or less affected than sour or salty or umami.

5.3. Chemesthesis

Chemesthesis is the ability to sense chemical stimuli that activate somatosensory receptors to create sensations of temperature, pain, or touch (Green, 2016). Examples include cooling from mint, heat/burn from chili peppers, and buzzing from Sichuan buttons/peppers (McDonald, Bolliet, & Hayes, 2016). These touch sensations are carried by multiple cranial nerves. As with taste and smell, anecdotal reports and surveys suggest chemesthesis may also affected by COVID19 infection (Parma et al., 2020; Hayes & Parma, 2020), although this needs to be confirmed via direct assessment using controlled stimuli and psychophysical testing. Still, sufficiently detailed patient reports of eating capsaicin or menthol containing products and experiencing no burn or cooling suggest such loss is real, at least in some patients for some period of time. Many, but not all, chemesthetic sensations occur via transient receptor protein (TRP) channels expressed on trigeminal axons that project from the trigeminal ganglion; critically, these fibers innervate both the nasal respiratory epithelium and non-taste epithelium of the tongue (Cooper et al., 2020). Different TRP channels are tuned to different stimuli. For example, TRPV1 responses to capsaicin or heat, while TRPM8 responses to menthol or other cooling compounds (Jordt, McKemy, & Julius, 2003). Anatomically and physiologically, chemesthesis is mechanistically distinct from gustation and olfaction, but as with taste and smell, chemesthesis is often conflated with other sensory modalities by naïve participants.

Mechanisms by which chemesthesis may be affected by COVID19 infection remain unclear. Similar to taste, it is thought that impairment of chemesthesis may result from infection of cells in the tongue and subsequent inflammatory cytokine release causes inflammation or damage. Another potential mechanism may involve solitary chemosensory cells, which detect several chemesthetic stimuli, subsequently initiating a neurogenic inflammatory response (Cooper et al., 2020). However, it has not been confirmed if solitary chemosensory cells express ACE2. Others have suggested that silencing of nerve endings via

initial viral infection may be a cause of impairment (Shiers et al., 2020). Further research is needed to elucidate these mechanisms.

5.4. COVID may affect multiple systems simultaneously.

The combination of COVID19 sensory losses is likely to magnify the consequences and the effects together could be much greater than separately, but we have had almost no opportunity to study this synergy prior to COVID19 because loss of both taste and smell is rare. In a survey of 1176 people attending a taste and smell clinic prior to COVID19, only 2 had severe loss of both taste and smell when tested in the clinical using standard protocols (Pribitkin, Rosenthal, & Cowart, 2003). While the consequences of losing both taste and smell are difficult to predict, it may be that all the problems that arise with anosmia are exacerbated when coupled with taste loss. As one example, to compensate for lost flavor, people with anosmia add more sugar and salt to their food (Ferris et al., 1985) but with a concomitant reduction in taste (in their ability to perceive sweet and salt), there may be further overcompensation, driving sugar and salt intake even higher. Losing all three senses, taste, smell and chemesthesis may also create new problems not encouraged with the single loss of these senses that are both difficult to predict and deserving of further study. These gaps in knowledge create new opportunities for researchers working to understand food perceptions or preferences.

6. Some lessons learned from GCCR –Taste and flavor in different languages, or "What's in a Name?"

The task of translating the original GCCR survey from English to many other languages was an eye-opening experience, specifically given the widespread, global confusion between "taste" and "flavor". We frequently observed how in English, "taste" and "flavor" are colloquially used as if they were synonyms, whereas chemosensory professionals in the field are classically trained to firmly insist (and even demonstrate) how they are not synonymous. The well-known Jelly Bean Test provides a fun and accessible demonstration to illustrate how taste is only a small portion of overall flavor, and how most flavor actually comes from the contribution of odorants traveling retronasally. Based on foundational work from Rozin (Rozin, 1982), we traditionally describe how a major issue in English is the lack of a verb for "flavor" obliges use of the verb "tasting" to describe the *action* of perceiving the flavor of a food, potentially giving rise to this common confusion.

The issue of explaining and translating these concepts becomes a real challenge for languages that use the same word for both taste and flavor – e.g., German (geschmak), Dutch (smaak), and Russian (ukus) to name a few. Remarkably however, the confusion persists even in Romance languages that provide different verbs for "taste" and "flavor". That is, English may *not* be uniquely limited in this regard. As part of the GCCR translation efforts, it was interesting to note the disagreement within speakers of the same language, and the hotly debated arguments on which word was the better term to translate "taste". It is fascinating that for both English and the Romance languages, the etymology of the word taste has its origin in Latin. Yet, in English, taste comes from taxare ("to touch, feel"), but Romance languages derive it from gustum (Spanish: gusto; French: goût; Italian: gusto; Portuguese: gosto), which relates to "gustation". Aristotle not only confused taste with flavor (Bartoshuk, Sims, Colquhoun, & Snyder, 2019), but he also thought of taste as a variant of touch: it seems we are still all confused. Clearly, more cross-cultural work is needed by sensory linguists to help resolve these issues. Of importance for those working in Sensory and Consumer Science, our experience underscores how the confusion between the senses appears to be inherent to most people, regardless of the language they speak, or the professional knowledge they may have. We have learned that taste versus smell versus flavor must be clearly defined in surveys and if this is omitted, it should be assumed that any survey items that ask about "taste" will refer to taste *and* retronasal olfaction *and* chemesthesis *and* other somatosensory aspects of food. If consumer tests and laboratory task need to separate these perceptions, conducting sensory tests with and without nose clips may be the most rigorous approach. Descriptive panelists are often trained to distinguish between these percepts (e.g., sweet aromatics versus sweet taste); however, the literature on multisensory integration of gustatory and olfactory signals suggests that this may be hard to do (Spence, Smith, & Auvray, 2015), given that odors can enhance tastes, and tastes can enhance odors, even if matching paradigms are used instead of rating scales (cf. Wang, Hayes, Ziegler, Roberts, & Hopfer, 2018 and Wang, Bakke, Hayes, & Hopfer, 2019).

7. Open science principles are adopted by the GCCR

From the outset, the GCCR chose to leverage modern best practices in Open Science and reproducibility, in response to the mounting criticism of a lack of scientific and methodological rigor in behavioral sciences. These criticisms impact most parts of the scientific process. A few of the most important criticisms that apply to research studies (in rough chronological order from design through publication) are detailed in Table 2.

Under the umbrella term of "Open Science", various initiatives have been developed to deal with different aspects of the replication crisis, including pre-registration, registered reports, public data, and analysis scripts, increased accessibility of Bayesian and other statistical approaches appropriate for confirming a null effect, and consortium studies. This is not an exhaustive list and there are many new and older initiatives that we do not include here.

Open Science practices are gaining a strong following in the life science. Consumer and sensory scientists may not be aware of these practices, perhaps in part because of the more descriptive nature of studies (rather than hypothesis driven) and also perhaps because restriction that may be imposed by funding sources (industry contracts) or local laws regarding participant privacy. However, there are advantages to using these practices beyond preventing publication biases. Below, we will highlight some that will be of most interest to the readers of this journal that were important for work completed by the GCCR.

7.1. Pre-registration

All GCCR research projects were done with pre-registration. A pre-registration is a public, time-stamped, uneditable document of a study's hypotheses, sample size, and analysis plan. Pre-registrations are flexible, they can be done *after* data collection for example, or for exploratory analyses without a hypothesis. The goal is to provide a transparent account of the original plan, that can be cited in a manuscript submitted for publication, and easily inspected by reviewers, editors and readers. The added transparency of posting the original plan, along with any deviations from that plan, increase the readers' confidence that the author has not HARKed or otherwise revised their hypotheses after getting their results. Tutorials and templates for pre-registration can be found at locations like osf.io and aspredicted.org.

7.2. Public data and analysis scripts

All GCCR publications provide de-identified data to the public and the associated data analysis scripts are available to the public. The ultimate Open Science best practice is providing a "research compendium" with a published manuscript. This is a set of documents and files that allows a reader to completely reproduce the results in the paper from beginning to end, including all data cleaning, processing, and statistics. The GCCR has done so with our main papers to date (Gerkin et al., 2021; Parma et al., 2020) despite the additional effort it requires (see https://github.com/GCCR/gccr002 and https://osf.io/5je93/); we also plan to do so for future work.

Table 1
Studies showing taste loss assessed using specified stimuli.

Lead Author	n	% with dysfunction	Stimuli	Method/Task	Reference
Niklassen	61	26	Sprays/Strips containing sucrose, citric acid, salt, or quinine hydrochloride	Identification	(Niklassen et al., 2021)
Singer-Cornelius	39	26	Strips containing sucrose, citric acid, salt, or quinine hydrochloride	Identification	(Singer-Cornelius et al., 2021)
Hintschich	41	20[a]	Strips containing sucrose, citric acid, salt, or quinine hydrochloride	Identification	(Hintschich et al., 2020)
Altin	81	27	Solutions made with sucrose, salt, dilute vinegar, coffee, applied to tongue with paper strips	Latency to identification	(Altin et al., 2020)
Salcan	94	35	Solutions made with sucrose, salt, dilute vinegar, coffee, applied to tongue with paper strips	Latency to identification	(Salcan et al., 2021)
Petrocelli	300	61	Self-made solutions with sucrose, salt, lemon Juice, decaf coffee	0–10 scale (ageusia to normal perception)	(Petrocelli et al., 2020)
Vaira	33	51	Self-made solutions with sucrose, salt, lemon Juice, decaf coffee	0–10 scale (ageusia to normal perception)	(Vaira, Salzano, et al., 2020)
Vaira	345	45	Self-made solutions with sucrose, salt, lemon Juice, decaf coffee	0–10 scale (ageusia to normal perception)	(Vaira, Hopkins, Salzano, et al., 2020)
Vaira	106	72	Self-made solutions made with sucrose, salt, lemon Juice, decaf coffee	0–10 scale (ageusia to normal perception)	(Vaira, Hopkins, Petrocelli, Lechien, Soma, et al., 2020)
Vaira	138	68	Self-made solutions with sucrose, salt, lemon Juice, decaf coffee	0–10 scale (ageusia to normal perception)	(Vaira, Hopkins, Petrocelli, Lechien, Chiesa-Estomba, et al., 2020)
Vaira	72	49	Solutions made with sucrose, salt, lemon Juice, decaf coffee	0–10 scale (ageusia to normal perception)	(Vaira, Deiana, et al., 2020)
Le Bon	72	7[b]	Strips containing sucrose, citric acid, salt, or quinine hydrochloride	Identification	(Le Bon et al., 2021)
Bidkar	76	84[c]	Solutions made with glucose and salt	Identification	(Bidkar et al., 2020)

[a] Although 20% of the patient group (8 of 41) scored as having hypogeusia, 10% of the COVID19 negative control group had also scores that were indicative of hypogeusia.
[b] testing was conducted ~5 weeks after infection, suggesting many patients may have recovered taste function, as retrospective reports of taste loss in the same patients was 89%;
[c] while the rate of taste dysfunction rate was significantly higher in COVID19 patients, 64% of the COVID19 negative patients also showed dysfunction in the test used, suggesting the task may have been excessively difficult.

Table 2
Summary of factors thought to contribute to the replication crisis.

	Description criticism	Abbreviation/short name
1	Lack of theory in formulating a research question	–
2	Hypothesizing (only) After the Results are Known, or changing the hypothesis post-hoc	HARKing
3	Underpowered study design due to small sample sizes	–
4	Running unreported iterative statistical tests on the same data until significant results are obtained	P-hacking
5	The bias that authors, peer-reviewers and editors of scientific journals have against null results or non-replications and in favor of significant results	Publication bias

7.3. Benefits of open science practices

The goal of Open Science is to improve science at large and this was our experience during the early pandemic and the formation of the GCCR. Adopting these practices required researchers to put more thought into our study design and methodological rigor, which we hope improved the quality of our studies. From a purely utilitarian perspective, there is also evidence that papers with pre-prints and open data receive more citations. Last, from our experience, participating in a consortium can lead to fruitful collaborations and consortium studies can be more fun to conduct because failures and successes are shared.

8. Conclusions

American President Harry S. Truman famously opined that "It is amazing what you can accomplish if you do not care who gets the credit." In Spring of 2020, scores of chemosensory scientists came together using collaborative tools like Zoom and Slack to see if we could apply our specialized knowledge and skills to a newly emerging global pandemic. We learned that the abrupt loss of taste and smell are cardinal features of COVID19 among people worldwide (Gerkin et al., 2021; Parma et al., 2020) and now sensory tests are a well-accepted tool for surveillance of new infections (e.g., (Pierron et al., 2020)). We were also inspired to look to the future and our collective vision includes the evaluation of taste and smell as a routine part of medical care.

Ultimately, loss of taste and smell can have lasting effects on food perception, eating habits, and the way people communicate. Chemosensory dysfunction can have severe negative consequences on quality of life as it can result in increase in risk of injury (e.g. inhalation of smoke or other noxious chemicals, eating spoiled food), fear of hazardous events, malnutrition and/or difficulty cooking, decreased appetite and displeasure of eating foods you once did, challenges with social isolation, social relationships, and personal hygiene, and general decreased quality of life. Thus, we hope the GCCR can serve as a model for Sensory and Consumer Scientists who are interested in applying collaborative open science practices to their work to further investigate the effects of COVID19 along with other chemosensory research interests.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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