Chemoreception Scientists Gather under the Florida Sun: The 31st Annual Association for Chemoreception Sciences Meeting

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The 31st Annual Association for Chemoreception Sciences (AChemS) met in Sarasota, Florida April 22–26, 2009, attracting approximately 600 registrants and nearly 400 abstracts. In addition to poster and platform presentations, the program offered symposia, special lectures, and various National Institutes of Health (NIH)-sponsored workshops, including one on computational approaches to olfaction.

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The Association for Chemoreception Sciences (AChemS) conference offered an exciting mix of both basic and applied research in the chemical senses, which includes central and peripheral processing of gustatory, olfactory, pheromonal, and common chemical stimuli, such as irritants. Levels of analysis ranged from molecular biology to ecology, and attendees included basic and clinical research scientists, scientists from flavors and fragrance industries, and of course, students. Many new and often surprising findings were reported. The following gives a taste (or whiff—depending on which chemosensory researcher you ask!) of some of the new work reported in the invited symposia. In some cases, citations of recent, related published work are included in addition to the symposia content to enable the reader to explore topics in greater depth. All of the meeting abstracts will be published in a forthcoming edition of the journal *Chemical Senses*. In addition, podcast interviews with some recent award-winning chemosensory scientists can be found on the AChemS website (http://www.achems.org/).

Making Sense of Fat Taste

The symposium "Making sense of fat taste," organized by Timothy A. Gilbertson (Utah State University), was a wonderful example of multidisciplinary and translational approaches to chemical senses questions. The epidemic of obesity has been closely linked with the increase in dietary fat intake commonly associated with Western diets. In order to gain a more complete understanding of the sensory cues involved in the recognition of dietary fat, a number of laboratories over the past decade have begun to

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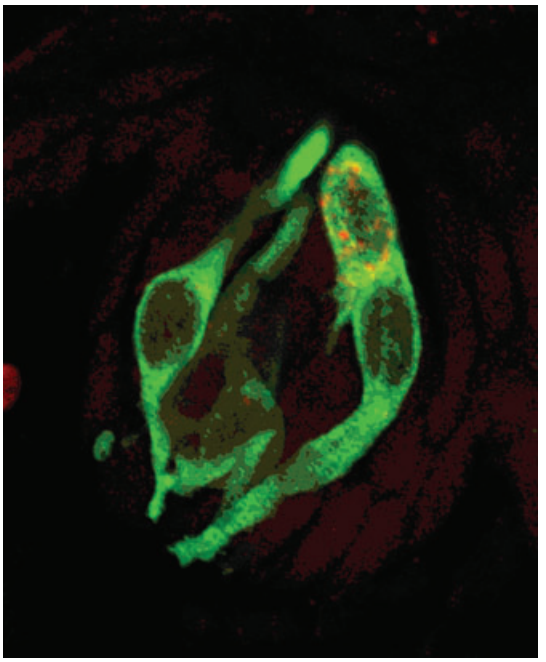

Figure 1. Dual labeling of a palatal taste bud showing *in situ* hybridization (red) for T1R1 and immunocytochemical localization for gustducin (green). Figure supplied by Tom Finger (Adapted from Stone, L.M., J. Barrows, T.E. Finger & S.C. Kinnamon. 2007. Expression of T1Rs and gustducin in palatal taste buds of mice. *Chem Senses* Mar; **32** (3): 255–256).

challenge the longstanding notion that pure fat was tasteless and that its only salient cue was its texture. This symposium, focused on research on genes and behavior in both rodents and humans, provided support for the emerging idea that fat, specifically free fatty acid, can activate the gustatory system, a conclusion that is clearly consistent with there being a "taste of fat" in addition to the classic tastes of sweet, sour, salty, bitter, and umami. Shigenobu Matsumura (Kyoto University) discussed the evidence surrounding the identification, characterization, and functional role of identified fatty acid cell surface receptors including the fatty acid transport protein, CD36, and the long chain fatty acid–activated G protein-coupled receptor (GPCR), GPR120.[1] Commonalities among the fatty acid transduction pathways in several chemosensory cells required for taste, texture, and post-ingestive responses to dietary fat (i.e., taste cells, trigeminal neurons, and enteroendocrine cells, respectively) were discussed by Tian Yu (Utah State University). She presented molecular and cellular evidence in support of a model for a single transduction pathway for fatty acid involving CD36, fatty acid–activated GPCRs, transient receptor potential (TRP)-like channels, and fatty acid–sensitive delayed rectifying K^+ channels. Behavioral data supporting the idea that fatty acids can be recognized by the gustatory system were reviewed by David Pittman (Wofford College) and Richard Mattes (Purdue University). Pittman discussed his own research using a conditioned taste aversion paradigm and short-term taste assays, which conclusively demonstrates that rats can recognize fatty acids. Further, he showed that the gustatory system of obesity-prone rats is more sensitive to fatty acids than the gustatory system of obesity-resistant rats,[2] tying together the notion of a role for fat perception in dietary fat intake. Importantly, Mattes provided compelling data consistent with a human capacity to recognize and respond to oral free fatty acid exposure.[3] These human studies reinforced the idea that fatty acids are the proximate stimulus (i.e., they directly interact with taste cell surface receptors) for fat taste and that understanding the sensory cues for fat will likely play an important role in understanding the processes that could eventually lead to the control of fat intake, and, ultimately, help stem the epidemic of obesity.

Presidential Symposium

The AChemS Presidential Symposium, organized by Peter Brunjes (University of Virginia), examined some of the complexities that have been uncovered in attempts to understand how the mammalian olfactory system integrates information about odors. The session began with an overview by Michael Shipley (University of Maryland School of Medicine) on signal processing at the first synaptic step[4]: the glomerulus. Using work from both his

Figure 2. Carla Shatz (Stanford University) delivering the opening keynote talk "Tuning up circuits: Brain waves, immune genes and synapse plasticity" sponsored by the Givaudan Corporation.

and other labs, he demonstrated that intra-, inter-, and multi-glomerular circuits are conditioned by inputs from higher olfactory areas, as well as by cholinergic and serotonergic systems, to temporally sharpen relay neuron firing and to cope with dynamic changes in odor concentration.

Tom Cleland and Christiane Linster (Cornell University) began their presentation by demonstrating that the "raw" input provided by sensory neurons in the nose demands considerable processing before meaningful information can be extracted, and therefore the need for higher-order processing.[5] They also showed how computational modeling methods can be used to understand the organization of olfactory pathways and as tools to compare and contrast processing strategies with other sensory modalities. Leslie Kay (University of Chicago) approached olfactory function from a neural population point of view.[6] Recording oscillating local field potentials in behaving animals, she showed that the kind of behavioral task used by an animal to identify an odor influences the type of oscillatory mode, the involvement of central brain areas, and the difficulty of the discrimination itself. The final two speakers focused on processing sensory input in "higher" olfactory areas. Kurt Illig (University of Virginia) described the organization and connectivity of the anterior olfactory nucleus (AON), a region located between the olfactory bulb and piriform cortex that has received relatively little attention.[7] He demonstrated that, through ipsilateral and contralateral projections, the AON is involved in processing sensory input at nearly every point in the olfactory pathway. The final speaker, Joel Price (Washington University at St. Louis), highlighted some of his landmark work on the organization, development, and plasticity of the olfactory system, utilizing it to place the olfactory system into the context of the rest of the mammalian brain; during his career, Price, working with a number of students, produced some of the most careful and thoughtful studies in this area (e.g., Ref. 8).

GABA in the Developing Olfactory System

The symposium "GABA in the developing olfactory system: From generation to differentiation," organized by Harriet Baker (Weill Cornell Medical College) explored significant and diverse roles for the amino acid neurotransmitter, gamma amino butyric acid

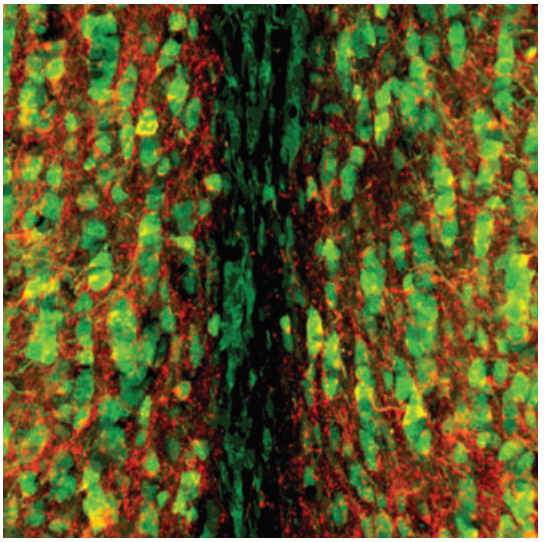

Figure 3. Neural progenitors in the center of the olfactory bulb exhibit promoter activity for the GABA synthetic enzyme, glutamic acid decarboxylase 67kDa (green). However, progenitors in the main migratory pathway do not yet express the protein itself (red). (Image provided by Adam Puche, University of Maryland.)

(GABA), during central nervous system (CNS) development and adult neurogenesis. The concept that GABA functions as a trophic factor, originally posited more than 20 years ago, has particular significance given the functional importance for adult neurogenesis in both the hippocampus and olfactory bulb. The five symposium speakers addressed a wide range of the non-neurotransmitter functions performed by GABA, including activity as a trophic factor, guidance cue, and differentiation factor, during the generation, migration, and differentiation of olfactory bulb interneurons.

Adam Puche (University of Maryland) showed that GABA provided guidance cues to GABA-expressing progenitors that followed a ventral route to populate the islands of Cajella. He also showed that, in contrast to the rostral migratory stream (RMS), GABA increased the rate of these ventrally migrating progenitors.

Angelique Bordey (Yale University School of Medicine) reported recent studies exploring the molecular mechanisms underlying the actions of GABA on migrating progenitors in the RMS.[9] These studies indicated that GABA released from neuroblasts depolarized neural stem cells (NSCs). In turn, these NSCs released glutamate that activated neuroblast kainate and *N*-methyl-D-aspartic acid (NMDA) receptors to control neuroblast migration and survival, respectively. John Cave (Weill Cornell Medical College) presented data showing that GABA modulates differentiation of olfactory bulb dopaminergic interneurons as indicated by the upregulation in expression of both tyrosine hydroxylase (TH) protein as well as a green fluorescent protein (GFP)-expressing transgene driven by the nine kilobase upstream regulatory regions of the TH gene.[10]

Daniel Jimenez and Nathan Urban (Carnegie Mellon University) demonstrated that siRNA knock-down of sodium channel function reduced integration of adult-generated, predominantly GABAergic granule cell layer progenitors. These findings support an activity-dependent competition model for integration of adult-generated precursors into pre-existing olfactory bulb neural circuits.[11] Last, David Willhite (Yale University), using virally expressed alexa dyes, demonstrated that individual mitral/tufted (M/T) cells receive input from nonoverlapping, columnar populations of GABAergic granule cells.[12] Combinatorial logic-gating analyses of M/T cell firing profiles supported the hypothesis that a columnar, nonoverlapping circuit mode allows M/T cells to employ information from multiple lateral sources while convergent connections place constraints on lateral influences. Taken together, these talks provided strong support for the conclusion that GABA performs diverse actions during adult neurogenesis in the olfactory system.

Primary Taste and Olfactory Processing Networks

Linda Hermer (University of Florida) organized and chaired the symposium entitled

"Reciprocal interactions between primary taste and olfactory processing networks and higher cognition." Research into the neural basis of perception, cognition, and behavior has begun "evolving" away from the view that individual brain sites or single neurons are responsible for particular psychological functions toward a more network-based or distributed view. An increasing number of taste and smell researchers now believe that the neural underpinnings of chemosensory-based psychological processes are distributed across different neuronal classes, both within and across traditionally defined brain regions, and across time. The goal of this symposium was to present recent data indicating that early taste and olfactory regions are both influenced by top-down processes and may themselves directly influence those processes.

Dana Small (Yale University) showed with elegantly designed functional magnetic resonance imaging (fMRI) studies of normal human adults that top-down factors, such as expectation of whether a gustatory stimulus (tastant) will be present, as well as attention to different features of a taste stimulus, markedly affect subjects' perceptual judgments of those stimuli.[13] Building on this theme, Edmund Rolls (Oxford Centre for Computational Neuroscience) used fMRI and computational modeling studies to demonstrate and partly explain how cognitive factors, including word-level descriptors, such as "rich delicious flavor," can by top-down biased competition influence the pleasantness of the representations of odor, taste, and flavor in the secondary olfactory and taste cortex in the human orbitofrontal cortex.[14] Furthermore, he showed that attention to the pleasantness of olfactory and taste stimuli modulate responses to these stimuli in the secondary olfactory and taste cortex in the orbitofrontal cortex, while attention to the intensity of olfactory and taste stimuli modulates responses to these stimuli in the primary olfactory and taste cortical areas. Together these two presentations underscored how important cognitive factors are in influencing how humans respond to taste and olfactory stimuli and the flavor of food.

The third speaker of this session, Alfredo Fontanini (SUNY Stony Brook), presented evidence regarding the way in which input from the basolateral amygdala (BLA) and ventral tegmental area (VTA) may interact with gustatory cortical neurons to enrich sensory codes with psychological dimensions. He used multielectrode recordings of spikes in behaving rats to reveal two populations of taste neurons in the BLA, one producing tonic responses to gustatory stimuli and apparently coding for the hedonic values of tastants, and the other displaying phasic responses to gustatory stimuli and apparently coding, along with the VTA, reward value and expectation.[15]

Finally, Linda Hermer (University of Florida) presented the reverse side of the symposium's theme—in her case, the apparently active influence of early olfactory and motor areas on executive processing—using multi-site, multi-electrode recordings of local field potentials from the rat olfactory, orbitofrontal, prelimbic, and forelimb motor cortices recorded as rats performed a GO/NO-GO decision-making task.[16] Her work indicated that the rat primary olfactory and motor cortices actively signal each other during the penultimate and final sniffs of a GO or NO-GO odor, in distinctive frequency bands, before the animal "decides" whether to act upon the stimulus. Moreover, she showed that at least part of this signaling occurs via prefrontal cortical routes, further suggesting that the signaling is decision related. As a whole, the talks in this symposium demonstrated that early taste and olfactory processing networks are not only altered by top-down processes, but may also directly participate in higher cognitive operations, such as decision making.

Top-Down Influences on Olfaction

A further analyses of top-down processing in chemical senses was described in the

symposium "Follow the head, not only the nose: Top-down influences on olfactory perception," organized by Monique Smeets (Utrecht University). Recently, there has been a growing body of evidence showing that experiential factors rather than structural stimulus features are critical for odor discrimination. These developments call for a shift from an emphasis on bottom-up processing of odor features—the traditional view—to an emphasis on top-down processing driven by previously stored information. Indeed, such a shift would be something of a revolution in how experimental psychologists conceive of olfactory perception. The purpose of this symposium was to provide a state-of-the-art review of the evidence to back up this position, and to address its theoretical and practical implications. Topics that were covered included learning mechanisms by which templates of "odor objects" are established and stored in the brain, applications of the proposed top-down view on odor-related health complaints, and the role of emotion. Donald Wilson (NYU School of Medicine) introduced the symposium with the reminder that odor perception, like all other sensory perception, is constrained by the physical properties of the stimulus, but ultimately is an active, interpretive process, heavily dependent on expectation, internal state, past experience, and various top-down influences.[17] The individual symposium speakers then described their recent work that clearly demonstrates this fact.

The second speaker, Wen Li (University of Wisconsin), talked about how learning via mere exposure or aversive association alters odor coding in the human piriform and orbitofrontal cortices and enhances olfactory acuity.[18] She also presented data highlighting the potential ecological impact of such plasticity. For example, aversive learning may interact with individual differences in anxiety and depression in modifying olfactory perception. One area of application of the general theory that top-down influences shape odor perception is related to the phenomenon than people may attribute illness to environmental odors. Monique Smeets (Utrecht University) and Patricia Bulsing (Unilever) showed how an odor can become associated with adverse health effects via classical conditioning and how perception of the odor changes as a result.[19] CNS responses to sensory stimulation (i.e., event-related potentials (ERPs)) can be recorded electrophysiologically through electrodes placed on the scalp. Early, short-latency components in ERPs recorded while smelling the odor were significantly affected by classical conditioning of that odor to trigeminal pain, suggesting that odors are perceived differently when illness is expected to follow. Pamela Dalton (Monell Chemical Senses Center) discussed the psychosocial, medical, and financial impact of adverse responses to benign odors in communities and occupational settings.[20] She used examples from the laboratory and the real world to illustrate how the application of an ecological model would facilitate both the investigation of adverse odor responses and their remediation. Finally, Denise Chen (Rice University) presented a number of recent studies[21] identifying interconnections between emotional sophistication and sociochemosensory competency. At the same time, her studies, based on fMRI, showed impaired neural responsiveness to sociochemosensory cues in socially anxious individuals. Taken together, her findings support the notion that a top-down processing involving emotional experience and personality traits influences chemosensory processing of human social information. All in all, the combined talks made a compelling case for the notion that odor perception is strongly determined by experience.

Development and Plasticity

There is little information about the nature, timing, and extent of dynamic processes that establish and maintain functional central nuclei in chemosensation. Formation of functional groups during development requires timed waves of cell birth, migration, and

Figure 4. Meeting participants at the conference reception and banquet.

differentiation to neuronal or glial lineages. Neuron clusters then attract and receive sensory input that often dramatically reorganizes the maturing circuit. With data from moth, lobster, chick, and rodent, speakers in the symposium "Development and plasticity: First central chemosensory relays," organized and chaired by Charlotte M. Mistretta (University of Michigan) and David L. Hill (University of Virginia) explored how neurons, across taste, olfactory, and respiratory systems, initially cluster and receive specific sensory input and execute feats of plasticity in central chemosensation. The focus of this symposium was on the first central afferent relays of three systems. In an introductory talk on general principles and mechanisms on the roles of chemoattractants in axonal guidance, Catherine Krull (University of Michigan) discussed neuronal clusters that function together and have similar targets in response to developmental influences from glia, extracellular matrix, and cell adhesion molecules.[22] Next, Lynne Oland (University of Arizona), the first of three speakers giving short talks and specific examples on early nucleus development, demonstrated multiple roles of glia in directing axon sorting and glomerulus construction and separation via cell and molecular envelopes in the moth.[23] Further, Oland presented evidence that without glia, glomerular structures are not stable. Manfred Schmidt (Georgia Sate University) reported data on neurogenesis continuing throughout adulthood by symmetrical division of neuron precursor cells in four proliferation zones[24]; each zone is associated with a readily identified, crustacean-typical neuroblast surrounded by a unique cell cluster. Schmidt proposed that adult neurogenesis is an extension of embryonic neurogenesis. Robert Bradley (University of Michigan) reported preliminary explorations of the developmental structure of the solitary tract, central tract projections, and nucleus.[25] Bradley showed evidence for stage-specific and structured alignments of radial glia and neuronal precursors during solitary tract projections into the brain stem and assembly of early neuronal clusters into nuclei. He further demonstrated early differentiation into functional cell types within the emerging taste nucleus in rodents.

Two concluding talks of this symposium emphasized plasticity in sensory relay nuclei in developing rostral and caudal rodent brain stem. First, Alev Erisir (University of Virginia)

presented data on plasticity in the anatomic organization of primary sensory axon projections.[26] He provided examples of developmental pruning in taste axon projections and suggested that activity-dependent competition may be in effect as inputs from different taste nerves converge on synapses. Lifelong capacity for plasticity in synaptic function was proposed for a subset of taste inputs. Diana Kunze (Case Western Reserve University) concluded the talks with a focus on hypoxia, a natural stimulus for carotid chemoreceptors, driving activity-dependent changes and altered expression of synaptic proteins in the caudal nucleus of the solitary tract.[27] Sustained but reversible changes in synaptic transmission are recorded, related to increased spontaneous transmitter release and decreased evoked release. The symposium stimulated new ideas and questions about an understudied area, formation of chemosensory nuclei—highly plastic central regions.

Evolution of Chemoreceptors

The evolution of chemosensory receptors, especially odorant receptors, has been a focal point in the field of chemical senses and evolutionary genomics since the surfacing of genome sequence data for various model species. In the symposium "Functional evolution of chemosensory receptors," organized by Hanyi Zhuang and Hiroaki Matsunami (Duke University), speakers addressed the molecular functional evolution of odorant receptors and related proteins using a unique combination of computational and functional analyses. Hanyi Zhuang showed evidence for positive Darwinian selection acting on various amino acid residues of OR7D4, the odorant receptor for androstenone and androstadienone perception,[28] throughout primate evolution. She also showed that the functional analysis of OR7D4 orthologs and hypothetical ancestral sequences had an extremely diverse range of functions. Using experimental approaches, such as paired-end mapping and sub-kilobase-resolution tiling arrays, Jan Korbel (EMBL, Heidelberg) showed striking enrichment of copy number variations among the odorant receptor gene family in a large population sample.[29] Specifically, there is an enrichment of copy number variations among odorant receptors having a close human paralog or such lacking an ortholog in the chimpanzee. Yoav Gilad (University of Chicago) demonstrated that by using multiplex polymerase chain reaction (PCR) in one 96-well plate and by sequencing the products in one lane per individual, they were able to establish a method to sequence the odorant receptor gene repertoire with enough coverage to call heterozygote sites in a large number of individuals, which can be applicable to future association studies and population genetic analyses using the entire repertoire of odorant receptors.[30] Takashi Matsuo (Tokyo Metropolitan University) showed that two odorant binding protein genes, Obp57d and Obp57e, are involved in the evolution of unique host-plant preference in *Drosophila sechellia*,[31] which exclusively reproduces on the ripe fruit of noni. He showed phylogenetic evidence suggesting that Obp57d and Obp57e arose by gene duplication at the early stage of the melanogaster species group evolution and behavioral analysis of various species, revealing that the feeding preference for noni is negatively correlated with transcripts level in the mouthparts. Dieter Wicher (Max Planck Institute) showed that application of odorants produced nonselective cation currents activated via both an ionotropic and a metabotropic pathway insect odorant receptor in HEK293 cells expressing Or22a and Or83b[32]; therefore, these insect odorant receptors form ligand-gated channels as well as complexes of odorant-sensing units and cyclic nucleotide-activated nonselective cation channels.

In conclusion, these studies have effectively shown that genomic information combined with functional biology approaches can provide powerful tools for investigating the

Figure 5. Meeting participants attending one of the symposia.

functional evolution and diversity of chemosensory receptors.

Gender and Chemosensation

The molecular and neural mechanisms that underlie most sensory processing are thought to be equivalent between males and females. An exception lies in the sensory response to chemical cues that regulate innate social behavior. The symposium "Gender effects on olfactory processing," organized by Lisa Stowers (Scripps Research Institute), highlighted recent progress in identifying the unique neural mechanisms that result in gender dimorphic differences in olfactory neural coding. The six symposium presentations each reported dimorphic mechanisms at various stages of olfactory detection from ligand production through central processing in *Drosophila* and mouse.

Through genetic analysis of *Drosophila*, Hubert Amrein (Duke University) revealed that a gustatory receptor (Gr32a) detects a male inhibitory pheromone that is specifically emitted by both mated females and males.[33] Interestingly, not all neurons expressing Gr32a project to the expected target, the ventrolateral protocerebrum; a fraction of these neurons target variably, a phenomenon that is more pronounced with age and social isolation. Ron Yu (Stowers Institute and University of Kansas) analyzed the response of vomeronasal neurons to male and female urine that contains gender-specific ligands. He reported that gender information was represented by a surprisingly small number of receptor cells and that female ligands vary depending on endocrine status.[34] Kazushige Touhara (University of Tokyo) engineered a genetic reporter in the mouse that confirmed that exocrine gland–secreting peptide 1 (ESP1) is detected by V2Rp5 (Vmn2r116)-expressing neurons that converge on a small number of glomeruli in the accessory olfactory bulb. He demonstrated that ESP1 promotes female mating behavior in wild-type mice and concluded that V2Rp5 is genetically determined to mediate behavior in females.[35] The role for this receptor in males remains unknown. Lisa Stowers (Scripps Research Institute) showed that, unlike males, vomeronasal sensory neurons of females do not detect most major urinary protein (MUP) ligands, including the variant that promotes male–male aggression. The production of female hormones leads to a rapid and plastic inhibition of sensory

response and singularly accounts for the fact that females lack MUP-induced aggression.[36] Michael Baum (Boston University) presented tract tracing experiments[37] revealing that urinary odors from opposite-, but not same-sex, conspecifics stimulated Fos expression in main olfactory bulb M/T cells that project directly to the medial amygdala. These volatiles also stimulate Fos in medial amygdalar neurons that send centrifugal projections to the accessory olfactory bulb. This suggests that opposite-sex urinary volatiles detected by the main olfactory system influence neural activation in the accessory olfactory pathway. Finally, Nirao Shah (University of California, San Francisco) created a genetic reporter of aromatase and showed that expression was restricted to the limbic system in gender dimorphic patterns. The manipulation of sex steroid hormones influenced gender dimorphic behavior in an aromatase-dependent manner and provides the molecular identity of neurons that encode central differences in sensory processing.[38] Together the symposium identified multiple cellular and molecular mechanisms that result in differential function between males and females and provides a framework to investigate dimorphic regulation of functional pathways.

Clinical Applications of Basic Research

Finally, the "Taste and smell in translation: Applications from basic research" symposium organized by Michael Meredith (Florida State University) is an annual event at the AChemS meeting aimed at both basic scientists and scientists in the food, flavors, and fragrance industries. This year, speakers explored recent advances in the chemical senses, presenting advances in basic research that have a potential application in industry, with a goal of exploring how collaborations between industry and academic scientists can benefit both, and particularly how basic science expertise can contribute. The speakers included Danielle Reed (Monell Chemical Senses Center), who discussed gustatory stimulus transduction on the tongue, and Nirupa Chaudhari (University of Miami), who presented recent advances in taste molecular mechanisms. Thomas Hummel (University of Dresden) described new work on human olfactory psychophysics, central processing, and perception, and Stuart Firestein (Columbia University) described new work on olfactory sensory neuron receptors and transduction cascades.

Conclusions

In summary, the meeting presented a wealth of information on the diversity of cellular and molecular mechanisms of transduction, stimulus–receptor interactions, central processing resulting in perception, and psychophysics. Many presentations emphasized the growing importance of understanding chemical senses in the identification, treatment, or prevention of health-related issues, such as obesity and Alzheimer's disease. The work presented demonstrated a steady advance in our understanding of these exciting and important sensory systems, offering promise as the field moves forward.

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