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Towards a Comprehensive Summary of Senses for Cognitive Architectures

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Abstract

It is widely accepted that there are five senses. There, however, appear to be many more. This paper provides a comprehensive list of sensors that will be found in a complete cognitive architecture. We also briefly note how widely used these senses have been and which ones could yet be implemented in an architecture.

Keywords: senses, cognitive architecture

Introduction

It is widely accepted that there are five senses (e.g., Sekuler & Blake, 2001). There has always seemed to be more. A recent review of cognitive architectures (Kotseruba & Tsotsos, 2020; in press) provides a wide enough review to suggest that there are other senses (ways of knowing the state of the world or the agent using a sensor) that have sometimes been included in cognitive architectures. Upon further reflection, there appear to be far more than five senses. This paper describes a comprehensive list of sensors that might be found in a complete cognitive architecture. We also briefly note how widely used these senses have been.

There are also numerous measures of the body that are not available or not completely available to cognition, such as calorie needs, water intake, blood sugar, and insulin levels. These measures have to be measured externally, suggesting that not all aspects of the human state are available directly as a sense.

Thus, the first column of Table 1 provides the start of a comprehensive list of human senses for inclusion in a comprehensive cognitive architecture. The table is divided into external senses, which measure the world, and internal senses that tell cognition about the body. The second column of Table 1 represents corresponding human sensory systems.

Additionally, aspects such as perception of time, emotional senses, and social tension perception could be considered integral aspects of human cognition that are not traditionally categorized as the five basic senses. These components may draw from multiple senses and aspects of cognition, contributing to the complex interplay of cognitive processes and should be acknowledged in discussions of cognitive architectures.

There are some further senses that some animals have, such as a measure of magnetic fields. If we are to build a cognitive architecture for animals, we will need those senses. If we are building a superhuman model, for example, or a robot, we may wish to have those as well. Or we way may find that humans have vestigial versions of these senses.

It is worth noting that the information presented in Table 1 is not exhaustive, and our scientific understanding is constantly evolving. Recent research suggests the possibility of a subconscious magnetic sensory system in humans (Wang et al., 2019), challenging previous assumptions.

The remainder of this paper explains each of these senses in more detail. With the description in hand, we then discuss the implications for modeling cognition and performance.

This is a conference paper, so the review will necessarily be brief and preliminary. If we have left out major results, we beg readers to allow us some grace and provide feedback—to not bite our finger but note where we are pointing.

Brief Description of the Senses

In this section, we briefly describe each sense in Table 1 and how they have been used in cognitive architectures. When we do not note a documented sense, we do not know of work using this sense in generative cognitive modelling.

External senses

These senses tie the body to world in various ways.

1 Sight. It is expected that the visual modality takes first place here, because it provides the fastest way to transmit information about objects in the environment. This modality is also most widely used in human-machine interfaces (HMI) (e.g., Rydström & Bengtsson, 2007). The importance of vision for obtaining information about the world around us and surviving is evidenced by the fact that the brain devotes more space and resources to processing information coming from the visual system than to information coming from all other senses combined. The visual modality in cognitive architectures is most often implemented using physical sensors or simulations (Kotseruba & Tsotsos, 2020).

2 Hearing. Audition is the second most frequently used modality in modern HMIs. It is often used to provide an adjunct to the visual channel, to unload the visual channel for receiving information and duplicating it. Auditory modality is recommended for use in cases of difficulty or unavailability of the visual system like high positive accelerations, oxygen deprivation, unnatural lighting or its absence, the need to change working position, etc.

There are two ways to transmit auditory information to a person: verbal and audio signals. Words are a fundamental aspect of auditory communication and can greatly impact human cognition and behavior. When presented verbally, words engage cognitive processes related to language comprehension, semantic interpretation, and working memory.

Table 1. A relatively complete list of human senses.

Senses	Sensory systems
External/Distal	
1 Sight	Visual system
2 Hearing	Auditory system
3 Taste	Gustatory system
4 Smell	Olfactory system
5, 6, 7, 8 Touch	Somatosensory System
- touch	- mechanoreceptors
- temperature	- thermoreceptors
- nociception (pain, skin)	- nociceptor
- vibrations	- mechanoreceptors
Internal	
9 Sense of balance or equilibrioception, vertigo (loss of balance)	Vestibular System
10 Air pressure (popping ears)	Auditory system Vestibular System
11 Time (passage of)	Interoceptive system and other systems
12 Proprioception (body position, all limbs & head)	Somatosensory System - proprioceptors
13 Energy level/fatigue	Interoceptive system and other systems
14 Need for sleep	Interoceptive system and other systems
15 Emotions (e.g., I am feeling anger)	Interoceptive system and other systems
16 Body temperature	Interoceptive system - thermoreceptors
17 Nociception (pain, inside)	Interoceptive system, Somatosensory System - nociceptors
18 Need for air up to suffocation	Interoceptive system - chemoreceptors
19 Thirst	Interoceptive system - osmoreceptors and other systems
20 Hunger	see Fig. 2
21 Nausea (Stomach, gut, lower gut)	Interoceptive system - mechanoreceptors - chemoreceptors - osmoreceptors
22 Need to void (urine)	Interoceptive system - mechanoreceptors
23 Need to void (solid)	Interoceptive system
24 Need to void (gas)	- mechanoreceptors - chemoreceptors

Sound signals, including tones, beeps, alarms, and melodies, serve various purposes in HCI and can significantly influence human cognition and behavior. The characteristics of sound signals, such as frequency, amplitude, duration, and temporal pattern, play a crucial role in determining their impact on the user.

The auditory modality in cognitive architectures is most often implemented simulating the results (hear: "Hello") or using physical sensors (Kotseruba & Tsotsos, 2020). ACT-R, for example, has a simple ear (Byrne, 2001). A design for a more complete auditory system has been contemplated (Ritter, Brener, Bolkhovsky, 2023). Most architectures do not yet hear all these kinds of sounds or even simulate them.

3 Taste. At its core, the gustatory system governs the execution of behavioral sequences necessary for locating, inspecting, and ingesting food, a critical function for the survival of all animals.

Taste perception involves complex cognitive processes that go beyond mere sensory input. Additionally, taste can evoke emotional and physiological responses, further shaping human behavior. For instance, the taste of certain foods may elicit pleasure or disgust, leading to corresponding emotional reactions and can influence decision- making processes regarding food selection and consumption. MicroPsi appears to be the only system with taste (Bach, 2008) because it models finding food, discriminating, and eating.

4 Smell. The olfactory system plays a significant role in human life but is underrepresented in scientific research (van Hartevelt & Kringelbach, 2015). This system not only helps us select food and ensure survival, but is also unique in its structure and functioning. Unlike other sensory systems, olfactory information does not pass through the thalamus, but goes directly to cortical areas such as the orbitofrontal cortex.

Numerous studies point to a deep relationship between the olfactory system and emotions. This is due to the fact that they use common brain structures for processing: amygdala, hippocampus, insula, anterior cingulate cortex and orbitofrontal cortex (Soudry et al., 2011). Smells can evoke emotional reactions, positive or negative, and can lead to nausea, which is then sensed and perhaps amplified as an emotional feeling. Some scents can systematically evoke certain emotions, and a person's emotional state can influence the perception of odors in the environment.

Impaired sense of smell can lead to anhedonia. This phenomenon leads to a decrease in motivation and pleasure and is a symptom of many mental illnesses: schizophrenia, Parkinson's disease, eating disorders, borderline personality disorder, etc. (Pelizza & Ferrari, 2012).

Smell is represented as a sensory modality in the DAC (Mathews et al., 2009), GLAIR (Shapiro & Kandefer, 2005) and PRS (Taylor and Padgham 1996) architectures. PSI (Dörner, 2000) and MicroPsi (Bach, 2008) also has it because their models find food and eat.

5,6,7,&8 Touch+Temperature+Nociception+Vibration. A human receives the majority of information in control systems through visual and auditory analyzers. The tactile analyzer is relatively rarely used in architectures, despite its immense potential. In real life, humans perform numerous gnostic (touch, palpation, contour following, etc.), controlling, and identifying movements with their hands.

There are numerous theories about cutaneous sensitivity, which are largely contradictory. However, it is established that cutaneous receptors (see Somatosensory system below) include receptors responsible for modalities such as touch, pressure, vibration, temperature, and nociception (pain).

Humans can fairly accurately determine the location of a stimulus, the distance on the skin between points of stimulation, distinguish the degree of stimulation, etc. Thus, with the help of a multidimensional signal (e.g., a combination of vibration frequency+point of stimulation+amplitude+interval between signals), a significant amount of information about the control object can be transmitted (such as its state, position in space, speed, and assessment of time intervals).

The vibrotactile modality is often used in devices such as smartphones and tactile navigation devices. The cutaneous sensory system has also been used for recognizing visual patterns using discrete points, duplicating the visual modality (Lindsay & Norman, 1972). In some cases, tactile perception surpasses vision. Through touch, a human can assess the weight of objects, and determine their temperature and hardness directly.

Many robotic platforms are equipped with sensor bumpers necessary for effective problem-solving in movement and ensuring safety during motion. The touch modality is implemented only in 21% of cognitive architectures (Kotseruba & Tsotsos, 2020).

Internal senses

These are senses that the architecture would use to recognize the state of cognition or of the body.

9 Sense of balance. Just as vision provides information about the external environment, the sense of balance, or equilibrioception, provides internal feedback about the body's orientation and movement in space, joint position, muscle force, and effort. Our sense of balance helps us maintain stability and adjust our posture to prevent falls and maintain equilibrium. Many of us can remember the emotions that arise even when we feel slightly dizzy, especially when we realize that this could happen in dynamic situations, such as driving a car. Even short-term difficulties perceiving the position or movement of body parts can lead to difficulty performing tasks that require precise movements or spatial navigation. The vestibular system is an important component of proprioception and is responsible for maintaining static, mixed or dynamic balance. A human can improve balance and movement perception by training proprioception (Zsolt, 2018).

10 Air pressure (popping ears). In addition to external stimuli like sound waves, our bodies also perceive changes in air pressure. Similar to how we perceive changes in external air pressure, such as when flying in an airplane or diving underwater, our internal sensors detect shifts in atmospheric pressure and respond accordingly by “popping” our ears and equalizing this pressure. In cognitive modeling of certain types of activities, knowledge of how to reset the sensor after pressure changes will be useful to match human behavior.

11 Time (passage of). The perception of time is fundamental to human cognition (e.g., Taatgen, Van Rijn, & Anderson, 2007; Stine, Klein, & Yatko, 2001; Wittmann, 2009) as it provides the framework within which events are ordered, episodic memories are formed, and plans are made. Understanding how the brain processes and perceives time is crucial for developing accurate cognitive models, especially in areas such as decision-making, planning, and memory.

12 Proprioception (body position, all limbs, and head). This internal sense allows us to coordinate movements and maintain balance without constant attention to external visual or tactile signals. Robots use this sense, but we know of no models that do.

13 Energy level/fatigue. Similarly to how we perceive external stimuli like temperature or texture through touch, our bodies internally perceive changes in energy level and fatigue in ourselves. This internal feedback informs us of our body's physiological state, ranging from feelings of alertness (which may be a separate sense) and vitality to sensations of tiredness and depletion, influencing our physical and mental performance. There are quite a few known models of physical fatigue. Liang et al. (2009) considered, for example, 24 static and three dynamic muscle fatigue models. Taking into account fatigue during mental work or social interaction is no less important, but no models are tied to cognition but for PSI.

Patzelt and Shepherd (2024) recently presented a fatigue model of social venturing and showed that social project fatigue leads to an entrepreneur's disengagement from goals and decreased sensitivity to social issues, diminishing the entrepreneur's prosocial motivation to achieve goals and/or prompting them to abandon social projects altogether. Correct assessment and modeling of various types of fatigue will be necessary to determine the optimal mode of work and rest and will be very important for cognitive modeling long-term tasks.

14 Sleep, need for. Comparable to how we respond to external cues like darkness or noise to initiate sleep, our bodies internally perceive signals indicating the need for rest and sleep. While this sense may be imperfect and not always align with external factors, such as work schedules or environmental conditions, it plays a crucial role in regulating our sleep-wake cycle and overall well-being. The need for sleep is essential for cognitive recovery, memory consolidation, and our overall brain health.

15 Emotions. Emotional senses, including the recognition and interpretation of emotions in oneself and others, play a central role in human social interaction, decision-making, and overall well-being. Some of this processing is just cognitive. This information might appear from vision, but noticing the emotions in oneself might be seen as a sense that varies across people and may be tied to the gut.

Social tension perception (external) refers to the ability to sense and respond to social cues, hierarchies, and dynamics in interpersonal interactions. This aspect of cognition is critical for navigating complex social environments, forming alliances, and predicting others' behavior. Incorporating social tension perception into cognitive models can lead to more realistic simulations of human behavior and societal dynamics. Knowing yourself (and others) is perhaps now a type of sense to put on our list.

Emotions and internal sensations are closely intertwined. Similar to how external stimuli can elicit emotional responses, our internal experiences of emotions such as anger or shame can be a form of sensory perception. Just as we interpret external stimuli to generate emotional responses, our internal emotional states also provide feedback about our psychological well-being and inform our thoughts, behaviors, and decision-making processes.

This highlights the importance of developing emotional models for cognitive architectures as well as in human-robot interactions. An emotion ontology (e.g., www.ebi.ac.uk/ols4/ontologies/mfoem) can be a starting point for this.

16 Body temperature. Analogous to how we perceive external temperatures, our bodies internally sense changes in our body temperature. This internal feedback informs us of our body's thermal state, whether we feel warm or cold, and triggers physiological responses such as shivering or sweating to maintain homeostasis.

Humans and animals have several internal highly sensitive (molecular) "thermometers", presented in the form of transient receptor potential channels (TRP), which ensure the maintenance of internal body temperature with minimal energy expenditure.

Temperature sensitivity has not yet been sufficiently studied. For example, "mild cooling is detected by the menthol-sensitive TRPM8 ion channel, but how painful cold is detected remains unclear" (Buijs & McNaughton, 2020).

17 Nociception (pain). A human has pain-sensitive receptors also in the internal organs. Experts distinguish between the concepts of "nociception" and "pain" (Sneddon, 2018).

Nociception is the ability to detect and respond to various stimuli. Our body instantly responds to the stimulus with protective reflexes, which are called nocifensive. If these reactions become long-lasting and change our behavior, it may be a sign of discomfort associated with pain. Thus, pain is not only a physical sensation, but also a complex emotional and behavioral experience. Here, we count internal pain.

Additionally, there is an understudied role for passive nociception. Passive nociception involves the participation of inactive nociceptors in controlling our behavior. They seem to "push" us and direct us to ensure that actions do not cause pain or injury (Armstrong, 2024). This, for example, explains periodic stretching during prolonged sitting. There may be multiple types of receptors. Autonomic systems may provide an analogy.

18 Need for air. Comparable to how we respond to external stimuli like smoke or carbon monoxide by seeking fresh air, our bodies internally perceive the need for oxygen and respond to insufficient oxygen levels with sensations of suffocation or breathlessness. This internal sense of respiratory distress prompts behaviors to ensure adequate oxygen intake, such as adjusting breathing patterns or seeking oxygen-rich environments. This is an important sense and can be confused by carbon monoxide and nitrogen.

19 Thirst. Analogous to how we respond to external cues like dryness or saltiness by feeling thirsty, our bodies internally sense the need for hydration through the sensation of thirst. Osmoreceptors of the interoceptive system play an important role in detecting water imbalance and drinking behavior in humans. This internal feedback signals dehydration and prompts behaviors to seek and consume fluids to maintain fluid balance and prevent dehydration. Dehydration can lead to cognitive deficits, including problems with concentration, memory, mood regulation, etc.

Mechanoreceptors of the interosceptic system, which respond to changes in pressure in the hollow organs, help us perform reflex acts of urination and defecation. ACT-R/Phi has worked in this area.

20 Hunger. See example description below.

21 Nausea (Stomach, gut, lower gut). A major aspect of human thought and knowledge has been left out of all cognitive architectures, even PSI (Bach, 2008; Dörner & Güss, 2013). This aspect is the gut brain (Mayer, Nance, & Chen, 2022) that mobilizes the movement of food through the body with around 100 million nerve cells, and has concurrent effects on mood and that informs or indirectly leads to changes in multiple internal measures, such as need to void.

Nausea serves as a warning sign of digestive disturbances or toxin exposure, influencing cognitive and behavioral responses. Nausea and hunger can impair concentration and decision-making, leading to decreased performance and motivation. Osmoreceptors, together with chemoreceptors, help a human determine the presence and concentration of harmful substances in the body. Mechanoreceptors are responsible for reflex coughing and vomiting.

22 Need to void (urine). The urge to urinate signals the body's need to eliminate liquid waste products and maintain urinary function. Ignoring or delaying this sensation can lead to discomfort and distraction, affecting cognitive focus and productivity, and has even killed people (e.g., Tycho Brahe). Acknowledging and responding to the need to void is essential for maintaining physical comfort and supporting cognitive well-being.

23, 24 Need to void (solid, gas). Humans, like animals, can generally know that they need to void their solid waste. They also often, but not infallibly know whether it will be solid, liquid, or gas.

Human Perceptual Systems

To understand how a human interacts with the world and how we can model this process, we briefly consider a few sensory systems. We leave out the most commonly covered, vision and hearing. This survey, in turn, will help us create a more advanced and comprehensively meaningful cognitive architecture.

Somatosensory System

Purpose: Provides the brain with information about various sensations inside and around the body, including touch, pressure, vibration, pain, temperature, and body position in space. It includes the cutaneous sensory system and the musculoskeletal sensory system.

Main Function: Transmitting sensations for awareness and response to external and internal stimuli.

Receptors: Mechanoreceptors such as Merkel discs and Meissner's corpuscles (sense touch, pressure and vibration), thermoreceptors (sense temperature), nociceptors (sense pain), proprioceptors (perceive body position in space).

As mentioned above, proprioception ranks third in number of implementations after vision and symbolic input. Therefore, we will present a brief look at the proprioceptor sensory system as a part of Somatosensory System:

Purpose: Provides the brain with information about movement, the position of body parts relative to each other, and the force necessary to perform movements.

Main function: Movement planning and control.

Receptors: Proprioceptors (this is a type of mechano-receptor) - in muscles, joints, tendons, ligaments and connective tissues.

Gustatory system

Purpose: Provides the brain with information about the taste of food.

Main Function: Perception of taste qualities of food.

Receptors: Proprioceptors in the tongue and other areas of the oral cavity react to various taste qualities of food, including sweet, salty, sour, bitter, and umami.

Olfactory system

Purpose: responsible for perceiving odors.

Main Function: Assessing appetitive aspects of food. The Olfactory System plays a vital role in evaluating the aromatic properties of food and can influence the desire to consume particular items.

Receptors: Olfactory receptors located in the nasal cavity. These receptors respond to chemical substances in the air we inhale. They detect various aromatic molecules.

Vestibular System

Purpose: responsible for perceiving body position and movement in space. It includes the ear and a set of neural connections that help maintain balance, coordinate movements, and control spatial orientation.

Main Function: The main function of this system is to maintain the body's balance and orientation in space. It allows an individual to assess whether they are in a vertical position, moving, or stationary.

Receptors: Vestibular receptors located in the inner ear. These receptors respond to head movements and body posture. They perceive acceleration and changes in head position, enabling the assessment of the body's position in space.

Interoceptive System

Purpose: Provides the brain with information about internal physiological states of the body, such as hunger, thirst, fatigue, pain, temperature, organ conditions, and other biological aspects. This system plays a key role in self-awareness of physiological states and responding to them.

Main Function: Perception of internal sensations.

Receptors: Interoceptive receptors in various organs including the stomach, intestines, and other internal parts, detecting glucose levels, pressure, temperature, and other internal parameters.

A semantic network (Fig. 1) was developed to formally describe this knowledge. It describes how a Human uses sensory systems to perceive the outside world, including: the Visual, Auditory, Gustatory, Somatosensory, Olfactory, Vestibular, and Interoceptive systems.

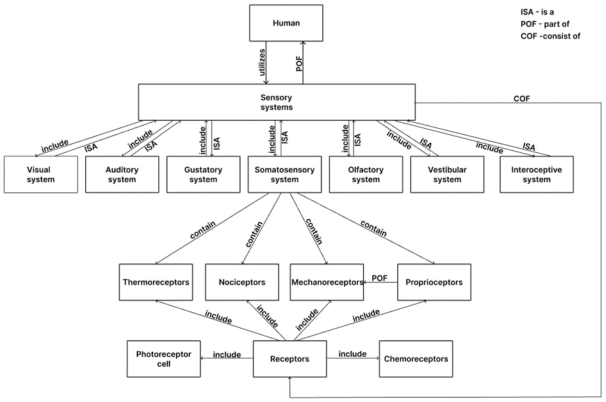

Figure 1. Formal representation of knowledge about the human sensory system.

In addition, the Sensory System consists of the following set of receptors: chemoreceptors, mechanoreceptors (that in turn include proprioceptors), photoreceptors, thermoreceptors, nociceptors. Figure 1 shows only a fragment of the semantic network to not make the picture noisy, only Somatosensory system receptors are indicated.

How do humans use their sensory systems?

Let's consider this using the example of a feeling that each of us has experienced at least once in our lives—the feeling of hunger. The main human sensory systems associated with feelings of hunger and satiety are:

- Taste. It is associated with the perception of the taste of food. Receptors in the tongue and other parts of the oral cavity respond to different taste qualities of food
- Olfactory system. The sense of smell plays a key role in assessing the appetizing aspect of food. Smells can greatly influence appetite and anticipation of food intake
- Somatosensory system. It is responsible not only for sensations associated with the bodily senses, but also for sensations associated with digestion. Mechanoreceptors in the stomach and intestines respond to organ distension and chemical changes associated with food intake. Chemoreceptors found in the stomach, intestines and other parts of the digestive tract respond to chemical changes in the body, including changes in the levels of hormones such as ghrelin (the hunger hormone) and leptin (the satiety hormone). They help regulate feelings of hunger and satiety by interacting with the hormonal systems, which are also involved in this regulation.

Based on information received from sensory systems, the brain decides how the body should respond. These reactions may include:

- Appetite regulation: The brain can regulate appetite levels by influencing hormonal systems such as hormonal appetite regulators including ghrelin and leptin
- Stimulate digestion: The brain can send signals that stimulate digestive processes in the stomach, intestines and other parts of the digestive system, preparing the body to eat. In doing so, the brain initiates a response that involves activating the autonomic nervous system (responsible for automatic body functions, including the digestive system) and coordinating this response within the digestive system
- Metabolic regulation: The brain influences the body's metabolism by controlling how quickly food is processed and how energy is distributed.
- Induction of hunger or satiety: The brain can induce feelings of hunger or satiety depending on the body's current needs, food information, and other factors.

Based on the above, a model was built (in the form of a semantic network) of how a human feels hunger (Fig. 2).

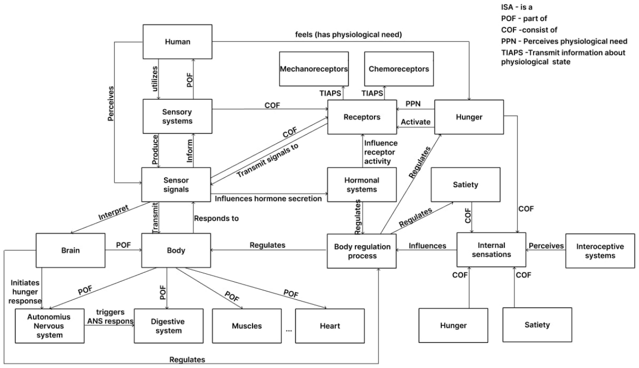

Figure 2. How a human feels hunger.

Discussion and Conclusion

What will we do with such lists? We can use the list to look for senses to include in cognitive architectures. First, there are many more senses than five! There are some external senses that can extend our cognitive and physiological (Hester et al., 2011) architectures. The internal senses are basically not included in cognitive architectures, but some are in agent and robots.

Kotseruba and Tsotsos (2020; in press) provide an extensive review of 84 cognitive architectures and defined the nomenclature of sensory modalities the architectures use. Here is their list, ordered in descending order of the number of modalities used: vision, symbolic input, proprioception, other sensors, audition, touch, smell and multi-modal.

External senses have tended to be more difficult to model than cognition; they require transducers to the real world (or models of them) and may require more knowledge and processing than cognition does. Including further external senses will also require tasks that use them. Most tasks studied to far do not use touch, smelling, hearing, or taste, partly because they are complicated to model and because psychology tends not to study them as often as the distal ones.

The internal senses are not often used in classic psychology studies. For example, only when we create longer running models (e.g., driving a great distance, Wu, Bagherzadeh, Ritter, & Tehranchi, 2023), will hunger, thirst, and voiding-related senses be necessary. Time estimation is a task, but it is not often used. It is used in more complex tasks that have not yet been modelled but is probably ubiquitous in all behavior.

The list of senses also suggests types of cognitive knowledge that are missing, for example, adjusting your body can reduce pain, or that a smell can be followed in the same way that active vision can lead to further information (Findlay & Gilchrist, 2003). How stress is perceived could be part of this story as well or for sense interaction.

When we consider the significance of this list of sensory modalities for cognitive architecture, it becomes evident that our understanding of sensory perception is constantly evolving. Recent discoveries, such as the identification of a sixth taste modality linked to lipid perception (Besnard, et al., 2016), complement traditional notions of sensory processing. Research on animal sensory systems also aids in designing and validating models for humans. For instance, insights into the sexual dimorphism of the olfactory system in mammals (Samaulhaq et al., 2008) corroborate findings (Oliveira-Pinto et al., 2014) showing that human dimorphism is conditioned by feminine characteristics. This, in turn, may explain the superior performance of women compared to men in olfactory tests.

Additionally, a number of studies have examined the intricate relationship between senses such as emotions and smells, as well as balance and nausea. Smells, just like emotions, can elicit positive, negative, or neutral reactions and influence our perception and behavior. This suggests common neural substrates underlying these phenomena.

The five senses have been mapped to brain regions. This larger list suggests that there are further regions to be assigned to the further senses. This mapping will help explain why we have such a big brain and how we use it.

This review shows that it is a big world out there still, and a big world even within ourselves yet to be modelled. We will need multiple sensors and multiple tasks to exercise these sensors.

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