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Exploring Cross-Species Multimodal Communication from a Life Perspective: Current State and Future Prospects

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Abstract

Traditionally, linguistics has focused primarily on human communication through visual and auditory modalities, while sensory modalities such as olfaction and gustation are relatively underutilized in human interaction, a trend influenced by evolutionary and societal factors. In contrast, animals employ a broad array of sensory modes in communication—olfactory, gustatory, photic, electromagnetic, and acoustic—thereby engaging in multimodal exchanges beyond the conventional realm of human language. This article reviews scientific discoveries, such as the role of pheromones in insect behavior and animals' perception of electromagnetic fields and spectrums, to reveal the richness of multimodal and supralinguistic communication in animals, highlighting the limitations within human communication. Inspired by these sensory communication models, we explore how future technologies might expand human sensory capacity, especially in olfaction, taste, vision, and touch, enhancing the multimodal experience in human interaction. Through technological advancements, such as augmented reality, virtual reality, electronic noses, tongues, and brain-computer interfaces, humans could adopt more diverse forms of supralinguistic communication, thus surpassing the limitations of traditional language and achieving a more comprehensive understanding of the natural world. This study aims to envisage, from a linguistic perspective, the possibilities of sensory-enhanced communication through technological development, fostering a revolutionary transformation in human perception and communication and enriching the research domain of linguistics.

Keywords: Multimodal Communication, Sensory Expansion, Sign Language, Braille, Supralinguistic Communication, Cross-Species Communication

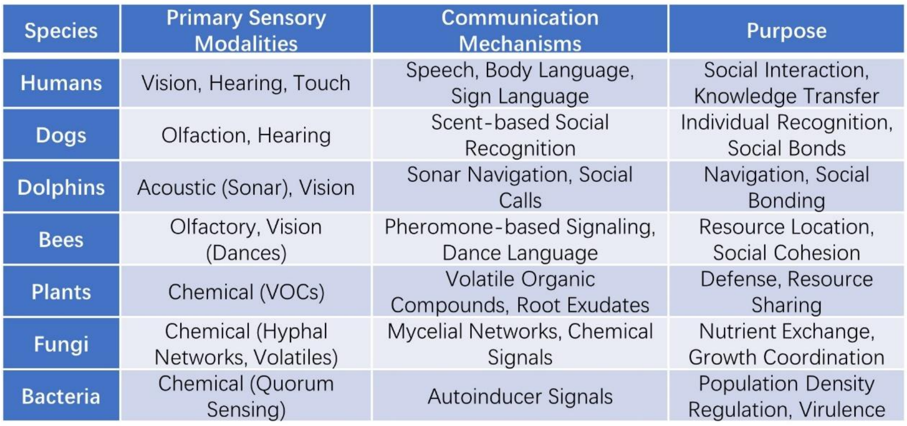
Introduction

Throughout history, human communication has evolved significantly, with language, writing, and symbolic systems introducing revolutionary advances. Language, traditionally understood as spoken or written, can also manifest multimodally [1,2]. Unique forms of multimodal communication, such as sign language and Braille, have emerged in response to the diversity of human capabilities, particularly among individuals with disabilities [3,4]. Sign language communicates through visual symbols, while Braille conveys information via touch, exemplifying the importance of diverse sensory contributions in communication. Nonetheless, human communication relies primarily on vision and hearing, with limited use of olfaction and taste. In a broader perspective, language might not need to be confined to human modes of interaction alone.

Across the biological world, a wide array of species exhibits unique modes of information exchange. Plants, for instance, though lacking sensory and communication organs like those of animals, release chemical compounds to convey messages, such as volatile organic compounds that signal other plants to activate defense mechanisms when under pest attack [5]. Animal communication is notably diverse, as bees convey nectar locations through intricate dances, dolphins use sonar for navigation, and mammals employ calls, postures, and scent-marking for territory and mating purposes

[6-8]. Even microorganisms communicate through chemical signals, and the interaction between viruses and host cells could, in some sense, be seen as a form of information exchange [9]. These modes encompass chemical, physical, and behavioral modalities, inviting a reevaluation of the essence and potential of communication itself.

In the human realm, language has long been conceptualized as spoken and auditory-based, relying on the production, transmission, and auditory reception of sound. However, sign language represents a breakthrough from this singular model. Sign language transmits information via gestures, facial expressions, and body posture, forming a rich and intricate linguistic system where each gesture holds specific meaning and grammatical structure. These elements, combined within a three-dimensional space, allow those with hearing impairments to communicate effectively, express emotions, transmit culture, and access knowledge [10]. Different regions and cultures have developed distinct forms of sign language, underscoring the complexity and diversity inherent in this modality. Moreover, even primates can use sign language [11]. Braille, on the other hand, represents a multimodal communication system that operates through touch and spatial-temporal interaction. Comprising raised dots on specialized paper, Braille encodes letters, numbers, and punctuation, enabling visually impaired individuals to read by touching dot configurations. This tactile language tightly links space and time, as readers perceive dot distributions within a defined spatial range and sequentially access information in time, thus opening the door to knowledge, culture, and social communication [12].



Species	Primary Sensory Modalities	Communication Mechanisms	Purpose
Humans	Vision, Hearing, Touch	Speech, Body Language, Sign Language	Social Interaction, Knowledge Transfer
Dogs	Olfaction, Hearing	Scent-based Social Recognition	Individual Recognition, Social Bonds
Dolphins	Acoustic (Sonar), Vision	Sonar Navigation, Social Calls	Navigation, Social Bonding
Bees	Olfactory, Vision (Dances)	Pheromone-based Signaling, Dance Language	Resource Location, Social Cohesion
Plants	Chemical (VOCs)	Volatile Organic Compounds, Root Exudates	Defense, Resource Sharing
Fungi	Chemical (Hyphal Networks, Volatiles)	Mycelial Networks, Chemical Signals	Nutrient Exchange, Growth Coordination
Bacteria	Chemical (Quorum Sensing)	Autoinducer Signals	Population Density Regulation, Virulence

Table 1: Comparison of Human and Animal Multimodal Communication Systems

The emergence and development of these multimodal communication systems (Table 1) prompt a reevaluation of language's core essence. Language now extends beyond mere spoken or written exchange to encompass broader categories of gestural and visual interaction, tactile and spatio-temporal engagement. Given the trajectory of technological advancement, novel communication methods are emerging at an unprecedented pace. Modern communication technologies, like mobile phones, allow people to interact through voice, text, and even video at any time, across the globe. With the rise of next-generation communication technologies, like 6G, we can anticipate reduced latency, greater bandwidth, and more stable connectivity, further enhancing the possibilities for realistic remote collaboration, holographic communication, and beyond. Satellite communications ensure worldwide information access, from remote locations to ships at sea, through the global network. In virtual reality (VR) and augmented reality (AR), new forms of interaction are being created [13]. In virtual environments, users communicate through customizable avatars, employing not only language but also multimodal information such as gestures and expressions [14]. For example, on certain virtual social platforms, users control avatar gestures through hand-tracking devices for a more natural exchange. Furthermore, with AI integration, virtual characters can better interpret human interaction, offering personalized engagement [15]. These new modes blur the boundaries between the real and virtual, bringing unprecedented dimensions to human communication.

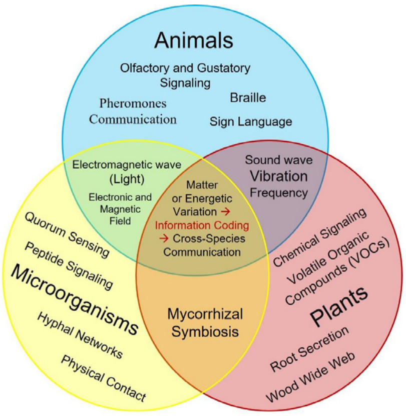


Figure 1: Cross-Species Communication Mechanisms

This flow diagram shows the diversity of communication mechanisms across biological kingdoms, including chemical signaling in plants, quorum sensing in bacteria, and sensory signals such as pheromones and light-based communication in animals. Each mechanism is represented by icons, highlighting the specific sensory channels and unique adaptations each species uses to transmit information.

Looking forward, we may witness even more integrated communication paradigms. For instance, by combining biometric technology with communication systems, face micro-expressions, gaze shifts, and even brainwaves could facilitate more precise, efficient interaction. Innovative immersive devices might allow people from different locations to experience communication as though face-to-face. Cross-species communication could also become a new frontier for exploration [16-18]. Although challenges are considerable, as our understanding of diverse biological communication grows, we may one day discover methods for basic information exchange with other species. Inspired by sign language and Braille, we recognize the diversity and potential of communication. The wealth of multimodal communication (Figure 1) in life and the human potential for sensory synthesis offer fertile material and imaginative breadth for advancing future communication methodologies, warranting deep academic exploration and discussion.

Definition and Current Status of Multimodal Communication

Multimodal communication refers to the use of multiple sensory modalities in interaction [19]. This concept originated in mid-20th-century linguistic and semiotic research, particularly focusing on nonverbal forms of communication. Representative examples of multimodal languages are sign language and Braille, which facilitate effective communication through visual and tactile modalities, respectively. Visual symbols, images, spoken language combined with gestures, among other methods, also contribute to multimodal communication to some extent.

Sign language is a gesture-based visual language that primarily conveys information through hand gestures, hand shapes, facial expressions, and body movements [20]. Far more than a set of gestures, sign language is a fully-fledged linguistic system with its own grammar, lexicon, and modes of expression. Each country or region has a unique form of sign language, such as American Sign Language (ASL), British Sign Language (BSL), and Chinese Sign Language (CSL). The diversity of sign languages reflects cultural specificity, and sign language research is significant for understanding the universality and diversity of human languages [21]. Systematic research into sign language grammar and linguistics began in the early 20th century, revealing both similarities and differences between sign and spoken languages [3]. For instance, in the 1960s, Stokoe developed a linguistic framework for studying sign language, laying the foundation for sign linguistics [22].

Braille is a tactile writing and reading system invented in the 19th century by French educator Louis Braille [23]. By using raised dots to represent letters, numbers, and punctuation, Braille allows individuals with visual impairments to access information through touch. The invention of Braille enabled blind individuals to read and write systematically, significantly improving their quality of life and educational opportunities. Braille’s structured dot system, based on various combinations to convey symbols, offers simplicity and broad applicability. The spread and application of Braille stand as a milestone in societal progress, representing the pursuit of equal rights and communication access.

Historically, multimodal communication in humans has extended beyond auditory and visual modalities. For example, in ancient times, dance and gestures were widely used as communication methods, particularly where language had not yet developed or where linguistic differences posed barriers [24]. Dance and gestures, as visual and action-based forms of communication, laid a foundation for the diversified development of language. Over time, scientific and technological advancements have further expanded multimodal communication, including modern augmented reality (AR) and virtual reality (VR) technologies that integrate visual, tactile, and auditory inputs, enhancing communication’s vividness and diversity [15]. Today, human communication primarily relies on auditory and visual modes, which, despite significant achievements, still have limitations.

Insights from Sensory Communication in the Animal Kingdom

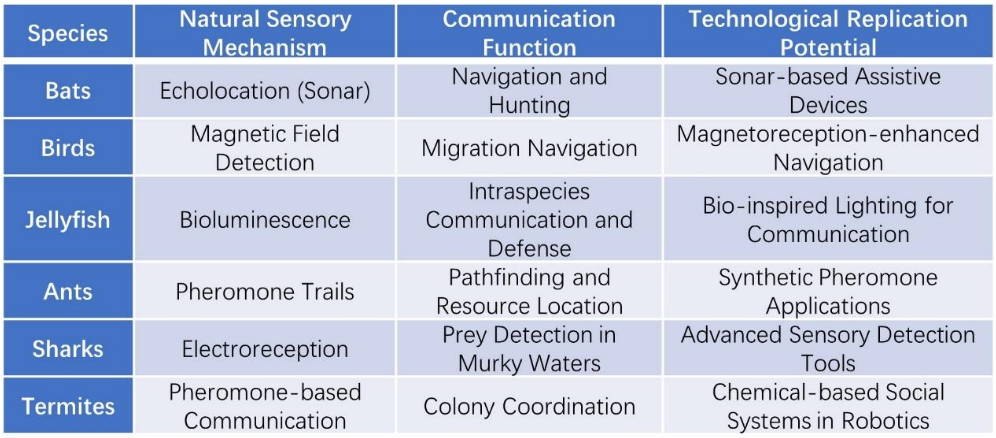
The animal kingdom offers a fascinating array of communication methods, resembling a symphony of life that plays a crucial role in survival, reproduction, and environmental adaptation. These interactions provide humans with a profound gateway to understanding and innovating in communication.

Animals exhibit a rich diversity of communication methods, with olfactory and gustatory signals particularly prominent. Dogs and pigs are renowned for their acute sense of smell, enabling them to identify individuals precisely through scent [25]. When tracking prey, smell acts as a navigational tool, guiding them through complex environments to locate their targets and even detect potential dangers. Insects excel at olfactory and gustatory communication through the use of pheromones—chemical signals essential for various forms of interaction [26,27]. In the early 20th century, Fabre’s in-depth research on insect behavior provided foundational evidence of pheromones' critical role in insect communication [28,29]. For example, bees release specific chemical signals to guide others to rich food sources, which is vital to their survival and reproduction [27]. Termites and ants similarly rely on pheromones, creating a complex network that acts as their "social media" to coordinate collective activities, such as food foraging and colony defense against predators [30].

Beyond olfactory and gustatory cues, animals use light, electromagnetic waves, and sound for communication, painting a vivid picture of natural interaction. In terms of light-based communication, jellyfish emit bioluminescent signals to communicate with one another, producing an effect akin to stars in the night sky, conveying unique messages [31]. Similarly, deep-sea fish utilize bioluminescent organs to communicate and lure prey in the ocean's dark depths, establishing a unique survival strategy. Fireflies use specific flashing patterns as a courtship "language," an intriguing phenomenon recorded by naturalists since the late 19th century. These light displays serve additional functions; for example, fireflies can use their bioluminescence to warn predators of potential toxicity, thus enhancing self-protection [32].

Sound waves also play an indispensable role in animal communication. Whales and dolphins employ intricate sonar systems, using sound waves to relay location, prey details, and social cues across vast ocean expanses. This acoustic method proves highly effective in underwater environments, as water facilitates sound propagation, allowing communication over great distances [33,34]. Birds communicate through songs and calls to attract mates, showcase their appeal, demarcate territories, alert others to threats, and even convey warnings [35-37]. Bats, with their unique echolocation ability, use ultrasound to navigate and locate obstacles and prey, maintaining social bonds by sharing food resources and roosting spaces [37-39].

Perception and communication through electromagnetic waves also captivate researchers. Sharks can detect weak electrical signals from other organisms through specialized electroreceptors, enabling them to locate prey even in murky waters [40]. Some animals, like birds and sharks, can perceive Earth's magnetic field, serving as an internal compass to navigate during migrations or long journeys. For example, pigeons navigate by sensing the magnetic field, a phenomenon studied extensively since the early 20th century, providing insights into the link between electromagnetic fields and animal behavior [41]. Certain birds, such as eagles, see ultraviolet light, granting them a unique visual advantage in spotting information that is often imperceptible to other species [42,43]. Rattlesnakes, capable of detecting infrared light, use this ability to sense environmental temperature shifts, helping them locate prey, avoid predators, and thrive in complex habitats (Table 2) [44].



Species	Natural Sensory Mechanism	Communication Function	Technological Replication Potential
Bats	Echolocation (Sonar)	Navigation and Hunting	Sonar-based Assistive Devices
Birds	Magnetic Field Detection	Migration Navigation	Magnetoreception-enhanced Navigation
Jellyfish	Bioluminescence	Intraspecies Communication and Defense	Bio-inspired Lighting for Communication
Ants	Pheromone Trails	Pathfinding and Resource Location	Synthetic Pheromone Applications
Sharks	Electroreception	Prey Detection in Murky Waters	Advanced Sensory Detection Tools
Termites	Pheromone-based Communication	Colony Coordination	Chemical-based Social Systems in Robotics

Table 2: Multimodal Communication and Potential for Technological Replication

Communication Among Other Species in the Biological World

Beyond animals, plants, viruses, bacteria, fungi, and protozoa each possess unique communication mechanisms, collectively forming a vibrant ecosystem of biological interaction.

Plants engage in a complex communication network through a variety of mechanisms that interweave to enable information transfer and resource sharing [45]. Chemical signals play a critical role, with volatile organic compounds (VOCs) serving as key "messengers" between plants. For instance, when a plant is attacked by pests or experiences mechanical damage, it swiftly releases specific VOCs such as terpenes, esters, and alcohols. In maize, for example, (Z)-3-hexenol is released upon insect attack, acting as a warning signal sensed by nearby plants, which then activate defense genes to enhance resistance and collectively respond to threats [46]. Root secretions also enable plant communication, as plants release organic acids, amino acids, and polyphenols through their roots to interact closely with soil microbes and other plants [47]. An example is the secretion of flavonoids by legumes, which attract rhizobia bacteria to form root nodules and facilitate biological nitrogen fixation, fostering a mutualistic relationship that promotes nitrogen cycling in ecosystems. Internally, plants transmit information through electrical signals, similar to an immune system, allowing rapid response to external stimuli and systemic defense activation across the plant [48]. Additionally, the mycorrhizal network, known as the "Wood Wide Web," provides a unique communication platform. Symbiotic relationships between mycorrhizal fungi and plant roots establish a vast underground network through which plants exchange nutrients (e.g., carbon, nitrogen, phosphorus) and signals, promoting growth and defense capabilities and optimizing resource allocation [49,50].

Bacterial communication centers around quorum sensing, a cell-density-dependent mechanism [51]. Through quorum sensing, bacteria coordinate group behavior via signaling molecules called autoinducers. Gram-negative bacteria typically use acyl-homoserine lactones (AHLs) as signals, whereas Gram-positive bacteria use peptide signals, each type playing a unique role in bacterial interaction. Quorum sensing has diverse functions, including regulating biofilm formation, enabling bacteria to aggregate in suitable environments and form protective biofilms, enhancing survival. It also manages antibiotic production, resource allocation, and virulence factor expression, increasing bacterial competitiveness during infection. For example, pathogenic bacteria modulate toxin secretion via quorum sensing, improving infection success and environmental adaptability [52].

Despite their apparent simplicity and lack of sensory systems, viruses also communicate uniquely [53-55]. Certain viruses utilize signaling molecules to coordinate life-cycle strategies. For instance, some bacteriophages infecting Bacillus species release a peptide signal known as "Arbitrium." When sufficient Arbitrium accumulates, it signals later-infecting phages to enter a lysogenic cycle, reducing host population damage and maintaining a long-term coexistence strategy [53]. Viruses are also observed to engage in quorum sensing, sensing other viruses or the host cell's metabolic state to regulate their own replication and gene expression. HIV, for example, regulates its replication by interacting with its RNA via the Tat protein, adjusting to changes within the host cell to enhance survival and transmission [56].

Fungal communication is diverse, encompassing hyphal networks, chemical signaling, and physical contact [57,58]. Multicellular fungi form extensive networks called mycelia, which function like transportation and communication highways for nutrient transfer and signaling, coordinating growth and development. In multinucleated fungi, nuclei and organelles can move freely between hyphae, creating an efficient resource-sharing network that operates as an integrated entity [57]. Fungi also employ chemical signals, releasing volatile organic compounds and water-soluble signals to influence behavior in themselves and nearby organisms. For example, yeast releases mating factors to induce the pairing of compatible cells, facilitating genetic exchange and increasing diversity. Mycorrhizal symbiosis represents a special form of communication between fungi and plant roots, where fungi provide water and nutrients in exchange for carbon, forming a bridge that not only enhances mutual growth but also strengthens ecosystem stability through resource and signal exchange [59].

Protozoa and microorganisms, as single-celled organisms, use chemical signals, chemotaxis, and physical contact for unique communication. They can release and detect chemical signals to regulate group behavior. For example, in a state of starvation, slime molds release cyclic AMP (cAMP) as a chemical signal to attract others, forming a multicellular structure to survive environmental challenges [60]. Chemotaxis is another hallmark of protozoan communication, as these organisms can detect chemical gradients and move towards nutrient-rich areas or away from harmful substances [61]. For instance, Paramecia are attracted to areas with high acetic acid concentration to obtain more nutrients. Certain protozoans also engage in direct contact, such as in conjugation, where cells fuse to exchange genetic material, enhancing diversity and adaptation potential. Microorganisms play essential roles in ecosystems through mutual symbiosis, competition, and antagonism. For example, bacteria and fungi communicate through volatile compounds that influence each other’s growth and metabolism. Some bacterial volatiles inhibit fungal growth, while fungi may release substances that impact bacterial activity, maintaining ecosystem balance and facilitating nutrient cycling.

Limitations and Future Development of Multimodal Sensory Communication in Humans

Human sensory communication is primarily centered on vision, hearing, and touch, while the roles of smell and taste remain relatively underdeveloped. This bias may be related to human evolutionary processes. During evolution, as linguistic ability developed and social structures grew in complexity, humans increasingly relied on visual and auditory cues, with a corresponding decline in dependence on chemical senses (smell and taste). Archaeological and anthropological evidence supports this trend; for example, Neanderthals and early Homo sapiens exhibited greater sensitivity to chemical cues in their environments compared to modern humans [62-65].

In contrast, many animals employ a broader spectrum of sensory modalities in communication, utilizing channels that humans have not fully harnessed. For example, dogs identify one another through scent, and insects communicate via pheromones—methods virtually absent from human interaction. This divergence not only reflects an increased human dependence on technology and social complexity but also highlights the diverse sensory evolution across species.

As scientific and technological advancements continue, humans may be able to more effectively utilize smell and taste in communication. Technologies to transmit scents could allow people to convey emotional cues through specific smells, while taste simulation devices might enable gustatory communication. These advancements would expand our capabilities for emotional expression and information transmission. Recent research breakthroughs in electronic nose and tongue technologies (Figure 2A), which can detect complex chemical compositions, lay the groundwork for future olfactory and gustatory communication [66-68]. Through augmented reality (AR) and virtual reality (VR), the integration of visual and tactile sensations can create immersive communication experiences (Figure 2B). Tactile feedback devices, for instance, allow individuals to perceive distant objects or experience a person’s touch remotely, enriching emotional exchange during virtual communication. Research into tactile communication, which dates back to mid-20th-century haptic feedback experiments, indicates that tactile feedback significantly improves the accuracy of information transfer and emotional impact [69].

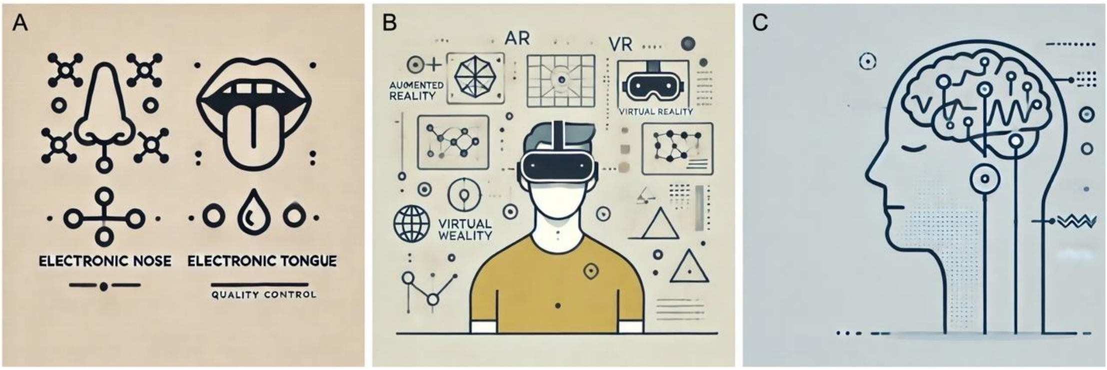
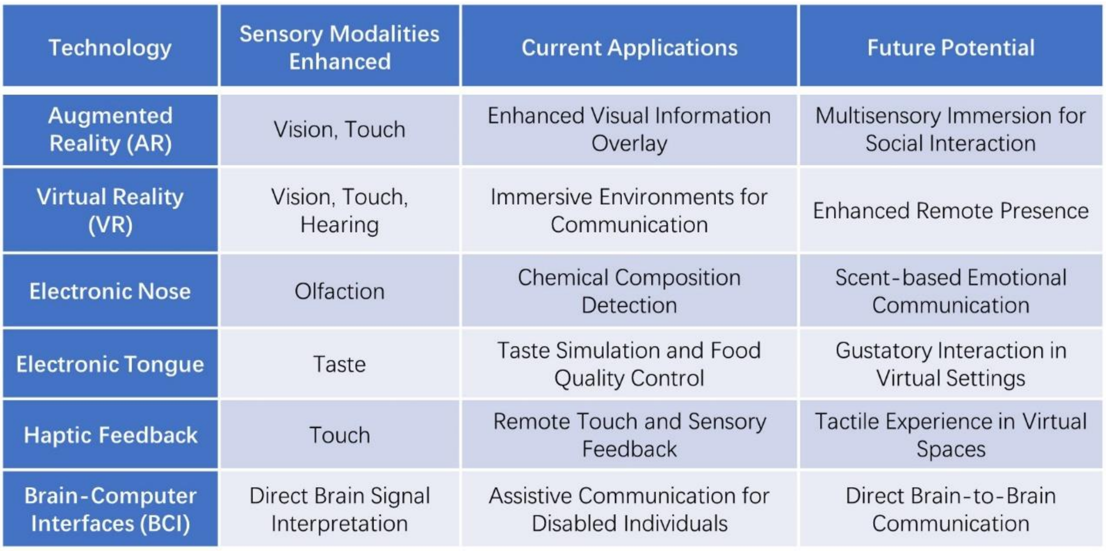


Figure 2: Technological Advances in Enhancing Sensory Communication

This infographic highlights recent advancements in sensory-enhancing technologies such as A) electronic noses and tongues; B) augmented reality (AR), virtual reality (VR); and C) brain-computer interfaces (BCI). Each technology is shown with its associated sensory modality—vision, touch, olfaction, gustation, and direct brain communication—illustrating how these tools expand or simulate sensory-based communication.

Additionally, the rapid development of brain-computer interface (BCI) technology opens possibilities for direct brain-to-brain communication (Figure 2C), potentially overcoming the constraints of language and physical gestures [70]. Originally applied in rehabilitative medicine to aid paralyzed patients, BCIs are also enhancing human sensory experiences, enabling users to control actions in virtual reality through thought alone, paving the way for novel multimodal communication systems (Table 3) [71].



Technology	Sensory Modalities Enhanced	Current Applications	Future Potential
Augmented Reality (AR)	Vision, Touch	Enhanced Visual Information Overlay	Multisensory Immersion for Social Interaction
Virtual Reality (VR)	Vision, Touch, Hearing	Immersive Environments for Communication	Enhanced Remote Presence
Electronic Nose	Olfaction	Chemical Composition Detection	Scent-based Emotional Communication
Electronic Tongue	Taste	Taste Simulation and Food Quality Control	Gustatory Interaction in Virtual Settings
Haptic Feedback	Touch	Remote Touch and Sensory Feedback	Tactile Experience in Virtual Spaces
Brain-Computer Interfaces (BCI)	Direct Brain Signal Interpretation	Assistive Communication for Disabled Individuals	Direct Brain-to-Brain Communication

Table 3: Examples of Multimodal Communication Technologies and Their Sensory Focus

Conclusion and Prospects

Exploring multimodal communication methods such as sign language and Braille reveals the immense potential for enhanced sensory engagement and supralinguistic communication in humans. Currently, human interaction primarily relies on vision and hearing, limiting communication diversity. In contrast, the animal kingdom's rich array of sensory-based communication offers valuable insights for linguistic research. With future scientific and technological progress, humans may expand sensory capacities in smell, taste, vision, and touch, developing additional supralinguistic communication methods. This evolution will not only enrich the multimodal experience in human interaction and broaden linguistic research but may also deepen our understanding and integration with the natural world, potentially enabling basic cross-species information exchange.

Cross-sensory integration of electromagnetic waves and sound waves represents another promising research direction. While humans already use these waves for long-distance communication and information transmission, techniques akin to bats' and dolphins' sonar could enhance environmental perception and communication. Furthermore, the extension of visual capabilities to infrared and ultraviolet spectra could reveal hidden aspects of nature. Recent technological breakthroughs have enabled the development of infrared-sensing and ultraviolet-imaging systems, which help humans explore previously invisible aspects of the natural world [72].

In the future, human vision may extend beyond the visible light spectrum, encompassing broader electromagnetic wavelengths. This expanded perception would deepen our understanding and exploration of the natural world, opening new linguistic research domains to investigate communication across sensory dimensions and enriching supralinguistic modes. Such advancements in sensory communication are poised to drive revolutionary changes in human perception and interaction, with profound implications for social progress and linguistic development. The field of linguistics must further explore theoretical frameworks for multimodal and supralinguistic communication, examining how different senses contribute to language and how new technologies can be integrated into linguistic practices. Looking forward, interdisciplinary collaboration among linguistics, neuroscience, computer science, and physics will become increasingly crucial, fostering innovative communication methods. Continued research and innovation promise to usher in a vibrant new era of communication, expanding the boundaries of linguistics and deepening our understanding of the essence of human interaction.

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