

Natural Language Processing in Voice Assistants

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ABSTRACT

Natural language processing (NLP) is one of the most transformative technologies in the field of artificial intelligence. It bridges the gap between human communication and computer understanding, allowing machines to interpret, process, and generate language in ways that feel increasingly natural. It combines computational linguistics with statistical modeling and machine learning to enable computers to process, understand, and generate human language. Chatbots and voice assistants represent two of the most visible and impactful applications of NLP in today's digital ecosystem. In the context of voice assistants like Amazon Alexa, Apple Siri, and Google Assistant, NLP is the critical technology that transforms raw acoustic data into meaningful interactions. Voice assistants have become one of the most pervasive and transformative technologies of the 21st century. This widespread adoption is largely powered by advancements in NLP, enabling these systems to understand and respond to human speech. This paper delves into the rise of voice assistants, the groundbreaking advances in NLP, and their real-world applications.

KEYWORDS: *natural language processing, NLP, computational linguistics, voice assistants, NLP voice assistants.*

INTRODUCTION

Imagine a world where your voice assistant knows your preferences so well that it can predict your needs before you even ask. We are close to achieving such a seamless interaction. The advent of voice assistants has revolutionized the way humans interact with technology, making it more intuitive and accessible. The way we interact with technology is undergoing a fundamental shift. The journey of voice technology has been long and complex. The “voice revolution” is no longer a futuristic concept; it is a multi-billion dollar reality that is reshaping productivity, commerce, and personal lives. Voice assistants have reshaped how people interact with technology. From answering simple questions on smartphones to controlling entire smart homes, these AI-powered tools allow users to interact with devices through natural spoken language rather than keyboards or screens [1].

Natural language processing (NLP) is that subpart of artificial intelligence that creates a communication interface between machines and human languages to understand, interpret, and even generate them. It

occupies the fascinating space of the confluence of computer science, artificial intelligence, and linguistics. It serves as the cognitive backbone of contemporary voice assistants, bridging the gap between human communication and machine comprehension. It has revolutionized human-computer interaction by enabling machines to understand, interpret, and respond to human speech in a natural, conversational manner. At the heart of this transformation are NLP-powered voice assistants—such as Amazon Alexa, Google Assistant, Apple's Siri, Microsoft Cortana, and more recent entrants like Grok's voice mode or advanced multimodal systems [2]. Voice assistants have become ubiquitous in modern life, seamlessly integrating into our homes, vehicles, and personal devices.

FUNDAMENTALS OF NLP

Natural language processing is a subfield of artificial intelligence that empowers computers to understand, interpret, and generate human language. It is a technique where machine can become more human and thereby making human to communicate with the

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machine easily. NLP seeks to make software intelligent enough to process a natural language as humans. For example, imagine a machine that takes instructions by voice.

NLP analysis generally consists of the following three levels [3]:

- *Syntax*, the study of sentence structure. Syntax deals with the formation of a sentence from individual words. Syntax alone suggests the proper interpretation of “Jimmy loves Lucy.”
- *Semantics*, the study of context-independent meaning. This derives the meaning of a sentence based on the meanings of the words/phrases. For example, semantics determines whether the word “bank” refers to a river bank or to a financial institution.
- *Pragmatics*, the study of context-dependent meaning. Pragmatics deals with how meaning changes in the presence of a specific context and how the contexts affect the meaning of the sentences. This level is concerned with the purposeful use of language in situations.

As a foundational pillar of modern artificial intelligence, NLP encompasses a wide array of tasks, including speech recognition, text classification, natural language understanding (NLU), and natural language generation (NLG). NLP encompasses a wide range of tasks, such as information retrieval (IR), named entity recognition (NER), relation extraction, text classification, topic modeling, semantic textual similarity, machine translation, and question answering (QA). Figure 1 shows how NLP transforms raw acoustic data into meaningful interactions [4].

Recently, large language models (LLMs) have shown their ability in learning universal language representations, text understanding and generation. LLMs refer to a model with a large number of parameters, vast training data, and substantial compute, enabling it to capture complex language patterns. In LLM-based NLP, pre-processing is followed by prompt engineering, which guides LLMs to produce outputs that align with extraction requirements during inference without altering the model’s parameters. Models like GPT are pushing the boundaries of language understanding, enabling nuanced and context-aware applications. The GPT (Generative Pretrained Transformer) is a large-scale language model developed by OpenAI that consists of multiple layers of transformer blocks, each with a self-attention mechanism and a forward neural network [5]. GPT-based systems can summarize complex reports or generate creative content like

essays, making them versatile in both academic and professional environments. ChatGPT uses NLP techniques to understand prompts. When you enter a prompt, the chatbot comprehends it and provides relevant replies.

CONCEPT OF VOICE ASSISTANTS

Voice is naturally one of the most intuitive forms of communication; communities verbally passed down memories, culture, and history through stories before the written word. An AI voice assistant is also known as a virtual assistant, which mainly adopts voice recognition technology and natural language processing algorithms to complete tasks. Voice assistants are AI-powered systems that let people interact with technology through spoken language, and they have rapidly evolved from early speech-recognition experiments into sophisticated, conversational tools embedded in phones, homes, and everyday services. They represent one of the most significant shifts in human–computer interaction, moving technology toward more natural, intuitive communication. Voice assistants, once relegated to simple command-and-response mechanisms, have evolved into sophisticated conversational agents. This transformation is driven entirely by the rapid evolution of natural language processing (NLP), a subfield of artificial intelligence that bridges the gap between human communication and machine understanding. The integration of NLP into voice assistants represents one of the most significant advancements in human-computer interaction of the 21st century [1].

Previously, a voice assistant had to transcribe voice to text, process that text through a brain (LLM), and then convert the response back to speech. This process often felt slow and robotic. Early systems relied on relatively basic rules and cloud-based processing for automatic speech recognition (ASR) and simple command execution. The foundations of modern voice assistants lie in early speech-recognition systems, which were limited in accuracy and vocabulary. The modern era of voice assistants traces back to 2010–2011 with Apple’s launch of Siri, the first mainstream voice assistant integrated into consumer devices. Siri was followed quickly by Google Voice Search (later Google Assistant) and Amazon’s Alexa. The introduction of large language models (LLMs) around 2022–2023, popularized by systems like ChatGPT, dramatically improved conversational abilities. OpenAI is one of the most renowned and most-used companies in this field. Its GPT models include writing tools, coding assistants, and enterprise software that are used across industries.

Today's voice assistants do not just “hear” words; they understand context, nuance, and even emotion. They are more than just software; they are becoming our collaborators, researchers, and personal organizers. Advances in machine learning and NLP allow these systems to handle complex queries, maintain conversational context, and personalize responses [2]. Voice assistants are no longer confined to simple tasks like setting alarms or playing music. They are now integral to complex operations in healthcare, customer service, and smart homes. Figure 2 shows an example of voice assistant [6].

NLP IN VOICE ASSISTANTS

Natural language processing (NLP) is a technology that allows computers to understand and respond to human language in a way that feels natural. When we talk to our devices, we do not use code; we speak normally, using phrases, slang, and even humor or sarcasm. In the case of voice assistants, speech recognition technology transforms sound waves into written text. For voice assistants like Siri, Alexa, or Google Assistant, speech recognition is the first and perhaps most critical step. This technology transforms the user's spoken input into text that NLP systems can analyze. This process, known as automatic speech recognition (ASR), involves acoustic modeling, language modeling, and signal processing. Once the spoken words are converted into text, the same NLP pipeline used by chatbots comes into play. Dialogue management is the process by which chatbots and voice assistants decide the next step in a conversation. Once the system decides what to say or do, it generates a response. Natural language generation (NLG) converts internal representations into grammatically correct, contextually appropriate sentences. Figure 3 shows how voice assistants understand what you say [7].

Natural language processing makes voice assistants and chatbots smarter and more user-friendly, improving their responses and applications in everyday tasks. It is the heart of what makes voice assistants and chatbots smart, interactive, and user-friendly. What is fascinating about NLP is that it combines science and creativity. It learns from patterns in language, drawing on large amounts of data to get better at understanding context. With NLP, voice assistants like Alexa and Siri can help us with tasks, answer questions, and feel almost human in their responses. Figure 4 shows how NLP powers voice assistants and chatbots [7].

EXAMPLES OF VOICE ASSISTANTS

Voice assistants have become an increasingly popular way for people to interact with their devices and access information. From Siri to Alexa, these voice-

activated assistants have made our lives easier by providing quick responses to our queries and performing tasks on our behalf. Some of the most popular voice assistants include [8]:

- *Siri*: Apple's virtual assistant, integrated into iOS devices
- *Google Assistant*: Google's virtual assistant, available on Android devices and Google Home smart speakers
- *Alexa*: Amazon's virtual assistant, integrated into Echo smart speakers and other devices
- *Microsoft Cortana*: Microsoft's virtual assistant, available on Windows devices

Amazon's Alexa, Google Assistant, and Apple's Siri are voice assistants most consumers have used before.

APPLICATIONS OF NLP VOICE ASSISTANTS

Industries increasingly rely on voice assistants for documentation, customer service, and remote assistance. Their applications now span virtually every domain of daily life, business, finance, healthcare, education, and accessibility, fundamentally changing how people access information, control their environment, and interact with technology. From enhancing healthcare delivery and customer service to revolutionizing smart homes and professional applications, the impact of these technologies is profound and far-reaching. Common applications of NLP voice assistants include the following [2,9]:

- *Smart Home*: One of the most visible and widespread applications of NLP voice assistants is in consumer electronics and smart homes. Users can control lighting, thermostats, security cameras, music systems, and appliances simply by speaking. Phrases like “Turn off the living room lights” or “Set the temperature to 65 degrees” are processed through sophisticated NLP pipelines that handle intent recognition, entity extraction, and context awareness. Devices like Amazon Echo and Google Nest allow users to control lights, thermostats, and security systems through voice commands.
- *Personal Assistance*: Voice assistants have become indispensable productivity tools. Professionals use them for scheduling meetings, setting reminders, drafting emails or messages via dictation, and retrieving information hands-free. NLP techniques such as named entity recognition and sentiment analysis help assistants understand nuanced requests like “Remind me to call Mom tomorrow afternoon” or “Summarize my unread emails from the team.” In mobile and automotive

environments, voice interaction is especially valuable. Drivers can navigate, make calls, send texts, or change music without taking their eyes off the road, significantly improving safety.

- **Healthcare:** NLP voice assistants are transforming healthcare by reducing administrative burden and improving patient care. Clinicians use voice-to-text systems powered by specialized medical NLP models to dictate clinical notes, reducing documentation time. AI voice agents are now acting as virtual receptionists and clinical assistants, helping doctors document patient visits in real-time and reducing administrative burnout. For patients, voice assistants provide medication reminders, answer basic health questions, monitor symptoms through conversational interfaces, and even support mental health through empathetic dialogue.
- **Education:** In education, NLP voice assistants serve as personalized tutors and learning companions. Students can ask questions in natural language—“Explain green chemistry” or “Help me solve this quadratic equation”—and receive step-by-step explanations, quizzes, or practice conversations for language learning. Voice interfaces lower barriers for younger children or those with learning disabilities who may struggle with typing or reading. Teachers use voice assistants for classroom management, grading spoken responses, or generating lesson plans. Accessibility is a major benefit: voice technology helps students with visual impairments or motor challenges participate fully in educational activities.
- **Business:** Businesses have widely adopted voice assistants and chatbots with voice interfaces to handle customer inquiries at scale. Call centers use interactive voice response (IVR) systems enhanced by modern NLP to understand complex queries, route calls intelligently, and resolve issues without human agents for routine matters. This reduces wait times and operational costs while maintaining 24/7 availability. In retail, hospitality, and banking, voice assistants manage reservations, track orders, provide account information, and offer personalized recommendations.
- **Ecommerce:** Walmart's integration of voice assistants into its shopping experience showcases how retail can benefit from this technology. Customers can use voice commands to add items to their shopping carts, check order statuses, and receive personalized shopping recommendations.

This functionality is particularly beneficial for busy customers who can manage their shopping lists while multitasking. The result is a more convenient and efficient shopping experience, contributing to increased customer loyalty and sales.

BENEFITS

The integration of advanced NLP techniques has revolutionized how users interact with technology, offering profound benefits in terms of accuracy, personalization, and accessibility. One of the primary benefits of NLP in voice assistants is the significant improvement in accuracy and intent recognition. Other benefits of NLP voice assistants include the following [1,2,9,10]:

- **Accessibility:** Perhaps one of the most socially significant applications of NLP voice assistants lies in improving accessibility and social inclusion. For individuals with visual impairments, motor disabilities, or conditions like arthritis or paralysis, voice provides a primary interface to smartphones, computers, and the Internet. Voice assistants empower users to read messages, browse the web, control devices, and communicate independently. Voice control enables independent management of lights, thermostats, entertainment, and communication, reducing reliance on caregivers and enhancing autonomy and quality of life.
- **Democratization of Technology:** Voice interfaces lower barriers for non-tech-savvy users and support multilingual capabilities, aiding adoption in diverse markets like India. By making technology more intuitive and human-centered, they democratize access to information and services, boost productivity, enhance safety, and promote inclusion.
- **Multilingual Support:** As chatbots and voice assistants become global, the ability to understand and generate multiple languages has become essential. NLP models are increasingly capable of supporting hundreds of languages and dialects, breaking down language barriers for non-native speakers of dominant languages. Multilingual NLP capabilities are expanding access in diverse linguistic communities. Real-time translation features in voice assistants break down language barriers during travel or international business. For people with speech impairments, advances in dysarthric speech recognition and augmentative and alternative communication tools integrated with NLP are opening new possibilities.

- *Contextual Awareness:* Contextual awareness is one great evolution in NLP that benefits a voice assistant. A major milestone in the evolution of voice assistants is the ability to maintain context over the course of a conversation. Traditional systems treated every query as an isolated event. However, advanced NLP models now support “contextual awareness,” which allows the assistant to remember previous interactions within a session. This reduces the cognitive load on the user, who no longer needs to repeat specific details, thereby creating a more seamless and efficient user experience.
- *Personalization:* One of the key advances in modern conversational AI is personalization. Chatbots and voice assistants are increasingly able to adapt their behavior based on user preferences, history, and context. This makes interactions feel more human and efficient. NLP facilitates a high degree of personalization by learning from user behavior and preferences over time. By analyzing past queries and interaction patterns, voice assistants can tailor their responses to individual users. This personalization extends to recognizing different voices and adapting to specific dialects or accents, which is crucial for global adoption. Personalization requires integrating NLP with other AI technologies, such as recommendation systems, user modeling, and contextual reasoning.
- *Sentiment Analysis:* One of the most impactful developments is the integration of sentiment analysis, which is meant to check the sentiment or emotion hidden behind the text. Sentiment analysis has evolved greatly, from lexicon-based basic techniques to neural architectures that could better capture the nuanced emotional contexts. Advanced models such as BERT and GPT have revamped the area with high accuracy for detecting sentiments across diversely different platforms, including informal settings such as social media. By analyzing the user's choice of words and tone of voice, modern assistants can detect frustration, satisfaction, or urgency. This allows the system to adapt its response dynamically. This capability enables the assistant to adjust its tone or prioritize certain actions, such as escalating a customer service issue if it detects a high level of user dissatisfaction. Such nuanced understanding significantly enhances the overall quality of the user experience.
- *Emotional Intelligence:* The application of generative AI has enabled emotional intonation in TTS systems. Voice assistants can now modulate

their acoustic characteristics to express empathy during a complaint or excitement when confirming a successful transaction. Research indicates that this emotional intelligence significantly increases user trust and engagement, making the interaction feel less transactional and more relational.

- *Continuous Improvement:* Every conversation teaches voice assistants something new. This is why Alexa, Google, and Siri are way better at answering questions today than they were a few years ago. The more they “experience,” the better they get.

CHALLENGES

Despite their benefits, voice assistants face notable ethical and technical challenges. Accuracy in noisy environments, handling accents and dialects, preserving privacy (voice data is highly sensitive), and reducing hallucinations or incorrect information in open-ended responses are areas of concern. There are also concerns about children forming attachments to synthetic voices or the spread of misinformation through voice responses. Other challenges of NLP voice assistants include the following [1,2,9,10]:

- *Privacy Concerns:* Always-listening devices raise fears of passive recording and data misuse. Recordings are typically sent to company servers, and high-profile incidents of unintended activations have fueled distrust. Many users express concerns about who is “listening” and how data is used for profiling or advertising. As voice assistants become more “ambient”—integrated into our homes, cars, and offices—concerns regarding privacy and data security have naturally intensified.
- *Ethical Concerns:* Ethical considerations around data collection, bias in training data, and over-reliance on AI companions require careful attention. As voice assistants become more integrated into daily life, several ethical and societal challenges related to NLP emerge. Privacy and security are paramount concerns. Voice data is considered biometric and highly personal, raising questions about how this data is collected, stored, and used.
- *Data Quality:* The scarcity and quality of data pose a substantial technical barrier. The overall quality of the training data defines the model’s ability and efficiency in terms of accuracy. For the best result, it takes a lot of time to choose a quality dataset, and it is better to use data cleaning or data augmentation to improve the quality of the dataset. Training robust NLP models requires vast

amounts of high-quality voice data, which includes transcribed and annotated speech. The process of collecting, transcribing, and annotating this data is expensive and time-consuming, particularly for specialized domains like healthcare. This data bottleneck can hinder the development of more sophisticated and inclusive voice assistant capabilities. Figure 5 shows some data engineers [4].

- *Noise*: A primary concern is the acoustic environment and noise. Voice assistants often operate in diverse and unpredictable settings, ranging from quiet rooms to bustling streets. Background noise, overlapping speech, and varying distances from the microphone can severely degrade the performance of automatic speech recognition (ASR) systems, making it difficult for the NLP component to accurately transcribe spoken words.
- *Ambiguity*: Another significant technical hurdle is contextual ambiguity. Human languages—English, Spanish, Mandarin, Bengali, Arabic, French, and thousands of others—are complex, ambiguous, and deeply tied to context. Unlike programming languages, which are structured and rule-based, human communication is full of nuance, metaphor, and variation. Human language is inherently ambiguous, with words often having multiple meanings and pronouns referring to previously mentioned entities. Resolving these ambiguities requires a deep understanding of the conversational context, which current NLP models struggle to achieve consistently. The inherent complexities of human language introduce a distinct set of linguistic challenges for NLP in voice assistants. One of the most prominent issues is dealing with accents and dialects.
- *Robustness*: Another challenge is robustness. Conversational systems must handle noisy input, including speech errors, background noise, slang, and code-switching between languages. They must also be able to recover gracefully when they misunderstand a user's request.
- *Accuracy*: Accents, dialects, background noise, and ambiguous language can still lead to errors. While accuracy has improved dramatically, failures in critical contexts (e.g., medical or financial commands) can erode trust. The NLP technology allows a voice assistant to practically interpret and react to human language with high accuracy. There is a constant tension between latency and accuracy. Voice assistants are expected to provide real-time responses, demanding rapid processing of spoken input. This real-time requirement often forces a trade-off, where the depth and complexity of NLP analysis might be limited to ensure a swift reply. Achieving both high accuracy and minimal latency remains a significant engineering challenge.
- *Bias*: Bias and inclusion are critical ethical considerations. Training data can embed biases related to gender, race, or socioeconomic factors in speech recognition and response generation. Bias in language models can lead to unfair decision-making in applications such as hiring and content moderation. If the training datasets for NLP models do not adequately represent diverse demographics, the resulting voice assistants can exhibit algorithmic bias. This can lead to poorer performance for certain ethnicities, genders, or age groups, effectively excluding segments of the population from fully benefiting from the technology. Addressing this requires intentional efforts to diversify data collection and implement fairness-aware AI development practices.
- *Integration*: NLP does not operate in isolation. Its integration with other branches of AI enhances the capabilities of chatbots and voice assistants. A trend that can be identified with current machine learning NLP models is the inclusion of other AI technologies, like computer vision and audio recognition. This integration results in the creation of enhanced and effective advanced intelligent systems that can handle both textual and graphical data. Computer vision, for example, allows systems to interpret gestures, facial expressions, and visual context, enabling multimodal interactions where users can speak, point, or look at objects. More profound interactivity would come into the scenario in which a voice assistant actually takes over control of all smart devices, effecting orders, and generally interacting with other platforms of technology without a bar.
- *Computational Efficiency*: With the rapid scaling of NLP models, computational efficiency has become a primary concern. Large models require significant processing power and memory, limiting their accessibility. To address this, researchers have introduced techniques such as knowledge distillation and quantization, which reduce model size while maintaining performance. Companies are exploring energy-efficient hardware to support AI workloads, optimizing GPU and TPU architectures to reduce

computational costs while maintaining high performance.

FUTURE OF NLP VOICE ASSISTANTS

The rapidly evolving field of NLP and a lot of new research are pointing toward a bright future for voice assistants. The future of voice assistants points toward deeper integration with everyday life. Improvements in AI will enable more natural conversations, emotional understanding, and multilingual fluency. As smart environments expand, voice assistants may become the primary interface for interacting with digital ecosystems, blurring the line between human and machine communication.

The trajectory of voice assistants points toward agentic AI. Future systems will transition from reactive responders to proactive agents capable of autonomous decision-making and complex task execution. Voice technology is converging with generative AI to create more capable “voice agents” that can reason, plan multi-step tasks, and handle complex workflows autonomously. As NLP technology advances—particularly with large language models (LLMs), multimodal AI, and improved reasoning capabilities—voice assistants are evolving beyond simple command-and-control systems into collaborative agents. The convergence of NLP with other technologies will expand applications further [2]. The trajectory of NLP suggests a future where chatbots and voice assistants become increasingly indistinguishable from human interlocutors. In the coming decades, the fusion of language understanding, reasoning, and emotional intelligence will reshape communication between humans and machines, dissolving the boundary between conversation and computation.

CONCLUSION

Natural language processing has fundamentally redefined the capabilities of voice assistants, transforming them from rudimentary novelties into indispensable tools for daily life and enterprise operations. The NLP voice assistants represent a fundamental shift in how humans interact with technology—from graphical user interfaces to conversational ones. They have moved from novelty gadgets to essential infrastructure across consumer, professional, medical, educational, and social domains. They are becoming as indispensable as the Internet itself. There are many voice assistants on the market nowadays using NLP technology like Siri and Google Assistant.

NLP is a subfield of artificial intelligence that combines computer science, artificial intelligence, and linguistics. It initiates the interaction between computers and human languages. It lies at the center

of language translation, sentiment analysis, and chatbot development. It powers the voice assistants that respond to commands and the chatbots that engage customers across websites, apps, and support centers. The NLP industry is highly competitive. It is crowded with major global corporations that have strong infrastructure and smaller innovative startups that bring new ideas to the market. As NLP continues to mature, voice assistants and chatbots will become even more intuitive and emotionally aware. The future of voice assistants and NLP is bright, with innovations poised to make these technologies even more integrated into our daily lives. More information about NLP voice assistants can be found in [11,12] and the following related journals:

- *Natural Language Processing Journal*
- *Journal of Emerging Technologies and Innovative Research*

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Figure 1 A representation of NLP [4].



Figure 2 A voice assistant [6].



Figure 3 How voice assistants understand what you say [7].



Figure 4 How NLP powers voice assistants and chatbots [7].



Figure 5 Some data engineers [4].