**Understanding Voice Naturalness**

Christine Nussbaum1,2, Sascha Frühholz3,4, and Stefan R. Schweinberger1,2,5

1Department for General Psychology and Cognitive Neuroscience, Friedrich Schiller University Jena, 07734 Jena, Germany

2Voice Research Unit, Friedrich Schiller University, 07743 Jena, Germany

3Department of Psychology, University of Oslo, 0371 Oslo, Norway

4Cognitive and Affective Neuroscience Unit, University of Zurich, 8050 Zurich, Switzerland.

5Swiss Center for Affective Sciences, University of Geneva, 1222 Geneva, Switzerland

Correspondence should be addressed to Christine Nussbaum, Department for General Psychology and Cognitive Neuroscience, Friedrich Schiller University Jena, Leutragraben 1, 07743 Jena, Germany. Tel: +49 (0) 3641 945939, E-Mail: [christine.nussbaum@uni-jena.de](mailto:christine.nussbaum@uni-jena.de). Supplemental materials to this work are accessible on the associated OSF-repository: <https://osf.io/asfqv/?view_only=62f8d88705bb4363903983c8bd08a2cf>

**Highlights**:

* Voices elicit impressions about their naturalness, which affect interactions between humans as well as with artificial agents
* Despite its intuitive appeal and practical importance, a systematic understanding of voice naturalness is elusive – the concept is scientifically ill-defined
* We show that current voice naturalness research is situated within different research domains that resemble echo chambers within science – they neither cross-refer to one another nor to current voice perception theory
* We offer a concise conceptual framework by proposing a taxonomy with two distinct types: deviation-based naturalness and human-likeness-based naturalness
* We develop practical recommendations and perspectives for naturalness research. We argue that, in a world of digital agents, understanding the determinants for how humans perceive naturalness in social stimuli is a priority

**Abstract**

Perceived naturalness of a voice is a prominent property emerging from vocal sounds, which affects our interaction with both human and artificial agents. Despite its importance, a systematic understanding of voice naturalness is elusive. We argue this is due to (a) conceptual underspecification, (b) heterogeneous operationalization, (c) lack of exchange between research on human and synthetic voices and (d) insufficient anchoring in voice perception theory. Here we reflect on current insights into voice naturalness by pooling evidence from a wider interdisciplinary literature. Against that backdrop, we develop a concise definition of naturalness and propose a conceptual framework rooted both in empirical findings and theoretical models. We identify gaps in current understanding of voice naturalness and sketch perspectives for empirical progress.

**Keywords:** Naturalness, Human-likeness, Voice perception, Authenticity, Voice synthesis

# Introduction

Human behavior is influenced by the perceived quality of objects and organisms that are encountered in our natural, social, and virtual environments. An important quality dimension concerns perceived “naturalness”. Assessing naturalness has an evolutionary meaning, as it influences interactions, food choice, and social trust (Quelle). Naturalness, from a biological perspective, can be understood as the adaptive norm, with extreme deviations supposedly being rather “unnatural” instances (Quelle). Besides the biological context, the recent emergence of AI-generated digital and virtual contexts has brought human-machine interactions to everyday life, and therefore questions of naturalness to the forefront of scientific research.

A domain where features of (un)naturalness are of particular importance is the voice, as one of the prime channels for communication for humans [1] and beyond: **unca** increasingly emerge as major carriers of communicative interactions, such as in customer service calls, gaming environments, or support platforms [2,3]. When listening to voices, we form an instant impression about them [4]. Crucially, listeners seem to be very sensitive to (un-)natural voice features, which affects communicative quality [5,6]. ToDo: Satz, wie eine unnatürliche Stimme klingen könnte. For **human voices**, consistent evidence from different speech-language pathologies shows that impairments in speech naturalness affect everyday interaction to a degree that can result in social isolation, reduced quality of life, and even depression [7,8]. Similarly, deliberate acoustic manipulations and distortions disrupt effective communication [9–12]. For **synthetic voices**, one can hardly keep up with the rapid developments which make indefatigable efforts to resemble human vocal expression [13,14]. However, as of today, synthetic voices are consistently rated as less natural than human voices, which simultaneously affects perceived likeability, trustworthiness, and pleasantness [15–19].

Given the widespread practical importance, it is crucial to put the role of voice naturalness into scientific focus. But although many recent studies provide useful empirical insights, we are currently looking at a rug rag rather than a research field. This has motivated us to take a step back and reflect on four problems in the present literature: (a) conceptual underspecification, (b) inconsistent operationalization, (c) lack of exchange between research domains and (d) insufficient anchoring in voice perception theory. We argue that these problems have so far precluded a systematic understanding of vocal naturalness, impeded the visibility to a wider readership, made us overlook crucial research questions, and led to a divergence between theory and practice. In what follows, we will elaborate on each of these problems, before proposing concrete measures to address them, starting with the development of a concise conceptual framework for voice naturalness. To this end, we aim to provide a useful basis for systematic and theory-driven research on voice naturalness in the future.

# Current Problems

## Conceptual Underspecification

Voice naturalness lacks a consistent definition and terminology in the literature (see **Figure 1, A-B**). In fact, the majority does not even provide an explicit definition of naturalness at all (see **Box 1**). In these studies, the conceptualization of naturalness can only be drawn implicitly from the empirical design. If definitions are provided, they vary tremendously across research contexts. In speech-language pathology, several researchers refer to the definition provided by Yorkston and collegues (1999): “*Naturalness is defined as conforming to the listener’s standards of rate, rhythm, intonation, and stress patterning and to the syntactic structure of the utterance being produced*” [8,20]. In contrast, research on synthetic and non-human voices usually defines naturalness as “*speech most closely perceived as a human voice*“ [21] or “*the degree to which a user feels a certain technology or system is human-like*” [22]. Accordingly, many studies using synthetic voices do not refer to naturalness but to human-likeness or **anthropomorphism** of voices.

Interestingly, these definitions seem to share two important assumptions: First, voice naturalness is a perceptual and subjective measure [23]. Second, listener’s naturalness perception is the result of a complex multifactorial impression formation, presumably based on the integration and weighting of many **acoustic cues** [24]. Beyond that, however, the conceptualizations are very heterogeneous because they are tailored to the respective empirical focus. Unfortunately, despite covering relevant aspects, these prevailing inconsistencies alongside the heterogeneous terminology make it very challenging to compare and integrate different insights into voice naturalness. We therefore see a strong need to unite them under a concise conceptual framework, which we provide in **Section 3**.

*[Insert Figure 1 about here, please]*

## Heterogeneous Operationalization

A common consequence of inconsistent conceptualization is heterogeneous **operationalization**. Primarily, this concerns the studied vocal categories and features, which include human vs. synthetic voices [25–30]; cartoon voices [31], pathological voices such as in individuals with Parkinson’s’ disease [32–34], **tracheoesophageal speech** [35,36], **dysarthria** [37–40], down syndrome [41], or stuttering [42]; acoustically manipulated human voices [43], vocal fry [44], as well as different accents [45,46], dialects [47], age groups [48–50], and gender identities [51–53]. In addition, it concerns the experimental designs and measurements, especially rating scales, which differ in the number of levels and denominations of endpoints. For example, in one study participants were asked “How natural is the audio?” [54], in another one they rated voices on a 10-point-scale from “very natural, human-like” to “very mechanical, robot-like” [46]. In principle, such empirical heterogeneity can be a powerful source of insight. However, an insufficient report of empirical details impedes a meaningful integration of findings. Specifically, it is often not stated how naturalness and the related experimental task was explained to the listeners – but precise instructions can be crucial determinants of study outcome. Further, the precise acoustic properties of the voice material often remain elusive, bearing a risk for potential undetected confounds. Finally, few studies only provide measurements on reliability [55]. To address these issues, we collected some practical recommendations as a guidance for future research in **Box 2**.

## Lack of exchange between different research domains

Research on voice naturalness is inherently interdisciplinary, with two main domains: speech-language pathology and synthetic voices. However, while the scientific output is well-received within disciplines, they are remarkably poorly interconnected. **Figure 1C** illustrates this via a cross-citation analysis using VOSViewer [56], showing several distinct clusters of studies reminiscent of echo chambers which are frequently discussed in social media [57]. One may argue that this is not problematic, because the different disciplines simply have different interests and readerships. However, some intriguing commonalities and systematic patterns only emerge when pooling evidence from all available angles. For example, across synthetic, pathological and acoustically manipulated voices, converging evidence emerges for a strong effect of pitch variation on perceived naturalness [12,15,58]. Further, while several studies failed to find an **uncanny valley** effect for synthetic voices [16,59], a recent study suggest it might exist for pathological ones [60]. In fact, we argue that the lacking exchange between research fields has not only precluded relevant insights but has impeded the visibility and impact of voice naturalness research as a whole.

## Insufficient anchoring in voice perception theory

The majority of naturalness research comes from applied fields, aiming to optimize artificial agents and improving the quality of life in patients with voice disorders. These findings equip us with valuable practical knowledge, but they are insufficiently anchored in voice perception theory. As an illustration, we added ten influential, theory-building voice perception publications to the VOSViewer analysis (**Figure 1C**), with the outcome suggesting that these tend to be ignored by most previous naturalness research. This leaves us with an intriguing divergence between increasing applied knowledge in rapidly developing branches (especially synthetic voices) on the one hand, but a simultaneous lack of understanding of basic mechanisms on the other. To fully understand how naturalness affects our perception and response to voices, this void needs to be filled.

# Toward a concise framework for voice naturalness

After identifying key problems that impede a systematic understanding of naturalness in voices, we now propose concrete measures to address them, starting with a conceptual framework for the explicit definition of naturalness in voices.

## Definitions of naturalness

We propose a taxonomy with two distinct types: Deviation-based naturalness and human-likeness-based naturalness (**Figure 2**). In **deviation-based naturalness**, naturalness is defined as the deviation from a reference that represents maximum naturalness. Example instructions for raters could be “Does this voice sound distorted?”, “Does this voice sound unusual”, or just “Does this voice sound natural?”. This conceptualization needs two important specifications: the **reference** representing maximum naturalness, and the **type of deviation**. In some cases, the reference is explicitly provided e.g. through a comparison or baseline stimulus (see [61]). However, in many studies, raters are instructed to use an inner implicit reference which is based on their experience and expectations, e.g. whether “*the voice stimulus is perceived as a plausible outcome of the human speech production system*“ [12]. The type of deviation is specified through the vocal material. It can virtually cover all acoustic features, ranging from specific manipulations (e.g. spectral features or speech rate [11,62,63]) to complex multivariate vocal patterns (e.g. in distorted or pathological voices [64]).

**Human-likeness-based naturalness** defines naturalness by its resemblance to a real human voice. An instruction for raters could be “Does this voice sound like a real human speaker?” or “How human-like does the voice sound to you?” Compared to the deviation-based definition, it comes with an important additional assumption: the existence of a non-human voice category, and hence a categorical boundary to human voices (although the transition between categories can be continuous). In other words, a definition of human-likeness is only meaningful if we assume that voices can be non-human in principle. Apart from this important distinction, human-likeness-based naturalness can be seen as a special case of deviation-based naturalness: the reference is a human voice (or listeners´ representation of a human voice), and the deviation lies on the human/non-human spectrum.

With this taxonomy, we provide a flexible and intuitive reference for the explicit definition of naturalness alongside with its underlying assumptions. With future research committed to one conceptual framework, systematic integration and comparison of findings could be greatly facilitated. In fact, both conceptualizations seem already prevalent, but often remain implicit through certain design choices only (see **Box 1**). For example, comparing human to synthetic voices typically implies human-likeness based naturalness, whereas assessment of pathological voices often employs the deviation-based approach. One study deserves particular mention: [60] studied the uncanny valley effect in different types of unnatural voices. They found that impressions of uncanniness resulted from “deviation from familiar categories” rather “categorical ambiguity”. This could reflect initial empirical observations in line with our proposed conceptual distinction.

*[Insert Figure 2 about here, please]*

## Delimiting distinctiveness and authenticity

In the following, we briefly discuss the demarcation of the proposed naturalness definitions from two established concepts in perception research, starting with distinctiveness. **Distinctiveness,** as opposed to typicality**,** has been defined as the degree to with faces or voices stick out due to rare or unusual features and this concept is commonly used to refer to voice identity [65,66]. According to face or voice space models, individual instances are represented along multiple perceptual dimensions, and they appear as distinctive if they deviate substantially from a central tendency or norm in that space [67]. Our deviation-based definition of naturalness is closely related to the concept of distinctiveness, as both share two critical features, a norm/reference and a deviation. However, we understand distinctiveness as a different concept which can capture multiple forms of deviations beyond naturalness. Accordingly, while unnatural voices would commonly be perceived as somewhat distinctive, natural voices can be distinct or typical. Impressions of human-based naturalness, however, could potentially be quite independent from impressions of distinctiveness, e.g. a person who is very accustomed with a smart-speaker device may not rate synthetic voices as very distinctive but still clearly non-human. In that vein, the link between distinctiveness and naturalness may not primarily be a conceptual but an empirical matter.

A second concept that deserves particular consideration is **authenticity**. In the scientific literature, authenticity is an established concept with meaning that may refer to vocal emotion, identity or gender – rather than the holistic impression of a voice. Emotional authenticity, for example, refers to the distinction between a posed and a “real” or spontaneous emotional expression, which leads to differential behavioral and neural outcomes [68–70]. In the context of voice cloning and the now very prevalent danger of **deepfakes** [71], identity authenticity is assessed with regard to a specific speaker. Likewise, voice gender cues can be rated for gender authenticity, which is closely related to judgement of gender conformity [72,73]. In fact, when prompted for synonyms of naturalness, authenticity was **ChatGPT**´s first reply (**Figure 1 B**), suggesting semantic relatedness between these two terms in openly accessible online sources. In principle, it can be argued that authenticity is just a special form of deviation-based naturalness, with a more specific reference. E.g. “Does this sound like a natural voice?” is converted into “does this sound like a natural emotional expression?”. However, if considered against the backdrop of voice perception theory, it becomes apparent that assessments of naturalness and authenticity appear at different stages of voice processing (see Section 5 and Figure 3). Thus, we tend to keep the concepts of naturalness and authenticity rather separate.

# Converging evidence

In our view, understanding of voice naturalness requires pooling evidence from all relevant fields. Even when these may nurture different perspectives on voice naturalness, they are united by overarching questions: How do we form an impression on voice naturalness? Which acoustic features affect this impression? How does naturalness impact perception, interaction, and communication? Can we understand differences across individuals and listening contexts?

We propose that conceptual progress for disintegrated – but also highly interdisciplinary – naturalness research can be achieved by two measures: (a) converting, via an integrative perspective, empirical heterogeneity (Section 2.2) from an impediment into an advantage and (b) fostering mutually beneficial exchange between fields. Awareness for the interdisciplinary nature of the field is crucial for implementing both steps: First, publications need to be findable and accessible, preferably through the establishment of common terminology that feeds into common keywords. Second, findings need to be communicated inclusively for readerships from diverse backgrounds. This entails providing explicit definitions, avoiding technical jargon, incorporating scientific standards from other fields where appropriate, and discuss own findings against a wider interdisciplinary naturalness literature. Finally, conceptual and empirical aspects need to be reported with sufficient detail to promote comparability. In **Box 2**, we converted these suggestions into practical recommendations.

We believe progress along these lines will not only enhance mutual inspiration between clinicians and engineers but could also foster innovative health technology. For instance, voice naturalness is a key objective for cochlear implant (CI) research, where a sensory prosthesis restitutes hearing in people with sensorineural deafness by resynthesizing auditory signals for direct electrical stimulation of the cochlea [74], and real-time synthesis in CI sound processors could be modified to achieve better perceptual outcomes, ultimately benefitting quality of life [75]. For people who are predicted to lose their personal voice due to progressive disorders such as ALS, or due to planned **laryngectomy**, current voice banking technology already allows for speech synthesis with the patient´s former individual voice, often with remarkably high ratings of both naturalness and authenticity [76,77].

# Naturalness research rooted in voice perception theory

Several authors have pointed out that research on voice naturalness is rather insufficiently rooted in theoretical perspectives on voice perception and voice analysis [8,13]. As discussed in Section 2.4, the topic of voice naturalness is highly influenced by research perspectives from applied sciences and seemingly less by basic voice research and its theoretical approaches. However, neurocognitive models of voice perception can provide processual perspectives on multi-level voice perception and voice information analysis. This allows rooting the mechanisms and types of voice naturalness assessments at relevant levels of voice analysis. Influential theories of voice perception propose sequential and partly hierarchical stages of voice processing, including a major distinction between mechanisms for voice object analysis as initial stages that are followed by the analysis of communicative and social content carried by the voice signal [1,4,78,79].

This processual distinction between voice object analysis and voice content analysis is relevant as it pertains to the necessary conceptual distinction between voice naturalness assessments on one hand and the assessment of the authenticity of expressed voice content on the other hand (**Figure 3**). Assessing the naturalness of voices is conceptually associated with the initial levels of voice object analysis, including the stages of low-level auditory analysis and the analysis of structural voice patterns. Humans presumably assess acoustic feature deviations and acoustic feature likeness as low-level naturalness assessments [80], whereas assessing pattern deviations and pattern likeness concerns the assessments of natural or unnatural spectrotemporal voice profiles [81].

Unlike the rooting of naturalness assessments at the processual levels of voice feature and object analysis, authenticity assessments most likely appear at the level of voice information analysis. Voices are used as carriers to express communicative and social content. For example, voices are used for speech communication, emotional expressions, and to produce individual voice characteristics that are detected by cognitive and neural recognition mechanisms. Such voice content could be either spontaneous and authentic, or it could be acted and thus rather nonauthentic [82]. This authentic/non-authentic distinction specifically also concerns person-specific identity information in voices, which could be real or fake [71]. Such authenticity assessments might be independent of naturalness assessments, although we consider the possibility of mutual influences. For instance, perceiving a voice as unnatural might bias non-authenticity judgments of voice content, and vice versa.

*[Insert Figure 3 about here, please]*

# Perspectives for future research

While this article focuses on understanding naturalness in voices from an interdisciplinary perspective, we wish to emphasize the multisensory perspective of naturalness research. In fact, substantial research in the domain of faces has compared the perceived naturalness or realism of synthesized versus real faces (for a systematic review and meta-analysis, see [83]). Recent research even demonstrated conditions in which synthesized faces can be perceived as more human than genuine human faces. Moreover, an attempt to identify the visual features that trigger such a paradoxical facial “hyperrealism” effect suggested contributions of typicality, familiarity, attractiveness and low memorability [84]. Although this interpretation was based on qualitative reports and requires converging evidence, it seems clear how such research can inspire systematic search for commonalities or differences between mechanisms that trigger voice or face naturalness. Ultimately, we believe that naturalness research should also systematically consider interactions between vocal and visual aspects of naturalness in combination. Indeed, accumulating evidence suggests a complex interplay of visual appearance, vocal features, behavior and the interactional context for the acceptance of virtual agents [18,85–95].

From a methodological viewpoint, the combination of voice synthesis methods – especially those that permit to selectively manipulate target acoustic parameters of voices – with brain recordings also seems promising. For instance, EEG/ERP recordings provide precise information about when in time acoustic manipulations that compromise perceived naturalness affect neural processing of emotional voices, and how this relates to listeners´ emotion perceptions [96–98]. Moreover, very recent fMRI research has uncovered a cortical-striatal brain network that is involved when listeners try to distinguish deepfake from real speaker identities [71]. Such research is relevant also because the accelerating spread of misinformation via social media is now considered a major problem which compromises societal cohesion [57,99]. While large-scale misinformation is still mostly text-based as of today, next-generation deepfakes likely will be even more efficient vehicles of misinformation. This is because they efficiently instrumentalize person-related trust via high-level perceptual deception. On that perspective, better understanding of characteristics of “successful” vocal deepfakes and their processing in the brain may be one important component for strengthening human resilience to fake information of the future.

# Concluding remarks

Naturalness in voices is a highly intuitive concept, but one that is scientifically underspecified and far from systematically understood, despite considerable research efforts. To address this, we propose a conceptual framework for voice naturalness. Our taxonomy, comprised of deviation-based naturalness and human-likeness based naturalness, is rooted in voice perception theory, and is inspired by diverse interdisciplinary empirical findings. The new framework offers the flexibility that is necessary to be applicable across diverse empirical designs, while at the same time promoting comparability across research domains. We complement this conceptual groundwork with several practical recommendations to bridge previously unconnected approaches and better integrate this highly interdisciplinary field. We hope to provide a foundation for conjoined efforts towards more systematic future research on numerous **outstanding questions** on voice naturalness. While we here focus on voices, we ultimately opt for a multisensory perspective on naturalness research. In a world that is increasingly dominated by digitally synthesized agents, it seems important to identify the multifaceted determinants for human perception of naturalness in social stimuli.

**Figure Legends**

**Figure 1**

Terminology and interconnectivity of voice naturalness research

*Note.* ***A)*** *Word cloud depicting synonyms and closely related concepts from* 72 *publications that target naturalness in voices (for details, see* ***Box1****). Word size represents number of occurences.* ***B)*** *A similar word cloud but generated by ChatGPT (*[*https://chatgpt.com/?oai*](https://chatgpt.com/?oai)*, 29.04.2024), when prompted to generate 10 synonyms each for pathological, synthetic/manipulated, and healthy voices, together with relative occurrence frequency. The full prompt and the generated response are accessible on* [*OSF*](https://osf.io/asfqv/?view_only=62f8d88705bb4363903983c8bd08a2cf)*.* ***C)*** *A bibliographic network visualization using VOSviewer [56], covering publications related to voice naturalness across different domains and 10 basic voice theory papers. Each colored dot represents a publication and grey links represent citations. Size of the dots indicate the number of links to other publications. Clustering (depicted by different dot colors) is performed automatically in VOSviewer. Closer inspection reveals that green refers to basic voice theory papers, red corresponds predominantly to papers on pathological voices and blue refers to synthetized/manipulated voices. A full documentation and an interactive version of the bibliographic network can be found on* [*OSF*](https://osf.io/asfqv/?view_only=62f8d88705bb4363903983c8bd08a2cf)*. [26]*

**Figure 2**

A conceptual framework for the definition of voice naturalness

*Depiction of the proposed taxonomy comprised of deviation-based naturalness and human-likeness-based naturalness. Left panel: Naturalness is assessed with regard to a reference frame that is rooted in the human voice production system and that represents maximum naturalness. The reference point can be either an explicit target voice, e.g. a comparison stimulus, or an implicit representation of a prototypical natural voice. Middle panel: In deviation-based naturalness, voice naturalness is assessed through the deviation from the reference point. The type of deviation can be manifold and is usually specified through the vocal material (e.g. clinical voice alterations, manipulations, or sound artefacts). Human-likeness-based naturalness defines naturalness by its resemblance to a real human voice. This definition implies that there is a non-human voice category and a categorical boundary to the human voice space. Right panel: both types of naturalness assessment are suitable for different kinds of voice samples, e.g. human voices, synthetic voice, or voice-like sounds.*

**Figure 3**

ToDo

**Outstanding questions:**

* Vocal communication is abundant in the animal kingdom, and many animals manipulate their vocal behavior in an adaptive manner – is there demand for a comparative perspective on voice naturalness?
* How is a listener´s perception of naturalness shaped through experience (e.g., with voice assistants, smart home devices, or patients with voice disorders)?
* With respect to the present conceptual framework, (how) are human-likeness based naturalness and deviation-based naturalness dissociable in the brain?
* In the trade-off between precise experimental control and open field recordings, can we identify converging evidence for how and when reduced naturalness in voices critically affects the ecological validity of research? In depth, will we need a dynamic definition of ecological validity in view of an ever more digital world of social interaction?
* Are natural voices always preferred, or is naturalness preference context dependent? Can natural voices impede rather than promote communication success in some situations?
* Many domains of social perception are characterized by substantial individual differences, but it is unclear whether there are substantial individual differences in the tolerance of or preference for unnatural voice features. If so, can these be related to other domains of auditory cognition, or to other person traits?
* To what extent is naturalness perception affected by factors such as age, gender, or cultural background?

**Box 1**: A field in numbers

For a more systematic overview on scientific insights into naturalness in voices, we conducted a literature search on Web of Science on 26 April 2023 using the search terms “naturalness AND voice” and “human-likeness AND voice”, which was repeated on 28 May 2024 to detect the most recent papers. This initial search resulted in 339 articles, to which we applied the following inclusion criteria: (1) Language of publication was English. (2) Papers were published in peer-reviewed journals or as a conference contribution. (3) Voice naturalness/human-likeness was either measures or manipulated. (4) Papers reported either a quantitative empirical analysis of human performance/perception data or a literature integration of such works. Thus, we excluded works on automatic naturalness classification and mere descriptions of toolboxes or datasets. (5) Finally, we focused on spoken utterances, excluding singing voices and non-linguistic vocalizations. Following these criteria, we also screened the reference lists of the identified articles for relevant publications. For a full documentation of all included papers, please refer to [*OSF*](https://osf.io/asfqv/?view_only=62f8d88705bb4363903983c8bd08a2cf)*.*

In total, we identified 72 articles, covering a time range from 1984 to 2024. Thirty-eight (53%) were published in the last 5 years. Sixty-seven report behavioral empirical data, of which 48 are predominantly ratings. Two are literature reviews, and three used neurophysiological measures. Regarding voice category, 33 used synthetic, 18 human-pathological, 6 human-manipulated and 5 healthy human voices. 10 used more than one of these voice categories. In only 32 papers, we could identify an explicit definition of naturalness. The full compilation of extracted definitions can be accessed on [*OSF*](https://osf.io/asfqv/?view_only=62f8d88705bb4363903983c8bd08a2cf)*.* We noticed that the articles presented a large variability in wording and vocabulary. In an attempt to capture this verbal space, we scanned all articles for synonyms and closely related concepts of naturalness. The output is captured in the word cloud in **Figure 1, A**. Subsequently, we compared these to the articles’ keywords: 58 papers provided keywords, but only 32 had keywords related to naturalness or any of its synonyms. Finally, we coded the conceptualization of naturalness according to the taxonomy proposed in Section 3. In case no definition of naturalness was provided, we inferred the ‘implicit’ conceptualization from the research design. With this approach, we concluded that 27 employed a deviation-based conceptualization, 35 used human-likeness, and 10 used a combination of both.

**Box 2**: Practical recommendations for voice naturalness research

Research on voice naturalness is highly interdisciplinary. To make future research accessible to a wider readership across disciplines, and allow comparability and integration of findings, sensible awareness for this interdisciplinarity is crucial. Here, we compiled a number of practical recommendations as a tentative roadmap for future research:

* Offer a concise definition of voice naturalness to both participants and readers. With the taxonomy of naturalness in section 3, we offer a conceptual framework that can be tailored to any empirical design, e.g. by specifying the reference and the type of deviation under study. If used consistently, this taxonomy offers quick orientation for readers and fosters comparability across findings.
* Use consistent keywords to make relevant research findable across disciplines. We recommend “naturalness”, “human-likeness” or, in cases discussed in section 3.2, “authenticity”.
* Include full reports on methodological details, including acoustic manipulations, measurements, instructions to raters, and report on reliability.
* Wherever possible, provide stimulus examples. Often, direct auditory impression can be complementary to, and more insightful than, a list of acoustic measures and descriptions. In some cases, differences in audio material may offer a straightforward explanation for different empirical outcomes.
* Communicate findings inclusively enough for readerships from diverse backgrounds. Provide explicit definitions, avoid technical jargon, adopt scientific standards from other fields where appropriate, and discuss findings against the wider interdisciplinary literature.
* Even if naturalness is not of primary interest in a research design, it could have important implications for ecological validity of the stimulus material. Many voice researchers use sophisticated acoustic manipulations such as voice morphing which could have unintended side effects on perceived naturalness [12,100]. If this cannot be avoided, perceived naturalness should be at least quantified, and where possible be considered as a moderating variable.

**Glossary:**

* Synthetic/artificial voice: computer generated voices. Common methods are articulatory synthesis concatenative synthesis, and statistical parametric synthesis, including deep learning algorithms (for a recent overview, see [14])
* Uncanny valley: a sudden feeling of eeriness evoked humanoid robots that almost approach, but do not entirely reach a human-like appearance [101]
* Anthropomorphism: the attribution of human characteristics, emotions, or behaviors to non-human entities
* acoustic cues: physical and measurable features of sounds (such as voices), e.g. fundamental frequency, intensity, timbre or temporal characteristics. Used by listeners to inform manifold impressions about voices, such as age, gender or naturalness.
* Operationalization: translation of a concept or hypothesis into concrete empirical design features
* Laryngectomy: removal of the larynx
* Tracheoesophageal speech: a method of vocalization following total laryngectomy via a tracheoesophageal prosthesis that enables speech through esophageal vibrations.
* Dysarthria: impairments of the speech motor subsystems due to various neurological conditions such as Parkinson’s disease, amyotrophic lateral sclerosis (ALS) or traumatic brain injury.
* ChatGPT: a chatbot developed by OpenAI, based on a large language model, that generates text based on input-prompts (GPT stands for generative pre-trained transformer)
* Deepfakes: digitally manipulated media, such as images, videos, or voice recordings, created using deep learning techniques with the goal to convincingly display the appearances of individuals.

**Acknowledgements**

We thank Simone Dahmen and Fatma Bilem for their support with the literature analysis and the members Voice Research Unit Jena (<https://www.voice.uni-jena.de/>) for helpful suggestions on this project.

**Funding**

The authors gratefully acknowledge the award of funding through an EU-MSCA doctoral network “Voice Communication Sciences” (action 101168998).

References

1. Young, A.W. et al. (2020) Face and voice perception: Understanding commonalities and differences. *Trends Cogn Sci* 24, 398–410

2. Rodero, E. (2017) Effectiveness, attention, and recall of human and artificial voices in an advertising story. Prosody influence and functions of voices. *Computers in Human Behavior* 77, 336–346

3. Rodero, E. and Lucas, I. (2023) Synthetic versus human voices in audiobooks: The human emotional intimacy effect. *New Media & Society* 25, 1746–1764

4. Lavan, N. and McGettigan, C. (2023) A model for person perception from familiar and unfamiliar voices. *Commun Psychol* 1, 1–11

5. Ilves, M. et al. (2011) The Effects of Emotionally Worded Synthesized Speech on the Ratings of Emotions and Voice Quality. In , pp. 588–598, Springer, Berlin, Heidelberg

6. Ilves, M. and Surakka, V. (2013) Subjective responses to synthesised speech with lexical emotional content: the effect of the naturalness of the synthetic voice. *Behaviour & Information Technology* 32, 117–131

7. Damico, J.S. and Ball, M.J., eds (2019) *The SAGE Encyclopedia of Human Communication Sciences and Disorders,* SAGE Publications, Inc

8. Klopfenstein, M. et al. (2020) The study of speech naturalness in communication disorders: A systematic review of the literature. *Clinical Linguistics & Phonetics* 34, 327–338

9. Birkholz, P. et al. (2017) Manipulation of the prosodic features of vocal tract length, nasality and articulatory precision using articulatory synthesis. *Computer Speech & Language* 41, 116–127

10. Birkholz, P. and Drechsel, S. (2021) Effects of the piriform fossae, transvelar acoustic coupling, and laryngeal wall vibration on the naturalness of articulatory speech synthesis. *Speech Commun* 132, 96–105

11. Moore, B.C.J. and Tan, C.-T. (2003) Perceived naturalness of spectrally distorted speech and music. *The Journal of the Acoustical Society of America* 114, 408–419

12. Nussbaum, C. et al. (2023) Perceived naturalness of emotional voice morphs. *Cognition & Emotion,* 1–17

13. Seaborn, K. et al. (2021) Voice in Human–Agent Interaction. *ACM Comput. Surv.* 54, 1–43

14. Triantafyllopoulos, A. et al. (2023) An overview of affective speech synthesis and conversion in the deep learning era. *Proceedings of the IEEE*

15. Baird, A. et al. (2018) The Perception and Analysis of the Likeability and Human Likeness of Synthesized Speech. In *Interspeech 2018,* pp. 2863–2867, ISCA

16. Kühne, K. et al. (2020) The Human Takes It All: Humanlike Synthesized Voices Are Perceived as Less Eerie and More Likable. Evidence From a Subjective Ratings Study. *Frontiers in Neurorobotics* 14, 1–16

17. Lee, E.-J. (2010) The more humanlike, the better? How speech type and users’ cognitive style affect social responses to computers. *Computers in Human Behavior* 26, 665–672

18. Lu, L. et al. (2021) Leveraging “human-likeness” of robotic service at restaurants. *International Journal of Hospitality Management* 94, 1–9

19. Schreibelmayr, S. and Mara, M. (2022) Robot Voices in Daily Life: Vocal Human-Likeness and Application Context as Determinants of User Acceptance. *Frontiers in Psychology* 13, 1–17

20. Yorkston, K.M. et al. (1999) *Management of motor speech disorders in children and adults,* Pro-ed Austin, TX

21. Mawalim, C.O. et al. (2022) Speaker anonymization by modifying fundamental frequency and x-vector singular value. *Computer Speech & Language* 73, 1–17

22. Hu, P. et al. (2021) Dual humanness and trust in conversational AI: A person-centered approach. *Computers in Human Behavior* 119, 106727

23. Nusbaum, H.C. et al. (1997) Measuring the naturalness of synthetic speech. *International Journal of Speech Technology* 2, 7–19

24. Mayo, C. et al. (2011) Listeners’ weighting of acoustic cues to synthetic speech naturalness: A multidimensional scaling analysis. *Speech Commun* 53, 311–326

25. Eyssel, F. et al. (2012) 'If you sound like me, you must be more human'. In *HRI' 12. Proceedings of the seventh annual ACM/IEEE Conference on Human-Robot Interaction : March 5-8, 2012 Boston, Massachusetts, USA* (Yanco, H. et al., eds), pp. 125–126, Association for Computing Machinery

26. Abdulrahman, A. and Richards, D. (2022) Is Natural Necessary? Human Voice versus Synthetic Voice for Intelligent Virtual Agents. *MTI* 6, 51

27. Moya-Galé, G. et al. (2024) Perceptual consequences of online group speech treatment for individuals with Parkinson's disease: A pilot study case series. *International Journal of Speech-Language Pathology,* 1–16

28. Urakami, J. et al. (2020) The Effect of Naturalness of Voice and Empathic Responses on Enjoyment, Attitudes and Motivation for Interacting with a Voice User Interface. In *Human-Computer Interaction. Multimodal and Natural Interaction* (Kurosu, M., ed), pp. 244–259, Springer International Publishing

29. Velner, E. et al. (2020) Intonation in Robot Speech. In *Proceedings of the 2020 ACM/IEEE International Conference on Human-Robot Interaction* (Belpaeme, T. et al., eds), pp. 569–578, ACM

30. Yamasaki, R. et al. (2017) Perturbation Measurements on the Degree of Naturalness of Synthesized Vowels. *Journal of Voice* 31, 389.e1-389.e8

31. Ko, S. et al. (2023) The Effects of Robot Voices and Appearances on Users’ Emotion Recognition and Subjective Perception. *Int. J. Human. Robot.* 20

32. Abur, D. et al. (2021) Feedback and Feedforward Auditory-Motor Processes for Voice and Articulation in Parkinson's Disease. *J Speech Lang Hear Res* 64, 4682–4694

33. Klopfenstein, M. (2015) Relationship between acoustic measures and speech naturalness ratings in Parkinson's disease: A within-speaker approach. *Clinical Linguistics & Phonetics* 29, 938–954

34. Klopfenstein, M. (2016) Speech naturalness ratings and perceptual correlates of highly natural and unnatural speech in hypokinetic dysarthria secondary to Parkinson’s disease. *JIRCD* 7, 123–146

35. Eadie, T.L. et al. (2008) Influence of speaker gender on listener judgments of tracheoesophageal speech. *Journal of Voice* 22, 43–57

36. Eadie, T.L. and Doyle, P.C. (2002) Direct Magnitude Estimation and Interval Scaling of Naturalness and Severity in Tracheoesophageal (TE) Speakers. *J Speech Lang Hear Res* 45, 1088–1096

37. Lehner, K. and Ziegler, W. (2022) Clinical measures of communication limitations in dysarthria assessed through crowdsourcing: specificity, sensitivity, and retest-reliability. *Clinical Linguistics & Phonetics* 36, 988–1009

38. Schölderle, T. et al. (2023) Speech Naturalness in the Assessment of Childhood Dysarthria. *American Journal of Speech-language Pathology* 32, 1633–1643

39. Vogel, A.P. et al. (2019) Speech treatment improves dysarthria in multisystemic ataxia: a rater-blinded, controlled pilot-study in ARSACS. *Journal of neurology* 266, 1260–1266

40. Yorkston, K.M. et al. (1990) The effect of rate control on the intelligibility and naturalness of dysarthric speech. *The Journal of speech and hearing disorders* 55, 550–560

41. Jones, H.N. et al. (2019) Auditory-Perceptual Speech Features in Children With Down Syndrome. *American journal on intellectual and developmental disabilities* 124, 324–338

42. Euler, H.A. et al. (2021) Speech restructuring group treatment for 6-to-9-year-old children who stutter: A therapeutic trial. *Journal of communication disorders* 89, 106073

43. Assmann, P.F. et al. (2006) Effects of frequency shifts on perceived naturalness and gender information in speech. In *INTERSPEECH*

44. Venkatraman, A. and Sivasankar, M.P. (2018) Continuous Vocal Fry Simulated in Laboratory Subjects: A Preliminary Report on Voice Production and Listener Ratings. *American Journal of Speech-language Pathology* 27, 1539–1545

45. Kapolowicz, M.R. et al. (2022) Effects of Spectral Envelope and Fundamental Frequency Shifts on the Perception of Foreign-Accented Speech. *Language and speech* 65, 418–443

46. Tamagawa, R. et al. (2011) The Effects of Synthesized Voice Accents on User Perceptions of Robots. *Int J of Soc Robotics* 3, 253–262

47. Mackey, L.S. et al. (1997) Effect of speech dialect on speech naturalness ratings: a systematic replication of Martin, Haroldson, and Triden (1984). *J Speech Lang Hear Res* 40, 349–360

48. Baird, A. et al. (2017) Perception of Paralinguistic Traits in Synthesized Voices. In *Proceedings of the 12th International Audio Mostly Conference on Augmented and Participatory Sound and Music Experiences* (Fazekas, G. et al., eds), pp. 1–5, ACM

49. Coughlin-Woods, S. et al. (2005) Ratings of speech naturalness of children ages 8-16 years. *Percept Motor Skill* 100, 295–304

50. Goy, H. et al. (2016) Effects of age on speech and voice quality ratings. *The Journal of the Acoustical Society of America* 139, 1648

51. Baird, A. et al. (2018) The Perception of Vocal Traits in Synthesized Voices: Age, Gender, and Human Likeness. *J. Audio Eng. Soc.* 66, 277–285

52. Hardy, T.L.D. et al. (2020) Acoustic Predictors of Gender Attribution, Masculinity-Femininity, and Vocal Naturalness Ratings Amongst Transgender and Cisgender Speakers. *Journal of Voice* 34, 300.e11-300.e26

53. Merritt, B. and Bent, T. (2020) Perceptual Evaluation of Speech Naturalness in Speakers of Varying Gender Identities. *J Speech Lang Hear Res* 63, 2054–2069

54. Aylett, M.P. et al. (2020) Speech Synthesis for the Generation of Artificial Personality. *IEEE Trans. Affective Comput.* 11, 361–372

55. Martin, R.R. et al. (1984) Stuttering and speech naturalness. *The Journal of speech and hearing disorders* 49, 53–58

56. van Eck, N.J. and Waltman, L. (2010) Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics* 84, 523–538

57. van der Linden, S. (2023) *Foolproof: Why we fall for misinformation and how to build immunity,* WW Norton & Company.

58. Anand, S. and Stepp, C.E. (2015) Listener Perception of Monopitch, Naturalness, and Intelligibility for Speakers With Parkinson's Disease. *J Speech Lang Hear Res* 58, 1134–1144

59. Romportl, J. (2014) Speech Synthesis and Uncanny Valley. In *Text, speech and dialogue* (Horák, A. et al., eds), pp. 595–602, Springer International Publishing

60. Diel, A. and Lewis, M. (2024) Deviation from typical organic voices best explains a vocal uncanny valley. *Computers in Human Behavior Reports* 14, 100430

61. van Prooije, T. et al. (2024) Perceptual and Acoustic Analysis of Speech in Spinocerebellar ataxia Type 1. *Cerebellum,* 112–120

62. Rao M V, A. et al. (2018) Effect of source filter interaction on isolated vowel-consonant-vowel perception. *The Journal of the Acoustical Society of America* 144, EL95

63. Ratcliff, A. et al. (2002) Factors influencing ratings of speech naturalness in augmentative and alternative communication. *Augmentative and Alternative Communication* 18, 11–19

64. Meltzner, G.S. and Hillman, R.E. (2005) Impact of Aberrant Acoustic Properties on the Perception of Sound Quality in Electrolarynx Speech. *J Speech Lang Hear Res* 48, 766–779

65. Valentine, T. et al. (2016) Face-space: A unifying concept in face recognition research. *Q J Exp Psychol (Hove)* 69, 1996–2019

66. Andics, A. et al. (2010) Neural mechanisms for voice recognition. *Neuroimage* 52, 1528–1540

67. Valentine, T. (1991) A unified account of the effects of distinctiveness, inversion, and race in face recognition. *Q J Exp Psychol A* 43, 161–204

68. Anikin, A. and Lima, C.F. (2017) Perceptual and acoustic differences between authentic and acted nonverbal emotional vocalizations. *Q J Exp Psychol (Hove)* 71, 622–641

69. Lima, C.F. et al. (2021) Authentic and posed emotional vocalizations trigger distinct facial responses. *Cortex* 141, 280–292

70. Sarzedas, J. et al. (2024) Blindness influences emotional authenticity perception in voices: Behavioral and ERP evidence. *Cortex* 172, 254–270

71. Roswandowitz, C. et al. (2024) Cortical-striatal brain network distinguishes deepfake from real speaker identity. *Communications biology* 7, 711

72. Kachel, S. et al. (2020) Gender (Conformity) Matters: Cross-Dimensional and Cross-Modal Associations in Sexual Orientation Perception. *Journal of Language and Social Psychology* 39, 40–66

73. Mills, M. et al. (2017) Expanding the evidence: Developments and innovations in clinical practice, training and competency within voice and communication therapy for trans and gender diverse people. *International Journal of Transgenderism* 18, 328–342

74. Eiff, C.I. von et al. (2022) Crossmodal benefits to vocal emotion perception in cochlear implant users. *iScience* 25, 105711

75. Schweinberger, S.R. and Eiff, C.I. von (2022) Enhancing socio-emotional communication and quality of life in young cochlear implant recipients: Perspectives from parameter-specific morphing and caricaturing. *Frontiers in Neuroscience* 16, 956917

76. Hyppa-Martin, J. et al. (2024) A large-scale comparison of two voice synthesis techniques on intelligibility, naturalness, preferences, and attitudes toward voices banked by individuals with amyotrophic lateral sclerosis. *Augmentative and Alternative Communication* 40, 31–45

77. Yamagishi, J. et al. (2012) Speech synthesis technologies for individuals with vocal disabilities: Voice banking and reconstruction. *Acoust. Sci. & Tech.* 33, 1–5

78. Belin, P. et al. (2011) Understanding voice perception. *Br. J. Psychol.* 102, 711–725

79. Belin, P. et al. (2004) Thinking the voice: neural correlates of voice perception. *Trends Cogn Sci* 8, 129–135

80. Staib, M. and Frühholz, S. (2023) Distinct functional levels of human voice processing in the auditory cortex. *Cerebral Cortex* 33, 1170–1185

81. Staib, M. and Frühholz, S. (2021) Cortical voice processing is grounded in elementary sound analyses for vocalization relevant sound patterns. *Progress in neurobiology* 200, 101982

82. Pinheiro, A.P. et al. (2021) Emotional authenticity modulates affective and social trait inferences from voices. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences* 376, 20200402

83. Miller, E.J. et al. (2023) How do people respond to computer-generated versus human faces? A systematic review and meta-analyses. *Computers in Human Behavior Reports,* 100283

84. Miller, E.J. et al. (2023) AI Hyperrealism: Why AI Faces Are Perceived as More Real Than Human Ones. *Psychol Sci* 34, 1390–1403

85. Im, H. et al. (2023) Let voice assistants sound like a machine: Voice and task type effects on perceived fluency, competence, and consumer attitude. *Computers in Human Behavior* 145, 107791

86. Cabral, J.P. et al. (2017) The Influence of Synthetic Voice on the Evaluation of a Virtual Character. In *Interspeech 2017,* pp. 229–233, ISCA

87. Ehret, J. et al. (2021) Do Prosody and Embodiment Influence the Perceived Naturalness of Conversational Agents’ Speech? *ACM Trans. Appl. Percept.* 18, 1–15

88. Ferstl, Y. et al. (2021) Human or Robot? Investigating voice, appearance and gesture motion realism of conversational social agents. In *Proceedings of the 21th ACM International Conference on Intelligent Virtual Agents,* pp. 76–83, ACM

89. Gong, L. and Nass, C. (2007) When a Talking-Face Computer Agent is Half-Human and Half-Humanoid: Human Identity and Consistency Preference. *Human Comm Res* 33, 163–193

90. Higgins, D. et al. (2022) Sympathy for the digital: Influence of synthetic voice on affinity, social presence and empathy for photorealistic virtual humans. *Computers & Graphics* 104, 116–128

91. Li, M. et al. (2023) Effects of robot gaze and voice human-likeness on users’ subjective perception, visual attention, and cerebral activity in voice conversations. *Computers in Human Behavior* 141, 107645

92. McGinn, C. and Torre, I. (2019 - 2019) Can you Tell the Robot by the Voice? An Exploratory Study on the Role of Voice in the Perception of Robots. In *2019 14th ACM/IEEE International Conference on Human-Robot Interaction (HRI),* pp. 211–221, IEEE

93. Mitchell, W.J. et al. (2011) A mismatch in the human realism of face and voice produces an uncanny valley. *i-Perception* 2, 10–12

94. Parmar, D. et al. (2022) Designing Empathic Virtual Agents: Manipulating Animation, Voice, Rendering, and Empathy to Create Persuasive Agents. *Autonomous agents and multi-agent systems* 36

95. Sarigul, B. and Urgen, B.A. (2023) Audio–Visual Predictive Processing in the Perception of Humans and Robots. *Int J of Soc Robotics* 15, 855–865

96. Duville, M.M. et al. (2022) Neuronal and behavioral affective perceptions of human and naturalness-reduced emotional prosodies. *Frontiers in computational neuroscience* 16, 1022787

97. Duville, M.M. et al. (2024) Improved emotion differentiation under reduced acoustic variability of speech in autism. *BMC medicine* 22, 121

98. Nussbaum, C. et al. (2022) Contributions of fundamental frequency and timbre to vocal emotion perception and their electrophysiological correlates. *Social Cognitive and Affective Neuroscience* 17, 1145–1154

99. Kauk, J. et al. (2024) The adaptive community-response (ACR) method for collecting misinformation on social media. *J Big Data* 11

100. Malisz, Z. et al. (2020) *Modern speech synthesis for phonetic sciences: a discussion and an evaluation,* Center for Open Science

101. Mori, M. et al. (2012) The Uncanny Valley. *IEEE Robot. Automat. Mag.* 19, 98–100