**Understanding Voice Naturalness**

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**Highlights** (900 characters):

* When hearing a voice, listeners immediately form an impression about its naturalness, which affects social interactions, both in a purely human context and in scenarios with human and artificial agents
* Despite its intuitive appeal and tremendous practical importance, a systematic understanding of voice naturalness is elusive and the concept is scientifically ill-defined.
* We show that voice naturalness research is situated within different research domains that resemble echo chambers within science, in that both neither cross-refer to one another nor to current voice perception theory.
* To address this, we offer a concise conceptual framework by proposing a taxonomy with two distinct types: deviation-based naturalness and human-likeness-based naturalness.
* Subsequently, we discuss a tentative roadmap to promote interdisciplinarity and meaningful exchange between research domains.

**Abstract** (120 words)

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

Inhalt

[1. Introduction – voice naturalness (450) 3](#_Toc160791725)

[2. Current Problems (800) 3](#_Toc160791726)

[2.1. Conceptual Underspecification (300) 3](#_Toc160791727)

[2.2. Inconsistent Operationalization (250) 4](#_Toc160791728)

[2.3. Lack of exchange between different research domains (150) 5](#_Toc160791729)

[2.4. Insufficient anchoring in voice perception theory (150) 5](#_Toc160791730)

[*3.* Proposition of a concise framework for voice naturalness (900*)* 6](#_Toc160791731)

[3.1. Definitions of naturalness (500) 6](#_Toc160791732)

[3.2. Differentiation from other concepts (400) 7](#_Toc160791733)

[4. Progressing in conjunction (400) 7](#_Toc160791734)

[5. Naturalness research rooted in voice perception theory (400) 8](#_Toc160791735)

[6. Open questions and future/outlook (400) 9](#_Toc160791736)

# Introduction – voice naturalness (450)

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 [93] and beyond: Synthetic voices increasingly emerge as major carriers of communicative interactions, such as in customer service calls, gaming environments, or support platforms [69,70]. When listening to voices, we form an instant impression about them [43]. Crucially, listeners seem to be very sensitive to (un-)natural voice features, which affects communicative quality [32,33]. 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 [15,40]. Similarly, deliberate acoustic manipulations and distortions disrupt effective communication [11,12,60,65]. For **synthetic voices**, one can hardly keep up with the rapid developments which make indefatigable efforts to resemble human vocal expression [78,80]. However, as of today, synthetic voices are consistently rated as less natural than human voices, which simultaneously affects perceived likeability, trustworthiness, and pleasantness [9,42,44,48,76].

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 (800)

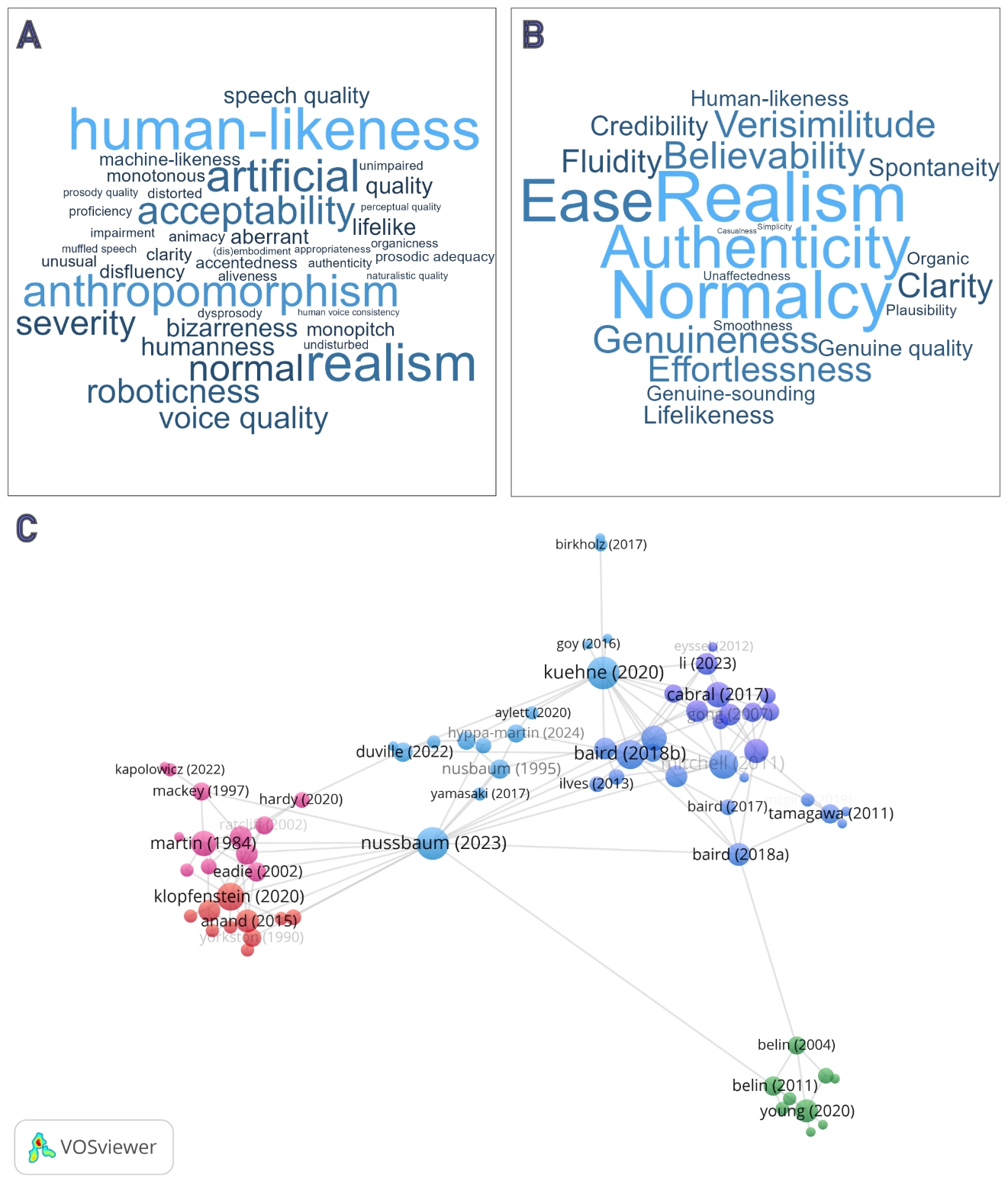
## Conceptual Underspecification (300)

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*” [40,92]. In contrast, research on synthetic and non-human voices usually defines naturalness as “*speech most closely perceived as a human voice*“ [51] or “*the degree to which a user feels a certain technology or system is human-like*” [30]. 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 [63]. 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 [52]. 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**.

**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.* ***C)*** *A bibliographic network visualization using VOSviewer [84], 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.*

## Heterogeneous Operationalization (250)

A common consequence of inconsistent conceptualization is heterogeneous operationalization. Primarily, this concerns the studied vocal categories and features, which include human vs. synthetic voices [1,62,81,86,90]; cartoon voices [41], pathological voices such as in individuals with Parkinson’s’ disease [2,38,39], tracheoesophageal speech [20,21], dysarthria [45,75,88,91], down syndrome [34], or stuttering [24]; acoustically manipulated human voices [5], vocal fry [87], as well as different accents [36,79], dialects [49], age groups [7,14,27], and gender identities [8,28,55]. 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?” [6], in another one they rated voices on a 10-point-scale from “very natural, human-like” to “very mechanical, robot-like” [79]. 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 [50]. 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 (150)

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 [84], showing several distinct clusters of studies reminiscent of echo chambers which are frequently discussed in social media [83]. 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 [3,9,65]. Further, while several studies failed to find an uncanny valley effect for synthetic voices [42,71], a recent study suggest it might exist for pathological ones [17]. 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 (150)

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 (900*)*

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 (500)

We propose a taxonomy with two distinct types: Deviation-based naturalness and human-likeness-based naturalness **(**Fig 2 ToDo**)**. 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 [85]). 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*“ [65]. 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 [60,67,68]) to complex multivariate vocal patterns (e.g. in distorted or pathological voices [54]).

**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: 16 [17] 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.

## Delimiting distinctiveness and authenticity (400)

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 (Quelle). 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 [82]. 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 [4,47,74]. In the context of voice cloning and the now very prevalent danger of deepfakes [72], 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 [35,58]. 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?”. ToDo: hier dann mit Grafik verbinden und auffangen. However, since these are two very different research questions, we tend to keeping the concepts of naturalness and authenticity rather separate.

# Converging evidence (400)

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 [23], and real-time synthesis in CI sound processors could be modified to achieve better perceptual outcomes, ultimately benefitting quality of life [77]. 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 [31,89].

# Naturalness research rooted in voice perception theory (500)

Several authors have pointed out that research on naturalness is not sufficiently rooted in theory [40,78]. As discussed in section 2.4, the strongly applied orientation of the field comes at the expense of basic research, although several influential models on voice perception offer good staring points: The voice-space model proposed by Quelle represents voices in terms of their acoustic deviation from one another or a potential reference. The functional model by 10 [10] assumes that an initial structural analysis of voices is followed by dissociable pathways processing vocal speech analysis, vocal affect analysis and voice recognition. Recently, 43 [43] integrated these previous models in a unifying framework, explaining how listeners form multiple impressions about both familiar and unfamiliar voices. Commonly studied person characteristics include identity, gender, age, emotion and personality of speakers.

Although voice naturalness is in principle covered by these models, it is never explicitly mentioned. This is particularly intriguing against the backdrop of a questions that has prompted extensive debate and empirical efforts in basic voice research: Are voices special (Belin 2011)? In other words, do voices recruit network and resources in the brain that are not recruited by other types of acoustic stimuli? Voices with varying degrees of naturalness provide a powerful tool to shed new light on this debate. What makes human voices special? What makes natural voices special? In a nutshell, trying to understand the impact of naturalness on voice perception means trying to answer these questions.

This is not all. Rooting naturalness research in voice perception theory prompts further crucial questions that are not fully answered yet. First, to which degree is naturalness a threat to ecological validity (Nussbaum 2023)? Many voice researchers use acoustic manipulation such as voice morphing which could have unintended side effects on perceived naturalness. If this cannot be avoided, perceived naturalness should be at least quantified, and where possible be considered as a moderating variable. Second, how does naturalness interact with the processing of other voice characteristics? For example, first insights into the interplay of naturalness and emotionality suggest that […] (Quellen, shall I go into detail?). Third, [ToDo, brain data?, or “is naturalness always better than unnaturalness”, role of experience and learning history] Note that all of these questions are of relevance beyond the vocal modality. For faces, several of these aspects are covered in recent meta-analysis (Miller 2023)

(grade noch ein ziemlicher Flickenteppich…,this is one of the sections where I hope for substantial refinement from collaborators – Stefan:\_ok can do this, but for now, let´s wait for Sascha´s thoughts)

# Perspectives for future research (400)

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 [57]). 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 [56]. 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 and behavior for the acceptance of virtual agents [13,22,25,26,29,46,48,53,59,66,73].

This undertaking is worthwhile despite adding a level of complexity, and we welcome that first efforts are currently being made in this direction [46,48].

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 [18,19,64]. 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 [72]. The accelerating spread of misinformation via social media is now considered a major problem which compromises societal cohesion [37,83]. 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. (342)

Topics to cover:

- link to multimodal and visual research

- putting the conceptualizations to the test and compare whether they lead to different outcomes  
- systematic comparison of human-pathological, human-distorted, and synthetic voices  
- categorical perception between human- and non-human voices?  
- naturalness implications for ecological validity?  
- in naturalness always better?  
- individual differences  
- neurocognitive insights (aaaaaall kinds of brain data)

# Concluding remarks (400)

Naturalness in voices is a highly intuitive feature, but it is scientifically underspecified and far from systematically understood, despite considerable research efforts. To address this, we proposed the first conceptual framework for voice naturalness. Out taxonomy, comprised of deviation-based naturalness and human-likeness based naturalness, is both rooted in voice theory and inspired by diverse interdisciplinary empirical findings. It therefore offers the necessary flexibility to be applicable across diverse empirical designs, while at the same time promoting comparability across research domains. We complemented this conceptual groundwork with several practical recommendations to unite this highly interdisciplinary field. Thus, we hope to provide the foundation for conjoined efforts towards systematic research on numerous **outstanding questions** on voice naturalness across disciplines. In a world that is increasingly dominated by artificial agents, we

**Outstanding questions** (2000 characters)**:**

* (How) are human-likeness based naturalness and deviation-based naturalness dissociable in the brain?
* Are there substantial individual differences in the tolerance / preference of unnatural voice features, and if so, can they be related to other domains of auditory cognition?
* How is a listener´s perception of naturalness shaped through experience? (e.g. with voice assistents, smart home devices, or patients with voice disorders)
* Are natural voices always preferred, or is naturalness preference dependent on context? Are there contexts in which natural voices hinder communication success?
* (How and when) does reduced naturalness in voices critically affect ecological validity of research?

**Box 1** (400 words): 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.

In total, we identified 72 articles, covering a time range from 1984 to 2024. 38 (53%) were published in the last 5 years. 67 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. 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** (400 words): 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.
* Finally, 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.

**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 [80])
* Uncanny valley: a sudden feeling of eeriness evoked humanoid robots that almost approach, but do not entirely reach a human-like appearance [61]
* 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
* tracheoesophageal speech: a method of vocalization following total laryngectomy (removal of the larynx) 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.

References

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

2. 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

3. Anand, S. and Stepp, C.E. (2015) Listener Perception of Monopitch, Naturalness, and Intelligibility for Speakers With Parkinson's Disease. Journal of Speech, Language, and Hearing Research 58, 1134–1144

4. 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

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

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

7. 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

8. 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

9. 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

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

11. 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

12. 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

13. 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

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

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

16. Diel, A. and Lewis, M. (2023) *The vocal uncanny valley: Deviation from typical organic voices best explains uncanniness*

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

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

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

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

21. 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

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

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

24. 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

25. 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

26. 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

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

28. 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

29. 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

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

31. 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

32. 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

33. 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

34. 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

35. 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

36. 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

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

38. 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

39. 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

40. 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

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

42. 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, 593732

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

44. 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

45. 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

46. 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

47. Lima, C.F. et al. (2021) Authentic and posed emotional vocalizations trigger distinct facial responses. Cortex; a journal devoted to the study of the nervous system and behavior 141, 280–292

48. Lu, L. et al. (2021) Leveraging “human-likeness” of robotic service at restaurants. International Journal of Hospitality Management 94, 102823

49. Mackey, L.S. et al. (1997) Effect of speech dialect on speech naturalness ratings: a systematic replication of Martin, Haroldson, and Triden (1984). Journal of Speech, Language, and Hearing Research 40, 349–360

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

51. Mawalim, C.O. et al. (2022) Speaker anonymization by modifying fundamental frequency and x-vector singular value. Computer Speech & Language 73, 101326

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

53. 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

54. 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

55. 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

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

57. 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

58. 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

59. 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

60. 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

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

62. 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

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

64. 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

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

66. 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

67. 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

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

69. 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

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

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

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

73. 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

74. Sarzedas, J. et al. (2024) Blindness influences emotional authenticity perception in voices: Behavioral and ERP evidence. Cortex; a journal devoted to the study of the nervous system and behavior 172, 254–270

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

76. 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, 787499

77. 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

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

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

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

81. 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

82. 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

83. van der Linden, S. (2023) *Foolproof: Why we fall for misinformation and how to build immunity,* 4th Estate

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

85. van Prooije, T. et al. (2023) Perceptual and Acoustic Analysis of Speech in Spinocerebellar ataxia Type 1. Cerebellum (London, England)

86. 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

87. 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

88. 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

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

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

91. 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

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

93. Young, A.W. et al. (2020) Face and voice perception: Understanding commonalities and differences // Face and Voice Perception: Understanding Commonalities and Differences. Trends Cogn Sci 24, 398–410