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Exploring Forensic Phonetics: Understanding Speech Intelligibility in Varied Acoustic Environments

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ABSTRACT: In forensic linguistics and more specifically in the field of forensic phonetics, the environment in which a recording is made exerts a considerable influence. This impact arises not only from the acoustic conditions of the space but also from how these conditions affect speech articulation and intelligibility. The way in which sounds are produced, transmitted and perceived can be significantly altered by factors such as background noise, reverberation or the proximity of the speaker to the recording device. This research delves into the analysis of speech intelligibility, as well as vocal characteristics such as f_0 and intensity, to demonstrate the intricate relationship between the concept of intelligibility and various vocal features, showing how these elements are interconnected and how they contribute to clearer or more accurate speech interpretation in forensic contexts.

Keywords: forensic phonetics; acoustics; speech intelligibility; vocal characteristics; environment.

RESUMEN: *Abordando la fonética forense: comprendiendo la inteligibilidad del habla en diversos entornos acústicos.* En lingüística forense, y más específicamente en el campo de la fonética forense, el entorno en el que se realiza una grabación ejerce una influencia considerable sobre la misma. Este impacto no solo proviene de las condiciones acústicas del espacio, sino también de cómo estas condiciones afectan a la articulación del habla y su inteligibilidad. La manera en que los sonidos son producidos, transmitidos y percibidos puede alterarse significativamente por factores como el ruido de fondo, la reverberación o la proximidad del hablante al dispositivo de grabación. Esta investigación profundiza en el análisis de la inteligibilidad del habla, así como en características vocales como la f_0 y la intensidad, para demostrar la compleja relación entre el concepto de inteligibilidad y diversas características vocales, mostrando cómo estos elementos están interconectados y cómo contribuyen a una interpretación más clara o precisa del habla en contextos forenses.

Palabras clave: fonética forense; acústica; inteligibilidad del habla; características vocales; espacio.

1. INTRODUCTION

In spoken discourse, the environment and its acoustic characteristics can significantly influence the production of a message, thereby shaping the speaker's intent or emotional state. The surrounding conditions, such as background noise, reverberation, or even the acoustics of the space, can affect how the speaker articulates words and phrases, impacting both the quality and clarity of the speech. These factors, in turn, have important implications for the intelligibility of the message, as well as for the ability to identify the speaker in situations where voice authentication is required. For instance, the environment in which the suspect is located may alter certain vocal characteristics, potentially making it more difficult to accurately recognize or authenticate his/her voice. This highlights the significance of considering environmental factors when analyzing speech for forensic purposes.

In light of these assumptions, the aim of this research is to analyze speech in both quiet and noisy environments in order to identify the differences in speech production. This pilot study seeks to observe how intelligibility and vocal characteristics such as f_0 and intensity vary depending on the level of ambient noise, providing a deeper understanding of the vocal adjustments individuals make under different acoustic conditions.

2. INTERFACE BETWEEN PHONETICS AND ACOUSTICS

Forensic Linguistics is an applied branch of Linguistics that serves as an intersection between the discipline of linguistics and the legal field, with the goal of applying linguistic knowledge to a social environment, typically legal in nature (Olsson and Luchjenbroers, 2014, p. 2). Upon examining the origins of this discipline, it becomes apparent that its roots trace back to the 1950s, when an event in British society had a profound impact on the judicial landscape, not only in the United Kingdom but also across the globe: the Evans case. In this case, the contradictory statements made by T. Evans to the police were analyzed by Swedish linguist J. Svartvik (Coulthard, 1994), who framed the findings of his investigation within the context of a new linguistic discipline, which he named Forensic Linguistics. Although the emergence of Forensic Linguistics can be traced to 1968, following Svartvik's work, it began to gain significant prominence in the 1990s, particularly with the establishment of the International Association for Forensic Phonetics and Acoustics (IAFPA) in 1991 and the International Association of Forensic Linguists (IAFL) in 1992 (Ramírez Salado, 2017, p. 530). Since then, Forensic Linguistics has contributed to numerous cases, including the Unabomber case, the kidnapping of Anabel Segura and the imprisonment of Óscar Sánchez.

In a rigorous lexicographical and conceptual analysis conducted by Ramírez Salado (2017, pp. 530-535) on the discipline of Forensic Linguistics in its role as the study of evidential language, drawing on the research of Gibbons (1999, 2003), Blackwell (2013), Garayzábal, Jiménez and Reigosa (2014) and Coulthard, Johnson and Wright (2017), several key areas of focus are identified: forensic phonetics, authorship analysis, plagiarism analysis and trademark analysis. In addition to these four areas, one must also consider the identification of speakers, which pertains to forensic phonetics and the forensic discourse analysis, as part of the broader study of evidential language, judicial language and legal language.

Regarding spoken discourse, it is examined from two distinct scientific disciplines: forensic phonetics and forensic acoustics. Forensic phonetics, being the most recognized and developed branch within Forensic Linguistics, focuses on the analysis of voice in legal contexts. This area involves various tasks, such as creating a phonetic profile of an unknown speaker, determining the authenticity of a recording, interpreting the content of a recording, designing and validating lineups and conducting forensic speaker comparisons (San Segundo Fernández, 2023, pp. 177-182). On the other hand, forensic acoustics, also known as audio forensics (see Maher, 2009), is a field of acoustics specialized in "the acquisition, analysis, and evaluation of audio recordings that may ultimately be presented as admissible evidence in a court of law or some other official venue" (Maher, 2009, p. 84).

As evidenced in these two fields, there exists an intersection between phonetics and acoustics, which was initially envisioned with the creation of the International Association for Forensic Phonetics and Acoustics (IAFPA). However, it is rare for phonetic and acoustic methods to be combined in forensic linguistic investigations.[1] In this context, it is particularly interesting to explore the impact of environmental noise on

[1] Some scholars focus exclusively on the forensic aspects of voice analysis using either phonetic methods (Wirdayanthi, 2022) or acoustic techniques (Costantini, Paoloni and Todisco, 2010). Conversely, most authors addressing the interface between these fields, such as Hollien (2001) or Pragati et al. (2024), approach it from a theoretical perspective, outlining the various tasks associated with this intersection. These tasks include, for instance, the analysis of voice stress, typically linked to phonetics, and the examination of machine or telephone "signatures", which falls under acoustic analysis

the voice. According to a study by Bottalico, Graetzer and Hunter (2015), environments with high levels of noise and stressful situations can cause an increase in the vocal effort of the speaker. This phenomenon, known as the Lombard effect, occurs because the speaker exerts additional effort to be heard and understood amidst background noise. The Lombard effect involves an automatic adaptation of the vocal system, which facilitates greater intelligibility in acoustically challenging conditions. Building upon this premise, it can be inferred that in quieter environments, speakers tend to reduce both the volume and the f_0 of their voice, as there is no need to exert additional effort to communicate effectively.

2.1. Speech Intelligibility

One of the key aspects analyzed in both phonetics and acoustics is speech intelligibility, which clearly demonstrates the interface between these two disciplines. However, this concept is typically studied separately within each field rather than from the interface perspective. It is important to emphasize that, from a terminological standpoint, speech intelligibility is a concept that belongs to both fields, involving distinct processes in each case and sometimes leading to certain ambiguities, particularly in the acoustic domain, where two different conceptualizations of intelligibility are presented.

From a linguistic perspective, intelligibility refers to the capacity to understand the linguistic material. Specifically, Calleja, Luque, Rodríguez and Liranzo (2015, p. 114) define this concept as the degree of acoustic signal, generated by the speaker, that can be correctly decoded by the listener. Calleja, Luque, Rodríguez and Liranzo (2015, p. 114), citing Lindblom (1990) and Hustad, Schueler, Schultz and Duhadway (2012), note that the measurement of speech intelligibility reflects the joint effort of both the speaker and the receiver of the message, assuring that the central element of this concept is determining how well the recipients of the message can align the acoustic signal with its corresponding lexical units, despite any segmental or suprasegmental challenges in the speech.

In acoustics, speech intelligibility is also referred to as word intelligibility. As Hidalgo, Sommerhoff and Rosas (2011, p. 39) state, the most important acoustic parameter for defining the acoustic quality of a place or space designed for spoken communication is intelligibility. Sommerhoff and Rosas (2011, p. 134) define this concept as a metric that evaluates the efficiency of comprehending spoken speech, which in one form or another quantifies the proportion of the message that is accurately interpreted.

Additionally, companies like Svantek define speech intelligibility as the sound quality of a space, stating that speech intelligibility refers to how clearly speech can be understood, but it is influenced by the acoustics of the environment. When sound travels through a space, such as a room or via a public address system, it is never received as an exact reproduction of the original sound. Background noise and distortions caused by reflections and reverberations from surfaces like walls, ceilings and furniture can blur the speech signal. As such, intelligibility is measured not by the speaker but by the channel through which the speech is transmitted. In this context, the intelligibility of speech through any given channel is affected by factors such as noise, echo and distortion. Considering these elements allows for the optimization of intelligibility in various listening environments.

It is worth noting that, in the acoustic domain, authors such as Sommerhoff and Rosas (2008, p. 179) or Hidalgo, Sommerhoff and Rosas (2011, p. 39) explain the process of measuring speech intelligibility as an analysis across two distinct areas: phonetics and acoustics, stating that intelligibility is assessed using both objective and subjective approaches. As Hidalgo, Sommerhoff and Rosas (2011, p. 39) describe, objective techniques involve the use of electronic equipment to take measurements, which are then compared with results from subjective methods,[2] while subjective methods rely on individuals performing articulation tests, where they count the number of syllables, words, or phrases correctly transcribed after hearing them.

In this context, Tschieder (2021) notes that, within the broader communication process, information travels from the speaker to the listener via a channel and intelligibility can be compromised due to problems with any of these components. As Tschieder (2021, p. 17) further elaborates, the intelligibility of speech can be influenced by various factors depending on the speaker, the channel, or the environment: if the issue originates with the speaker or the source, intelligibility can be reduced by the degradation of the speech signal, as seen in conditions like dysarthria, dysphonia, speech from individuals who are deaf, poor articulation, or

(Hollien, 2001). With regard to the practical aspects of the interface, few authors reflect both their phonetic and acoustic knowledge in their research, such as Rosas and Sommerhoff (2006), who adopt a more integrative approach, employing methods from both disciplines.

[2] These authors state that the most prominent objective method is the Speech Transmission Index (STI), created by Houtgast and Steeneken.

rapid speech,[3] although the channel itself significantly impacts intelligibility, with factors such as the acoustic properties of the environment, reverberation, noise, overlapping conversations, or even the use of telephones all playing a crucial role.

3. METHODOLOGY

The methodology employed in this study combines both phonetic and acoustic tools. The aim of this investigation was to record various subjects in the semi-anechoic[4] and reverberant[5] chambers of the Instituto Universitario de Investigación en Lingüística Aplicada (University Institute of Applied Linguistics) at the University of Cádiz, as well as in the control room of the same institution, to analyse speech intelligibility and correlate it with other vocal characteristics such as f_0 and intensity.

The task consisted of describing a different image in both the semi-anechoic and reverberant chambers, followed by a comparative analysis of both descriptions in the control room. Additionally, the participant was asked to relate the image to a personal event or memory.

Before beginning the recordings, the speech intelligibility of each room was measured using the Speech Transmission Index (STI), a globally recognized parameter for evaluating and quantifying speech intelligibility. To measure speech intelligibility, a specialized acoustic signal (the STIPA test signal) is played and the quality of the received signal is simultaneously analyzed at various measurement points. The results of this measurement are shown in the following table:

Table 1: Intelligibility of each room. Measurements conducted through STI analysis.

ROOM	STI
SEMI-ANECHOIC CHAMBER	89%
REVERBERANT CHAMBER	49%
CONTROL ROOM	74%

To record the participants, a Neumann TLM 103 microphone was used, equipped with a windscreen to minimise breath-related artefacts. The microphone was positioned at a distance of 15 centimetres from the speaker, and the recordings were captured using the REAPER[6] software. The recordings took into account sociological variables such as sex, age and education level, with a particular focus on male and female students and professors of the Linguistics degree program at the Faculty of Philosophy and Letters at the University of Cádiz. As a pilot study, we choose six people for each group.

For the analysis of the collected data, we selected complete utterances (ranging from 15 to 25 seconds of audio) from the section in which each participant related the images to a personal event or memory. The aim of the study was phonetic in nature. To this end, the acoustic software ArtemiS SUITE[7] was used to assess speech intelligibility, while the phonetic analysis of f_0 and speech intensity was conducted using the software Praat.[8]

[3] Tschieder (2021, p. 17) expands this information by saying that, in cases involving hearing-impaired listeners, the challenge may also lie with the receiver.

[4] A semi-anechoic chamber is an enclosed space with walls and a ceiling covered with materials specifically designed to absorb electromagnetic radiation (Esparza Becerra, 2012, p. 3).

[5] According to the acoustical terminology glossary (Sociedad Española de Acústica, 2012), the reverberant chamber is an enclosure isolated from external noise, with internal surfaces that are highly reflective in such a way as to achieve a long reverberation time across a wide range of frequencies. It is specially designed to create a sufficiently diffuse acoustic field within

[6] REAPER is a software platform for digital audio production that offers "a full multitrack audio and MIDI recording, editing, processing, mixing and mastering toolset" (Cockos Incorporated, 2023).

[7] ArtemiS SUITE is a versatile and modular software platform designed for the measurement and analysis of sound and vibration. Its primary objective is to optimize product acoustics and environmental noise, offering a comprehensive solution that integrates multiple tools within a standardized software environment. This platform facilitates the precise analysis of acoustic properties, enabling users to enhance sound quality and reduce noise levels in both product development and environmental settings (HEAD Acoustics, 2024).

[8] Praat is a specialized tool used in linguistic scientific studies, primarily focused on analyzing the spectrogram of recorded sounds. This software enables detailed examination of various acoustic features, providing researchers with the ability to study speech signals and their properties, such as pitch, intensity and duration (Boersma and Weenink, 2024).

4. RESULTS

The results obtained using the ArtemiS SUITE software regarding the speech intelligibility of the participants were as follows:

Table 2: Speech intelligibility analysis. Results extracted using ArtemiS SUITE.[9]

	FS	FP	MS	MP
SAC	75.58%	59.83%	63.64%	56.87%
RC	78.08%	67.47%	67.08%	57.92%
CR	71.78%	54.33%	57.48%	55.03%

Additionally, using Praat, the f_0 and intensity of the speakers' voices were analyzed, yielding the following results:

Table 3: Analysis of voice's f_0 and intensity in the semianechoic chamber. Results extracted using Praat.

	FS	FP	MS	MP
f_0	195.78 Hz	190.16 Hz	125.13 Hz	109.69 Hz
INT.	67.3 dB	68.4 dB	69.08 dB	70.50 dB

Table 4: Analysis of voice's f_0 and intensity in the reverberant chamber. Results extracted using Praat.

	FS	FP	MS	MP
f_0	189.3 Hz	192.99 Hz	126.6 Hz	108.57 Hz
INT.	66.36 dB	67.06 dB	67.06 dB	70.35 dB

Table 5: Analysis of voice's f_0 and intensity in the control room. Results extracted using Praat.

	FS	FP	MS	MP
f_0	195.98 Hz	186.12 Hz	127.69 Hz	107.48 Hz
INT.	68.80 dB	68.21 dB	70.46 dB	70.85 dB

After reviewing the results of this preliminary study, relationships were observed between the acoustic study of speech intelligibility and the phonetic study of f_0 and voice intensity.

In terms of speech intelligibility, an interesting fact to consider is that the participants are not more intelligible in the semi-anechoic chamber, which is unexpected based on the results from the STI analysis. In this context, participants are more intelligible in the reverberant chamber and less intelligible in the control room. This is due to the fact that the semi-anechoic chamber is a room with no background noise, which causes people to feel more uneasy and tend to raise their voices to hear their voices and not their breathing or their heart. In contrast, in the reverberant room, they tended to lower their voices to avoid hearing their own echo.

Regarding the analysis carried out with Praat, female students show a similar f_0 and intensity in both the semi-anechoic chamber and the control room, with lower values in the reverberant room. On the other hand, male students exhibit higher f_0 and intensity in the control room. However, the lowest intensity value is observed in the reverberant chamber, while the lowest f_0 value is found in the semi-anechoic chamber. In terms of professors, female professors have a higher f_0 in the reverberant room and a lower one in the control room. However, their intensity is higher in the semi-anechoic chamber and lower in the reverberant chamber. On the contrary, male professors show a higher f_0 in the semi-anechoic chamber and a lower one in the control room.

[9] Due to space limitations in the table, the participant headings will be abbreviated as follows: female student (FS), female professor (FP), male student (MS), and male professor (MP). Additionally, the locations where the recordings were conducted will be abbreviated as: semi-anechoic chamber (SAC), reverberant chamber (RC), and control room (CR).

Regarding intensity, although the values are very similar, the intensity in the control room is slightly higher and somewhat lower in the reverberant chamber.

Therefore, by combining phonetic and acoustic analyses, we find that, in female students, higher intelligibility is associated with lower f_0 and lower intensity. When intelligibility decreases, speech intensity notably increases. The f_0 also rises, but the difference between the f_0 in voices recorded in the semi-anechoic chamber and the control room is minimal.

In the case of male students, higher intelligibility is linked to lower intensity and vice versa. However, there are differences concerning f_0: in the reverberant chamber, where intelligibility is higher and intensity is lower, f_0 is medium. On the other hand, f_0 is lower in the semi-anechoic chamber, where intelligibility and intensity are both medium, and higher in the control room, where intelligibility is low and intensity is high.

Female teachers show that, with higher intelligibility, there is a higher f_0, but lower intensity. Moreover, as intelligibility decreases, f_0 also decreases. However, as intelligibility drops, intensity increases, although this vocal characteristic does not show significant differences when intelligibility falls below 60%.

Finally, male teachers exhibit a pattern where higher intelligibility corresponds to lower intensity and vice versa. However, in this group, the f_0 is higher in the semi-anechoic chamber, where intelligibility is medium and lower in the control room, where intelligibility is low. Similar to female teachers, when intelligibility drops below 60%, the differences in intensity are not substantial.

Thus, we can observe that the relationship between intelligibility and vocal characteristics, such as f_0 and intensity, varies with sociological factors like sex and age, although professional experience may also interfere,[10] with notable differences in the relationship between these three concepts across the different groups analyzed. While the relationship between speech intelligibility and intensity remains consistent between male students and male teachers, variations occur regarding the relationship of f_0 with these two concepts.

5. CONCLUSIONS

To conclude, this research highlights the importance of the interface between phonetics and acoustics in voice analysis, specifically in the intelligibility of speech. As outlined in the theoretical sections of this document, speech intelligibility is a process that can be conducted manually, semi-automatically and automatically, drawing from both linguistics and acoustic engineering. From a phonetic perspective, a more perceptive manual analysis or semi-automatic analysis is carried out using software like Praat to extract data from various vocal characteristics. On the other hand, from an acoustic standpoint, an automatic analysis is performed using a software like ArtemiS SUITE to extract data from the analysis of speech intelligibility.

This research aimed to conduct a pilot study to assess whether there was a correlation between the acoustic concept of speech intelligibility and the phonetic concepts of fundamental frequency and intensity. As demonstrated in our section, this relationship does indeed exist, and it is further influenced by sociological factors such as gender and age. In young women, greater speech intelligibility correlates with a lower fundamental frequency and reduced intensity, and vice versa. In young men, the more intelligible their speech, the lower the intensity they produce, and conversely. In adult women, higher speech intelligibility is associated with a greater fundamental frequency but a lower intensity, and vice versa. Older men, much like their younger counterparts, exhibit a pattern where increased intelligibility results in lower intensity, and inversely.

Additionally, it is significant to bear in mind that this analysis is important for forensic analysis for two reasons: on one hand, when we need to transcribe and analyze what is being said in a recording, there are often cases where a recording with significant background noise and poor audio quality can be challenging. Through the analysis of speech intelligibility, we can provide, from a computational perspective, a percentage of speech comprehension that would support the results of our analysis and help determine the extent to which we can proceed with transcription and analysis. On the other hand, when analyzing a subject's voice in speaker identification, tonal or intensity data may appear that differ from the speaker's usual voice, which could be due to the context in which the subject was recorded. Thus, through the analysis of speech intelligibility, we can provide more information to our analysis, supporting that the obtained results are based on a certain percentage of speech comprehension and that the actual vocal characteristics of the speaker may vary depending on the location and the speaker's emotional state at the time of recording.

[10] It is worth noting that professors, unlike students, work by speaking in front of an audience, teaching in environments that are more or less noisy. In this regard, thanks to this experience, most could have modulated their voices in the semi-anechoic chamber, reverberant chamber, and control room to adapt it to the varying levels of noise in each room.

Finally, this pilot study paves the way for future research on the relationship between speech intelligibility and other vocal characteristics, such as vowel and consonant articulation, the tonal curve and speech dynamics. Given the findings related to f_0 and intensity, further investigations could explore how other phonetic and acoustic features contribute to intelligibility and how these features may vary across different contexts or speaker characteristics. This research could enhance our understanding of the complexities involved in speech perception and contribute to more effective applications in the field of forensic phonetics.

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DECLARATION OF COMPETING INTEREST

The author of this article declare that they have no financial, professional or personal conflicts of interest that could have inappropriately influenced this work.

AUTHORSHIP CONTRIBUTION STATEMENT

Rocío Pérez Vargas: Conceptualization, Data curation, Resources, Formal analysis, Investigation, Methodology, Project administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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