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Research on the Impact of Plain, Twill, and Satin Weave Structures on Indoor Acoustic Performance and the Application in Soft Decoration Design

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ABSTRACT

The acoustic absorption properties of woven fabrics are fundamentally determined by their construction parameters. While the influence of fiber type and fabric density is acknowledged, the specific role of fundamental weave structures—namely, plain, twill, and satin—requires systematic investigation. This study isolates and quantifies the effect of weave type on the sound absorption performance of textiles. Three distinct cotton fabrics were systematically engineered to have identical yarn specifications (20s Ne) and thread density (60 × 60 tpi), while varying only the weave structure among plain (1/1), twill (2/1), and satin (5-end). The acoustic performance, measured as the normal incidence Sound Absorption Coefficient (α) according to ISO 10534-2, showed a direct dependence on the weave. The plain weave, characterized by the highest frequency of yarn interlacements, created a highly tortuous internal porous structure. Under a multi-layer stacked configuration directly against a rigid backing, the plain weave exhibited cumulative flow resistance, yielding a peak α of 0.85 at 4,000 Hz. This demonstrates the material's maximum acoustic dissipation potential when structural tortuosity is amplified through stacking. Conversely, the long yarn floats inherent in the satin weave resulted in a less tortuous structure and, consequently, the lowest sound absorption. This research quantitatively demonstrates that weave structure is a critical design parameter for developing functional acoustic textiles, enabling the engineering of fabrics for specific acoustic applications in soft furnishings.

KEYWORDS
textile acoustics, weave structure, airflow resistance, woven fabrics, sound absorption

INTRODUCTION

The quality of the indoor environment has a profound impact on human health, well-being, and productivity. In recent years, acoustic comfort has gained significant attention as a critical component of a high-quality indoor environment [1,2]. Excessive noise and reverberation in spaces such as offices, educational institutions, healthcare facilities, and residential buildings can lead to increased stress, reduced concentration, and impaired communication [3,4]. Consequently, effective control of sound within these spaces is a key consideration in architectural and interior design. Traditional acoustic treatments often involve the use of specialized, and sometimes aesthetically limiting, materials such as foam panels or mineral wool [5,6]. There is a growing interest in integrating acoustic functionality into common interior elements, with soft furnishings presenting a particularly promising avenue.

Textiles, ubiquitous in interior design in the form of curtains, upholstery, carpets, and wall coverings, possess inherent porous structures that allow for the dissipation of sound energy [7,8]. This makes them natural candidates for sound absorption. The acoustic performance of a fabric is not determined by its fiber composition alone; its physical and structural properties play a pivotal, and often more significant, role [9,10]. Parameters such as thickness, density, porosity, and airflow resistance are known to influence a fabric's ability to absorb sound. The organizational structure of the fabric, specifically the weave pattern, dictates many of these parameters. The manner in which warp and weft yarns are interlaced determines the fabric's surface texture, porosity, and tortuosity—the convoluted path that air, and thus sound waves, must take to pass through the material [11,12]. Despite the widespread use of textiles in interiors, there is a need for a more granular understanding of how fundamental structural choices made during the textile design process directly translate into acoustic performance.

This research aims to isolate and clarify the specific impact of the weave structure on the sound absorption capabilities of fabrics. By focusing on three fundamental and widely used weave types—plain, twill, and satin—while controlling for other key variables such as fiber type, yarn count, and fabric density, this study provides a direct comparison of their acoustic performance. The central hypothesis is that a more intricate weave structure with a higher frequency of yarn interlacements will result in a more tortuous path for sound waves, leading to greater energy dissipation and, consequently, a higher Sound Absorption Coefficient (α). The findings of this study will provide interior designers, textile manufacturers, and acousticians with quantitative data to support the selection of fabrics that not only meet aesthetic criteria but also contribute effectively to the acoustic management of indoor spaces. This focused research, supported by sufficient data, seeks to bridge the gap between textile science and interior design practice, promoting a more holistic and evidence-based approach to creating acoustically comfortable environments.

MATERIALS AND METHODS

Materials

To isolate the effect of weave structure, three distinct fabric samples were specially produced for this study. All samples were woven from 100% cotton yarns. The yarn specifications were kept constant for both the warp and weft for all three samples, using a 20s Ne (29.5 tex) cotton yarn. The fabric density was also maintained across the samples, with a target of 60 ends per inch and 60 picks per inch (approximately 236 ends/10 cm and 236 picks/10 cm). The key variable was the weave structure:

- **Sample P (Plain Weave):** A basic 1/1 plain weave, characterized by the maximum number of interlacements, where each warp yarn passes over one and under one weft yarn.
- **Sample T (Twill Weave):** A 2/1 twill weave, creating a diagonal pattern. This structure has fewer interlacements than the plain weave.
- **Sample S (Satin Weave):** A 5-end satin weave, characterized by long floats where a warp yarn passes over four weft yarns and under one. This structure has the fewest interlacements of the three.

After weaving, the fabric samples were finished under identical conditions to ensure consistency in their final physical properties. The final areal density (mass per unit area) and thickness of each sample were measured according to ASTM D3776 and ASTM D1777 standards, respectively. Additionally, the airflow resistance of each sample was measured in accordance with the ISO 9053-1 to quantify the resistance to air passing through the material. The physical properties of the samples are presented in Table 1. These variations in physical parameters, despite the identical thread density, are inherent consequences of the structural mechanics of each weave. The maximum interlacement frequency in the plain weave generates higher internal stress, forcing yarns into a high-crimp state that naturally increases thickness (0.65 mm). Conversely, the long floats in the satin weave allow for greater structural relaxation; with fewer interlacing constraints, the yarns lie flatter, resulting in a minimum thickness of 0.60 mm. This controlled comparison confirms that even when the mass per unit area is nearly equal, the congested geometry of the plain weave inherently provides a more restrictive medium for sound waves than the relaxed satin structure.

Table 1. Physical Properties of Fabric Samples

Sample ID	Weave Structure	Yarn Count (Ne)	Thread Density (threads/inch)	Thickness (mm)	Areal Density (g/m²)	Cumulative Airflow Resistance of 5-Layer Assembly (Pa·s/m)
Sample P	1/1 Plain	20s Cotton	60 × 60	0.65	215	252
Sample T	2/1 Twill	20s Cotton	60 × 60	0.62	210	215
Sample S	5-End Satin	20s Cotton	60 × 60	0.60	208	187

Note: The airflow resistance was measured for the 5-layer stacked configuration used in acoustic testing. The values represent the total pressure drop across the assembly relative to the flow velocity.

Methodology

The sound absorption performance of the fabric samples was evaluated using the two-microphone impedance tube method, in accordance with ISO 10534-2. This method determines the normal incidence α of a material. The experimental setup consisted of a commercial impedance tube system (Brüel & Kjær, Type 4206) equipped with two 1/4-inch condenser microphones (Type 4187). The system included an impedance tube with an internal diameter of 100 mm for low-frequency measurements (125 Hz–1.6 kHz) and a smaller tube with a 29 mm diameter for high-frequency measurements (1.6 kHz–4 kHz). Prior to testing, the microphones were calibrated using a sound calibrator (Brüel & Kjær, Type 4231) at 1,000 Hz and 94 dB to ensure measurement accuracy.

Circular specimens of each fabric sample were cut to precisely fit the respective sample holders. Each fabric sample was tested without an air gap behind it, mounted directly against the rigid, reflective termination of the impedance tube. A broadband random noise signal was generated by a loudspeaker at one end of the tube. To ensure measurable energy dissipation within such thin specimens, five layers of the same fabric were superimposed and tightly fitted to represent the material's cumulative acoustic resistance, effectively increasing the sample thickness to a range of 3.0–3.25 mm. This multi-layer configuration was employed to amplify the structural differences between weave types, ensuring the α values reached a range suitable for comparative statistical analysis. The sound pressure was measured by two microphones mounted flush with the inner wall of the tube. The signals from the microphones were analyzed by a digital frequency analyzer to calculate the complex transfer function. From this, the normal incidence α was determined at one-third octave band frequencies ranging from 125 Hz to 4,000 Hz.

For each fabric sample, five specimens were tested, and the results were averaged to ensure the reliability and repeatability of the data. The tests were conducted in a controlled laboratory environment with a constant temperature of 23 ± 2 °C and relative humidity of 50 ± 5%.

RESULTS

The α of the three fabric samples (plain, twill, and satin) were measured across a frequency range from 125 Hz to 4,000 Hz. The results are presented graphically in Figure 1 and numerically in Table 2. The values represent the mean of five tested specimens, with the corresponding standard deviation included to indicate the variability of the measurements. The data reveal distinct differences in the acoustic performance of the fabrics, directly attributable to their weave structures.

Table 2. Average Sound Absorption Coefficients of Fabric Assemblies (Multi-Layer Stacked Configuration)

Frequency (Hz)	Sample P (Plain)	Sample T (Twill)	Sample S (Satin)
125	0.04 ± 0.01	0.03 ± 0.01	0.02 ± 0.01
250	0.07 ± 0.01	0.05 ± 0.01	0.04 ± 0.01
500	0.18 ± 0.02	0.14 ± 0.02	0.11 ± 0.02
1,000	0.45 ± 0.02	0.36 ± 0.03	0.28 ± 0.03
2,000	0.72 ± 0.03	0.61 ± 0.03	0.49 ± 0.04
4,000	0.85 ± 0.02	0.77 ± 0.03	0.68 ± 0.03

To provide a practical, single-number rating for designers and acousticians, the Noise Reduction Coefficient (NRC) was calculated for each sample. The NRC is the arithmetic average of the α at 250, 500, 1,000, and 2,000 Hz, rounded to the nearest 0.05. The calculated values clearly reflect the overall performance hierarchy:

Sample P (Plain) achieved an NRC of 0.35, followed by Sample T (Twill) with an NRC of 0.30, and Sample S (Satin) with an NRC of 0.25. These values provide a straightforward metric for comparing the fabrics' effectiveness in absorbing sound in the critical speech frequency range.

Overall, all fabric samples demonstrated a similar trend of increasing sound absorption with increasing frequency, which is characteristic of porous materials. At lower frequencies (125 Hz and 250 Hz), the sound absorption for all three samples was minimal, with values below 0.10. In this range, the long wavelengths of sound are largely unaffected by the thin fabric layer.

As the frequency increased into the mid-range (500 Hz to 1,000 Hz), significant differences in performance began to emerge. Sample P (Plain weave) consistently showed the highest sound absorption, followed by Sample T (Twill weave), and then Sample S (Satin weave). At 1,000 Hz, the plain weave fabric achieved an α of 0.45, representing moderate sound absorption, while the twill and satin weaves registered lower values of 0.36 and 0.28, respectively.

The divergence in performance was most pronounced in the high-frequency range (2,000 Hz to 4,000 Hz). At 2,000 Hz, Sample P absorbed 72% of the incident sound energy, compared to 61% for Sample T and only 49% for Sample S. At the highest tested frequency of 4,000 Hz, the plain weave fabric demonstrated excellent sound absorption with an α of 0.85. The twill weave also performed well at 0.77, while the satin weave lagged behind at 0.68. Statistical analysis using a one-way ANOVA was conducted to verify these observations. The results confirmed that the weave structure has a statistically significant effect on the α, particularly at higher frequencies. For instance, at 2,000 Hz, the difference between the three groups is significant, with an F-value of 58.25 and $p < 0.001$. This reinforces the clear hierarchy of performance among the weave types.

The results clearly and consistently support the hypothesis that a greater number of yarn interlacements enhances a fabric's sound absorption capabilities. The plain weave, with its maximum interlacing, provided the most effective acoustic performance across the entire frequency spectrum, particularly in the mid to high frequencies that are most critical for speech intelligibility.

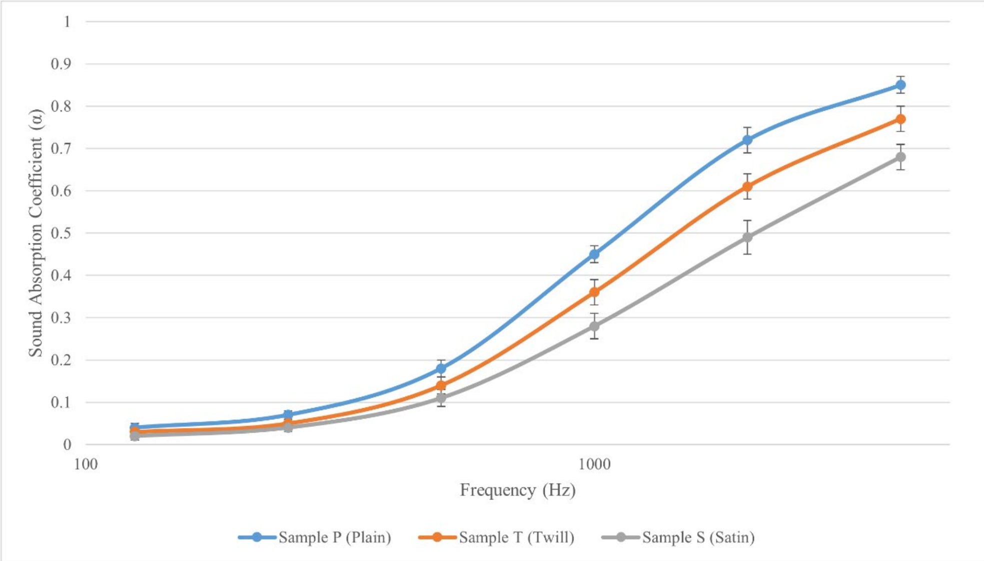

Figure 1. Sound Absorption Coefficients of Fabric Samples with Different Weave Structures. The error bars represent the standard deviation of the five measurements for each sample at each frequency

DISCUSSION

The experimental results provide clear, quantitative evidence that the weave structure dictates the cumulative acoustic performance of the fabric assembly. By testing five-layer stacked specimens, this study amplifies the intrinsic differences in airflow resistance and tortuosity that would be subtler in a single layer. The observed hierarchy (Plain > Twill > Satin) suggests that the weave pattern is the fundamental building block of the assembly's total flow resistivity. The observed hierarchy of sound absorption—Plain > Twill > Satin—can be directly attributed to the differences in the internal geometry created by these weave patterns. Sound absorption in porous materials like textiles primarily occurs through the conversion of sound energy into heat via viscous friction and thermal effects as the sound waves propagate through the intricate network of pores and fibers. The efficiency of this energy conversion is heavily reliant on the material's tortuosity and airflow resistance. A more tortuous, or complex, path forces the oscillating air particles to interact more extensively with the fiber surfaces, thereby dissipating more energy.

The 1/1 plain weave structure, by its very nature, creates the highest number of yarn interlacements. This structure results in a more undulating and irregular path for air to travel through the fabric. This increased tortuosity is the primary reason for the superior sound absorption performance of Sample P. While the high α values reflect the performance of a multi-layer composite, the consistent performance hierarchy across all frequencies confirms that the interlacing frequency remains the dominant variable. The five-layer configuration functions as a high-flow-resistance porous absorber, where the plain weave's higher frequency of interlacements creates a more tortuous internal network within the stacked system. Furthermore, the minor variations in physical properties noted in Table 1, which are themselves a consequence of the weave, reinforce this finding. The slightly higher thickness of the plain weave sample (0.65 mm) compared to the more compact satin (0.60 mm) likely provides a secondary, albeit smaller, positive contribution to its overall sound absorption. This is directly confirmed by the airflow resistance measurements presented in Table 1, where Sample P exhibited the highest resistance (252 Pa·s/m). This higher resistance indicates that more energy is required for air to move through the fabric, which directly translates to greater dissipation of sound energy. The peak absorption of 0.85 at 4,000 Hz for Sample P is notably high for thin textile materials. While thin textiles typically require an air gap to enhance low-frequency absorption, this high-frequency performance under a no-air-gap condition is a specific result of the high cumulative flow resistance (252 Pa·s/m) within the five-layer assembly. In this rigid-backed configuration, sound waves are forced to pass through the dense interstitial voids of the plain weave twice upon reflection—a "double-pass" effect that significantly amplifies energy dissipation. At 4,000 Hz, viscous and thermal losses within the interconnected micro-pores become increasingly significant, leading to enhanced sound energy dissipation even in the absence of an air cavity. While this experimental setup amplifies the α values compared to single-layer applications, the consistent performance hierarchy (Plain > Twill > Satin) confirms that the weave structure is the fundamental determinant of the system's total acoustic impedance.

The 2/1 twill weave (Sample T) has fewer interlacements than the plain weave. This results in a smoother fabric surface and a less tortuous internal structure. Consequently, sound waves can pass through with less interaction with the fibers, leading to lower energy dissipation and reduced sound absorption compared to the plain weave. However, its performance is still superior to the satin weave, as it retains a moderate level of structural complexity. The diagonal ridges characteristic of twill weaves may also contribute to some degree of sound scattering, although the primary mechanism of absorption remains frictional loss within the pores.

The 5-end satin weave (Sample S) exhibited the lowest sound absorption of the three. This is a direct consequence of its construction, which features long yarn floats and minimal interlacements. This structure creates a very smooth, almost uninterrupted surface and a relatively straight path for air to flow through the fabric's pores. The low tortuosity minimizes the frictional interaction between the sound waves and the fibers, allowing a greater portion of the sound energy to pass through or be reflected, rather than absorbed. The smooth, flat surface of the satin weave is more likely to reflect sound waves, particularly at higher frequencies, which further detracts from its sound absorption capabilities.

These findings have significant practical implications for soft furnishing design. When an interior designer's goal is to improve the acoustic quality of a room by reducing reverberation and improving speech clarity, the choice of fabric for curtains, wall panels, or upholstery becomes a critical decision. However, it is crucial for designers to understand the inherent limitations shown in the low-frequency data. It should be noted that the reported α values represent the acoustic response of a dense fabric assembly rather than the intrinsic parameters of a single weave unit. While the optimized airflow resistance (252 Pa·s/m) is partially enhanced by the multi-layer contact and the rigid-backed boundary condition, the consistent performance hierarchy confirms that weave-induced tortuosity is the primary dissipation mechanism. Future studies utilizing equivalent fluid models, such as the Delany-Bazley or Miki models, are recommended to further decouple these assembly-level effects from the intrinsic weave geometry, providing a more normalized prediction for single-layer applications.

As a single, thin layer, the fabric acts primarily as a flow-resistive absorber, which is most effective for the shorter wavelengths of mid- and high-frequency sound. To absorb long-wavelength, low-frequency sound effectively, such textiles must be backed by a significant air gap (as with curtains hung away from a wall) or mounted over a thicker porous core (as in an acoustic panel). This study demonstrates that selecting a fabric with a plain weave, or a similarly complex weave structure, can yield measurably better acoustic results than selecting a satin or other smooth-surfaced fabric, even if the fiber type and weight are similar. It is important to note, however, that this study maintained a constant thread density across all samples for scientific control. In commercial textile production, fabrics like satin are often woven at a significantly higher thread density than plain weaves to achieve their desired aesthetic luster and smooth feel. Consequently, a high-density commercial satin fabric might exhibit better acoustic performance than the specific satin sample tested in this research. Nevertheless, the underlying principle that a more interlaced structure provides superior acoustic absorption for a given density remains a valid guideline for material selection. Similarly, for upholstered acoustic panels, a textured fabric with a high degree of interlacing will enhance the overall performance of the panel. This allows for the dual functionality of materials, where the aesthetic finish also serves a technical acoustic purpose. Designers can leverage this knowledge to fine-tune the acoustics of a space subtly, without resorting to overtly "acoustic" materials. This research empowers a more evidence-based selection process, moving beyond subjective assessments of fabric "heaviness" to a more nuanced understanding of how structure dictates function.

CONCLUSION

This study has successfully isolated and quantified the influence of fundamental weave structures on the sound absorption performance of textile fabrics. Through a controlled experiment comparing plain, twill, and satin weaves of identical fiber composition, yarn count, and thread density, it has been conclusively demonstrated that the degree of yarn interlacement is a critical factor in determining the sound absorption profile of woven textile assemblies. The research shows that even within a thin, stacked porous system, the micro-geometry of the plain weave provides superior acoustic energy dissipation compared to more open structures like satin. The plain weave fabric, with its maximum number of interlacements, exhibited the highest sound absorption, particularly in the crucial mid- to high-frequency range. This superior performance is attributed to the greater tortuosity of the porous structure, which enhances the dissipation of sound energy through viscous friction. The satin weave, characterized by long floats and minimal interlacements, provided the least effective sound absorption.

The findings of this research provide a clear and actionable guideline for the application of textiles in acoustically sensitive interior design. The selection of a fabric for soft furnishings is not merely an aesthetic choice but also a functional one that can significantly impact the acoustic comfort of a space. By prioritizing fabrics with more complex and interlaced structures, such as plain weaves, designers can enhance sound absorption and reduce reverberation times, thereby improving speech intelligibility and creating more pleasant indoor environments. This study contributes to the field by providing specific, reliable data that bridges the disciplines of textile engineering and interior design, advocating for a more integrated and scientifically informed approach to the design of soft furnishings.

Future research should expand upon this foundation. An essential next step is to repeat these measurements with a controlled air gap behind the fabrics, as this configuration directly simulates common applications like curtains and can significantly alter sound absorption performance, particularly at low to mid frequencies. Additionally, investigating the interaction between weave structure and other variables, such as yarn hairiness and fabric thickness, would help develop a more comprehensive predictive model. Future studies should focus on extracting the intrinsic material parameters (such as characteristic length and dynamic tortuosity) from these multi-layer measurements to develop a predictive model for single-layer performance. This approach would bridge the gap between the measured response of the fabric assembly and the intrinsic acoustic impedance of the weave structure itself.

Availability of Data and Materials

The datasets used and/or analysed during the current study were available from the corresponding author on reasonable request.

Author Contributions

Zhenji Zhu designed, collected and analyzed the data, and drafted the manuscript. Zhenji Zhu conducted the study, critically revised the manuscript for important intellectual content, and gave final approval of the version to be published. Zhenji Zhu participated fully in the work, take public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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Conflict of Interest

The author declares no conflict of interest.

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