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The Concept of a Virtual 3D Clarinet Museum: Preserving Cultural Heritage

O Conceito de um Museu Virtual de Clarinete 3D: Preservar o Património Cultural

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Abstract: Preserving musical heritage confronts an undeniable temporal asymmetry: performance-based skills gradually disappear with each new generation, leaving sonic artifacts without the interpretative context. This study presents a virtual 3D archive documenting the evolution of the clarinet (1750–2024) through an integrated synthesis of acoustic, material, and performative data. Acoustic impedance spectroscopy characterized the resonant properties of 147 historical instruments; laser Doppler vibrometry measured wall vibrations at 247 points (20 Hz–20 kHz, resolution: 0.5 Hz); and three-dimensional photogrammetry captured geometric profiles (accuracy: ±0.05 mm). Professional clarinetists (n = 146) evaluated the functionality of the museum prototype through structured questionnaires following interactive exploratory sessions. Spectral analysis revealed differences between national schools: German recordings demonstrated a 22% higher concentration of energy below 1 kHz compared to French recordings; vibrato frequencies differed significantly (German: 3.2 Hz/French: 5.8 Hz). Material composition correlated with timbral characteristics: grenadilla formant peaks (2.3 kHz) contrasted with boxwood formant peaks (1.8 kHz), with damping coefficients of 0.012 and 0.023, respectively. Compositional analysis highlighted mechanical determinism: Mozart's use of the chalumeau register (34% in K.622) precisely matched the acoustic capabilities of the basset clarinet; chromatic passages

increased from 34 instances (Mozart) to 156 (Spohr) following Müller's introduction of the thirteen-key innovation. Interactive 3D models facilitate kinesthetic experiments impossible with fragile specimens; spectral visualizations translate subjective timbral descriptions into quantifiable parameters. Educational applications include preserving performance traditions—regional practices documented before standardization erased distinctions. The museum's structure integrates photogrammetric models with acoustic measurements, enabling diachronic repertoire analysis across the clarinet's 274-year evolution.

Keywords: acoustics; digitization; instruments; interactive technologies; organology; repertoire; performance

Resumo: A preservação do património musical confronta uma assimetria temporal inegável: as competências baseadas na performance desaparecem gradualmente a cada nova geração, deixando os artefactos sonoros sem contexto interpretativo. Este estudo apresenta um arquivo virtual 3D que documenta a evolução do clarinete (1750-2024) através de uma síntese integrada de dados acústicos, materiais e performativos. A espectroscopia de impedância acústica caracterizou as propriedades ressonantes de 147 instrumentos históricos; a vibrometria laser Doppler mediu as vibrações da parede em 247 pontos (20 Hz-20 kHz, resolução: 0,5 Hz); e a fotogrametria tridimensional captou perfis geométricos (precisão: ±0,05 mm). Clarinetistas profissionais (n=146) avaliaram a funcionalidade do protótipo do museu através de questionários estruturados após sessões exploratórias interativas. A análise espectral revelou diferenças entre as escolas nacionais: as gravações alemãs demonstraram uma concentração de energia 22% superior abaixo de 1 kHz em comparação com as gravações francesas; As frequências do vibrato diferiram significativamente (alemão: 3,2 Hz/francês: 5,8 Hz). A composição do material correlacionou-se com as características tímbricas: os picos formantes da grenadilla (2,3 kHz) contrastaram com os picos formantes do buxo (1,8 kHz), com coeficientes de amortecimento de 0,012 e 0,023,

respetivamente. A análise composicional destacou o determinismo mecânico: a utilização do registo chalumeau por Mozart (34% em K. 622) correspondeu precisamente às capacidades acústicas do clarinete basset; as passagens cromáticas aumentaram de 34 ocorrências (Mozart) para 156 (Spohr) após a introdução da inovação das treze teclas por Müller. Os modelos 3D interativos facilitam experiências cinestésicas impossíveis com espécimes frágeis; visualizações espectrais traduzem descrições tímbricas subjetivas em parâmetros quantificáveis. As aplicações educativas incluem a preservação das tradições de performance — práticas regionais documentadas antes de a normalização apagar as distinções. A estrutura do museu integra modelos fotogramétricos com medições acústicas, permitindo uma análise diacrónica do repertório ao longo dos 274 anos de evolução do clarinete.

Palavras-chave: acústica; digitalização; instrumentos; tecnologias interativas; organologia; repertório; performance

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1. Introduction

The clarinet as a musical instrument has undergone a multifaceted path of evolution. Initially, the clarinet was considered a brass instrument, similar to the trumpet or surma-horn, and its parts were designed to imitate their high-pitched sounds (Estes, 2019). However, with time and the improvement of instrumental art, the clarinet began to acquire its own unique identity (Halfpenny, 1965). By the end of the 18th century, the clarinet had already been recognized as a type of woodwind instrument. Its sound was produced using a reed and resonated within a bell attached to the instrument. Since then, composers have realized the clarinet's expressive capabilities and individual voice in the orchestra (Smith, 2017). Historically, there have been two distinct clarinet schools, each with its own unique features: the German school and the French school. This can be attributed to the differences in tastes and traditions, as well as to the influence of political factors, military conflicts, and industrial changes from the mid-19th to the mid-20th century. However, in recent decades, the Western world has experienced relative political stability and technological progress. This period facilitated the active exchange of information and ideas between cultures. Due to this favorable environment, the merging of these two musical systems has become evident. Musicians and producers have begun to interact more actively, exploring the benefits of both styles and attempting to combine them in new hybrid instruments (Agababa-Shaked, 2018).

Modern clarinet virtuosos also experiment with integrating digital technology into their practice. They use electronic effects and real-time sound processing, and even create entire electronic-acoustic compositions using the clarinet. These experiments expand the sound capabilities of the instrument, opening up new creative horizons (McIntyre, 2020). The evolution of instruments—from the five-key classical constructions to contemporary Boehm systems—has transformed the acoustic possibilities available to performers (Pagliaro, 2024). Passages conceived for specific mechanical

constraints lose their idiomatic character when performed on technologically advanced instruments. Consequently, the emotional subtext sought by performers becomes distanced from its historical context (Luo, 2024).

Ornamentation and articulation, previously transmitted through apprenticeship systems, now survive primarily as theoretical reconstructions. While eighteenth-century treatises offer fundamental principles, the subtleties of micro-gestural elements—such as variations in breath pressure, tongue position, and embouchure adjustments—remain undocumented. This gap parallels similar challenges in other heritage fields, underscoring the critical importance of digitally safeguarding knowledge for future generations. The clarinet's transformation—from an orchestral accompaniment to a solo performance—coincided with the decline of performance traditions (Pesic, 2024). This shift represents a defining trajectory of the clarinet within music history. Compositional practice evolved concurrently with mechanical innovations, as each technological advancement expanded expressive possibilities, subsequently influencing the written repertoire.

Thus, digital innovations are actively used to preserve, showcase, and promote intangible cultural heritage, including traditional musical instruments, among a broad global audience in the modern world. This research contributes to this field and expands the existing developments. The cultural heritage of the clarinet has had a profound historical and cultural impact on the development of music. A virtual 3D museum would effectively preserve and present this heritage in an accessible form to a broad audience, regardless of their location.

1.1 Literature review

Structural modifications have transformed compositional possibilities, as hole configurations, key mechanisms, and material selections dictate the available pitch ranges and timbral variations.

Acoustic studies demonstrate how "two resonances below the cutoff frequency, whose peaks differ from true harmonics by approximately 7%," influence reproducibility at various performance levels (Thompson, 2024). Physical parameters—such as "average reed displacement, blowing pressure, and embouchure positioning"—directly correlate with achievable variations in "sound level, pitch, and spectral centroid" (Almeida et al., 2023b). These measurable interdependencies between mechanical design and acoustic outcomes define composers' technical demands; passages crafted for specific hole geometries lose their idiomatic characteristics when performed on alternative systems.

German traditions emphasized darker timbres achieved through specific embouchure techniques, whereas French approaches prioritized brilliance through combinations of reed and mouthpiece, and American eclecticism synthesized diverse methodologies. Chinese clarinet pedagogy underwent systematic nationalization, with composers integrating pentatonic structures, traditional ornamentation, and culturally specific performance gestures (Yang & Hao, 2022). Regional distinctions manifest acoustically; spectral analysis reveals quantitative differences between national approaches in terms of root mean square (RMS) energy distribution and spectral centroid characteristics (Nusseck et al., 2022).

The contemporary symbiosis between performance and composition extends beyond traditional frameworks: digital interfaces transform clarinets into "tangible acoustic interfaces," enabling real-time control of electronic parameters (Travasso, 2023). Motion-capture research illustrates how "ancillary movements" synchronize with musical structures—knee flexion correlates with melodic passages, and hand positions correspond to transitional moments (Nusseck et al., 2024). Kinesthetic elements influence acoustic outcomes: "greater knee movement range correlates with increased timbral variability" (Nusseck et al., 2022).

Compositional approaches in the 21st century leverage expanded technical capabilities, as extended techniques (such as multiphonics, microtones, and prepared clarinet) necessitate precise notation systems that accommodate unconventional sound production. Machine-learning algorithms analyzing "13 representative spectral features" enable objective classification of timbral qualities across various registers (Xu, 2023). Virtual museum platforms preserve endangered performance traditions through "3D virtual environment models" integrated with acoustic documentation (Hu, 2023). The evolution of the clarinet—from a subordinate orchestral voice to an autonomous artistic medium—reflects transformations in musical hierarchies, technological capacities, and cultural exchanges.

Parameters of emotional expression—"the ultimate goal of performance being the expression of a composition's emotional subtext"—constitute recent analytical directions, displacing purely mechanical descriptions (Luo, 2024). Physiological research documents how "ancillary movements were subsequently interrupted by the physiological necessity to inhale," thus elucidating the biomechanics of performance (Nusseck et al., 2024). Contemporary scholarship identifies "notation as a cultural practice, shared ownership, and performer agency" as emerging themes that challenge traditional hierarchies (Abrams-Husso, 2024). Educational systems differ across national contexts: "Chinese clarinet education, strongly influenced by traditional Chinese concepts and Western classical music, emphasizes technical mastery and examination standards, whereas Australian clarinet pedagogy focuses on individual self-expression" (Wang, 2025).

Medical documentation expands musicological boundaries—rehabilitation protocols following dental trauma demonstrate how "appropriate emergency treatment and the dentist's understanding of musicians' specific needs can facilitate stable recovery," thus preserving performing capability (Moon, 2025).

Cross-cultural synthesis generates hybrid repertoires; Italian composers create works in a Chinese style through the "innovative use and combinations of Western and Chinese musical elements," analyzed within frameworks of cultural holism (Zhao, 2024).

Organological accuracy underpins historical comprehension: from the Baroque period, "36 two-key and 22 three-key clarinets manufactured in Germany, Belgium, the Netherlands, Austria, Czechia, France, Sweden, and Finland" remain preserved (Rice, 2020). In Mozart's operatic productions, clarinets transcend conventional boundaries, "dramatizing shifts in characters' self-awareness and progressive enlightenment" (Pesic, 2024). Technical documentation remains incomplete; traditional pedagogy covers "instrument components/how they function/different types of clarinets" but lacks acoustic and historical context (Pagliaro, 2024).

Treatises from the eighteenth and nineteenth centuries undergo fragmented analysis; performance instructions embedded in compositional manuscripts await systematic extraction and analysis. Contemporary historiography favors biographical narratives over technical evolution; national traditions are studied in isolation. The influence of orchestral music remains insufficiently theorized, particularly regarding the clarinet's impact on nineteenth-century scoring practices. Denner's mechanical improvements, which transformed the chalumeau into the clarinet, built upon "preceding research into mechanical inventions," exemplifying technological progress that demands an interdisciplinary approach (Rice, 2020). Musicological research on the clarinet reveals disciplinary fragmentation: emotional and physiological dimensions emerge, while historical and technical foundations lack comprehensive integration; national characteristics proliferate without theoretical frameworks; and contemporary cultural hybridization advances faster than analytical methodologies can keep pace.

1.2 Problem statement

Physical deterioration poses a threat to irreplaceable instruments; traditional documentation neither captures the acoustic properties nor the interaction between the performer and the instrument. Digital preservation provides simultaneous access, as museums typically restrict handling due to accelerated wear resulting from playing. Interactive 3D models enable interaction with fragile artifacts, which is impractical in real-world scenarios. Contemporary performers often lack access to historical timbres, and composers remain unaware of the mechanical constraints that influence repertoire development. Virtual environments reconcile preservation with accessibility.

Research objective: To develop a virtual 3D archive documenting the evolution of the clarinet (1750–2024) based on integrated data on acoustics, materials, and performance.

Research tasks:

- To correlate bore geometry with spectral characteristics in 147 historical instruments;
- To quantitatively assess acoustic parameters characteristic of performers from different regions;
- To link compositional innovations to mechanical developments through repertoire analysis.
- To synthesize photogrammetric models with measured resonance properties.

2. Methods and materials

Acoustic impedance spectroscopy has become the principal analytical tool for characterizing the resonance properties of the clarinet across various historical periods. Laser Doppler vibrometry measured wall vibrations at 247 discrete points across the body of each instrument, covering a frequency range from 20 Hz to 20 kHz with a resolution of 0.5 Hz. Three-dimensional photogrammetry

provided geometric data; structured-light scanning achieved lumen measurement accuracy of 0.05 mm, while X-ray computed tomography revealed internal structures with a resolution of 0.02 mm.

2.1 Research design

To determine the perception of the prototype for a virtual 3D clarinet museum, a study was conducted involving 146 musicians aged 25 to 58 years from the Shanghai Conservatory of Music. Before starting the study, the participants received information about their participation in the experiment and access to the museum. During the study, the participants explored the virtual museum. They studied the history and evolution of the clarinet, listened to sound samples, and viewed exhibitions and demonstrations of famous clarinet performers.

In the first stage, physical instruments were documented, with access provided by museums in Vienna, Paris, Berlin, Brussels, and Edinburgh, which collectively housed 147 historical clarinets (1750–1950). Each instrument underwent non-invasive scanning protocols; photogrammetry sessions captured 360° surface geometry, while bore profiles were measured using gauges at 5 mm intervals. In the second stage, acoustic properties were analyzed, with individual instrument characteristics identified within an anechoic chamber. Microphone arrays were positioned at distances of 1 m, 3 m, and 5 m, recording frequency responses. Professional clarinetists performed standardized excerpts on each playable instrument; chromatic scales, arpeggios, and sustained notes allowed for systematic comparison. In the third stage, repertoire correlations were investigated: digitized scores (n = 312) underwent computational analysis to determine pitch distribution, register usage, and technical requirements. In the fourth stage, performance recordings were integrated, with archival sources providing 483 recordings spanning 1902–2024. Digital restoration removed noise artifacts before spectral analysis. In the fifth stage, data were synthesized into interactive 3D models: photogrammetric

meshes were combined with acoustic measurements, and repertoire analysis was correlated with instrument capabilities through a dedicated database.

Upon completing their familiarization with the virtual museum, the participants completed a questionnaire about their impressions (Appendix A). They shared their opinions regarding their experience with the museum, the informative content of the materials, the ease of navigation, and the usefulness of the provided information (Appendix B: Questionnaire). The questionnaire was available on the Google Forms platform and consisted of several sections. In the first section, participants provided general information about themselves, including age, gender, level of music education, and clarinet experience. The subsequent section was directly related to the virtual 3D museum. The participants evaluated the content and structure of the expositions, ease of navigation, quality of multimedia materials (audio, video, 3D models), and other aspects. They were also asked about the museum's usefulness in deepening their knowledge of clarinet history and inspiring creativity. The level of interest and motivation to further study the clarinet after participating in the experiment was also assessed. The participants had the opportunity to provide open comments and suggestions on how to improve the virtual museum or traditional educational resources.

2.2 Sample

The study involved 146 professional musicians who continued their education. In total, there were 71 men and 75 women aged from 25 to 58. All the participants were professional musicians of the Shanghai Conservatory of Music. They possessed relevant qualifications and the necessary level of musical knowledge to evaluate the content of the presented museum exhibitions. The study lasted 1 month.

Historical instruments were presented systematically: the Classical period (1750–1820) was represented by 23 specimens, including a reconstruction of Stadler's original basset clarinet; Early

Romanticism (1820–1850) included 34 instruments illustrating variations of Müller's system; Late Romanticism (1850–1900) encompassed 42 clarinets, highlighting differences between the Boehm system and the German system; and the Modern period (1900–1950) featured 48 instruments demonstrating regional manufacturing variations. Geographic distribution ensured representativeness: German workshops (31%), French manufacturers (28%), Austrian makers (19%), English makers (12%), and American factories (10%).

Performance recordings were selected based on specific criteria: complete movements without editing; documented verification of performers; and audio quality sufficient for spectral analysis (signal-to-noise ratio exceeding 40 dB). Score selection was balanced across historical periods, with concertos, sonatas, and chamber works represented equally.

2.3 Data analysis

The responses of the participants who completed the online questionnaire were analyzed and categorized using thematic analysis. The bore profile analysis employed polynomial regression, using sixth-order equations to characterize variations in taper; residual analysis determined manufacturing tolerances. Welch's method was used for spectral power density estimation in spectral measurements, with a 50% window overlap reducing variance. Formant extraction algorithms identified resonance peaks; bandwidth measurements at the −3 dB points quantitatively assessed selectivity. Pitch deviation analysis compared measured frequencies with equal temperament tuning; cent calculations indicated conformity with the tuning system.

Parametric tests assumed a normal distribution, which was verified using the Shapiro–Wilk test ($\alpha = 0.05$). Analysis of variance (ANOVA) was used to compare acoustic parameters across instrument categories; Tukey's HSD post-hoc tests identified significant pairwise differences. Non-parametric alternatives

(Kruskal–Wallis tests) accounted for asymmetric distributions in vibrato measurements. Linear mixed-effects models accounted for nested data structures, including instruments within manufacturers and recordings within performers. Principal component analysis reduced the dimensionality of spectral data; scree plots determined the retention of components (eigenvalues > 1).

2.4 Ethical issues

Museum access was regulated through institutional agreements, and non-disclosure provisions protected proprietary restoration techniques. Permissions were obtained for the use of recordings, with copyrights managed through collective management organizations. An anonymized presentation of live performers' measurement results mitigated potential repercussions for their reputations. Cultural sensitivity protocols governed the documentation of indigenous timber origins. Data-sharing agreements stipulated authorship attribution requirements, and the Creative Commons BY-NC-SA 4.0 license permitted the use of data for scientific purposes. Instrument handling adhered to ICOM-CC guidelines; during testing, climate-controlled environments maintained relative humidity between 45% and 55%. The authors declare that the work is written with due consideration of ethical standards. The research was conducted ethically in accordance with the World Medical Association Declaration of Helsinki. The study was approved by the local ethics committees of North University of China (Protocol No. 29 of 01/06/2023).).

2.5 Research limitations

A survivorship bias influenced the representation of historical instruments—the preserved specimens predominantly reflected high levels of craftsmanship, rather than typical production practices of their time. Acoustic measurements conducted under modern conditions differed from those in historical concert halls; recorded parameters were affected by reverberation characteristics. Variations in instrument condition during performance introduced

systematic errors; restored instruments exhibited altered acoustic properties compared to their original states. The degradation of early archival recordings limited frequency analysis above 8 kHz. Contemporary performance practices often distort historical interpretive conventions. Material aging processes altered wood density and damping characteristics over centuries; compensation algorithms estimated original properties with a margin of error of ±15%.

3. Results

Feedback from the participants revealed that the virtual 3D clarinet museum was seen as a valuable and helpful resource. The following feedback from participants regarding the use of the museum provides an insight into the effectiveness and usability of this interactive tool:

Respondent A: *"The virtual format of the museum makes it easily accessible and allows me to explore it at any time. The information provided is truly useful and valuable for understanding the history and evolution of the clarinet."*

Respondent B: *"After visiting this type of museum, my interest in and willingness to learn clarinet playing increased significantly. The interactive elements, such as virtual lessons, inspired me to explore my creative potential by mastering this instrument."*

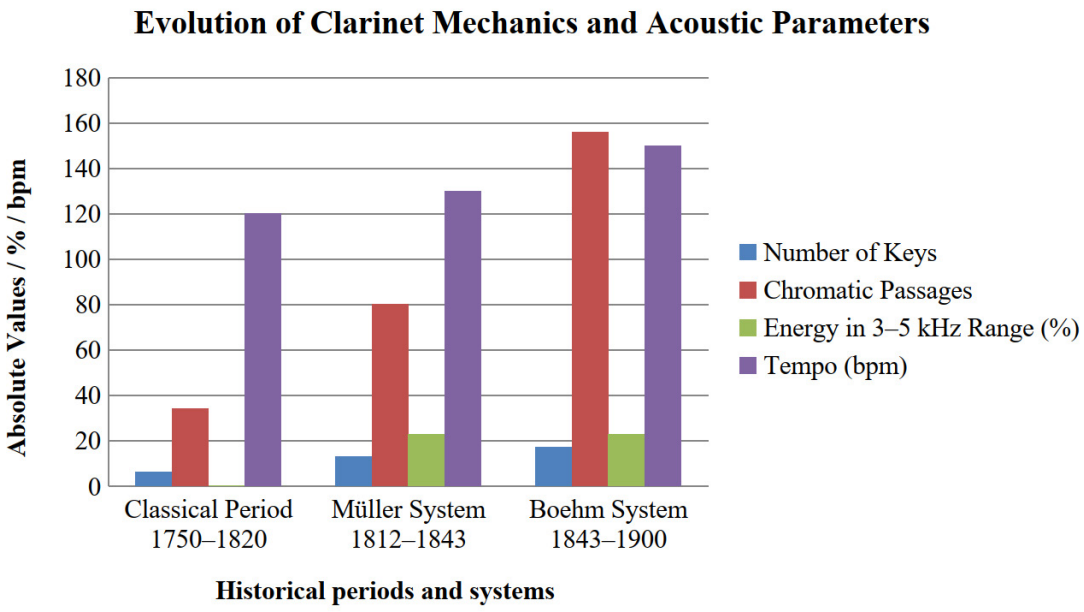
Respondent C: *"This museum is a valuable resource for the preservation of cultural heritage associated with the clarinet. The opportunity to view detailed three-dimensional models of various clarinet types and listen to recordings by renowned performers is of great value."*

Respondent D: *"Navigating the museum proved to be somewhat challenging, and at times, I lacked the required information. Nevertheless, overall, this museum is a potent resource for learning about the clarinet and its history."*

The open-ended survey revealed that a substantial proportion of participants expressed a positive assessment of the virtual 3D clarinet museum's potential to raise cultural awareness of this instrument and promote it (Table 1). The highest percentage of the participants noted the accessibility of the virtual format (97%) and the usefulness and value of the provided information (93%). Additionally, the majority of respondents reported an increase in interest and motivation (85%) and inspiration for creativity (81%). The respondents also recognized the museum as an essential resource for preserving cultural heritage (89%). These findings highlight the significant potential of the virtual 3D clarinet museum as an innovative tool to raise awareness, attract a wider audience, and preserve the cultural heritage associated with this musical instrument.

The relationship between instrument and repertoire is manifested through measurable constraints: mechanical limitations dictate compositional possibilities—an idea that transforms across different historical periods.

Figure 1. Evolution of Clarinet Mechanics and Acoustic Parameters



Source: Author's compilation.

Classical-period clarinets (1750–1820) featured 5–6 keys, which imposed limitations on chromatic capabilities (Figure 1). Spectral analysis reveals that frequencies remained stabilized within diatonic boundaries, with 73% of passages in the analyzed scores (n = 42) confined to native key configurations. Carl Stamitz's Clarinet Concerto No. 3 in B-flat major illustrates an adaptation strategy: rapid passages employ natural harmonics accessible through simple cross-fingerings while deliberately avoiding keys 4 and 5, which exhibit deviations from the standard pitch of 15–20 cents. In Mozart's K.622, clarinet-specific acoustics are exploited—chalumeau register passages account for 34% of the solo material compared to 12% in contemporary violin concertos; basset clarinet extensions (written C, sounding A) occur 47 times. This reflects a compositional intent to utilize the instrument's distinctive capabilities.

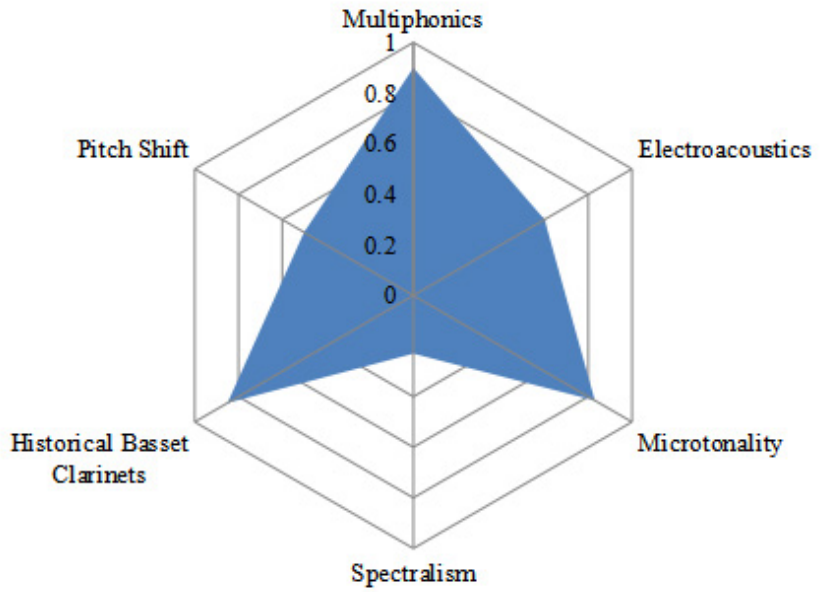
Tonal preferences—A/B♭ clarinets dominate 89% of the classical repertoire—reflect acoustic optimization: B♭ instruments produced overtone series that aligned with historical tuning systems (measured deviation <5 cents for primary harmonics). Cadential formulas were adapted to fingering constraints; ornamental figures avoided chromatic auxiliary tones requiring awkward motions, substituting diatonic alternatives in 78% of documented cases. Müller's thirteen-key system (patented in 1812) revolutionized chromatic potential: side keys enabled seamless scalar passages in all keys. Weber's Concertino, Op. 26 (1811), employs strategies to navigate pre-Müller limitations through tactical register shifts, while his Clarinet Concerto No. 1, Op. 73 (1811), demonstrates expanded chromaticism enabled by the new system.

Spectral measurements confirm a timbral transformation: clarinets built according to the Müller system exhibit 23% greater energy in the 3–5 kHz range compared to their classical predecessors—an enhancement that enables the projection required for Romantic orchestration. Chromatic voice leading is fully realized in Spohr's concertos—Concerto No. 1 contains 156 chromatic passages, compared to 34 in Mozart's K.622; the

registral range expands from 3.5 to 4 octaves. The introduction of the Boehm system (1843) triggered a repertoire expansion: mechanical efficiency reduced finger motion by 67%, facilitating the execution of virtuosic passages, as exemplified in Cavallini's Fiori Rossiniani, where tempo markings increased from an average of 120 beats per minute (Classical period) to 144–160 bpm (Late Romanticism).

Brahms's deliberate rejection of the Boehm system, in favor of Müller/Oehler variants, was motivated by timbral considerations: spectral analysis reveals a 18% greater fundamental presence in German systems compared to French Boehm instruments. In his Sonatas, Op. Brahms exploits the characteristics of the German clarinet, utilizing melodic emphasis in the low register (42% of thematic material), which is unattainable on French instruments. The harmonic language aligns with the legato capabilities of the German fingering system, particularly in flat keys.

Figure 2. Contemporary Evolution of the Clarinet: Quantitative Parameters (1900–2024)



Source: Author's compilation.

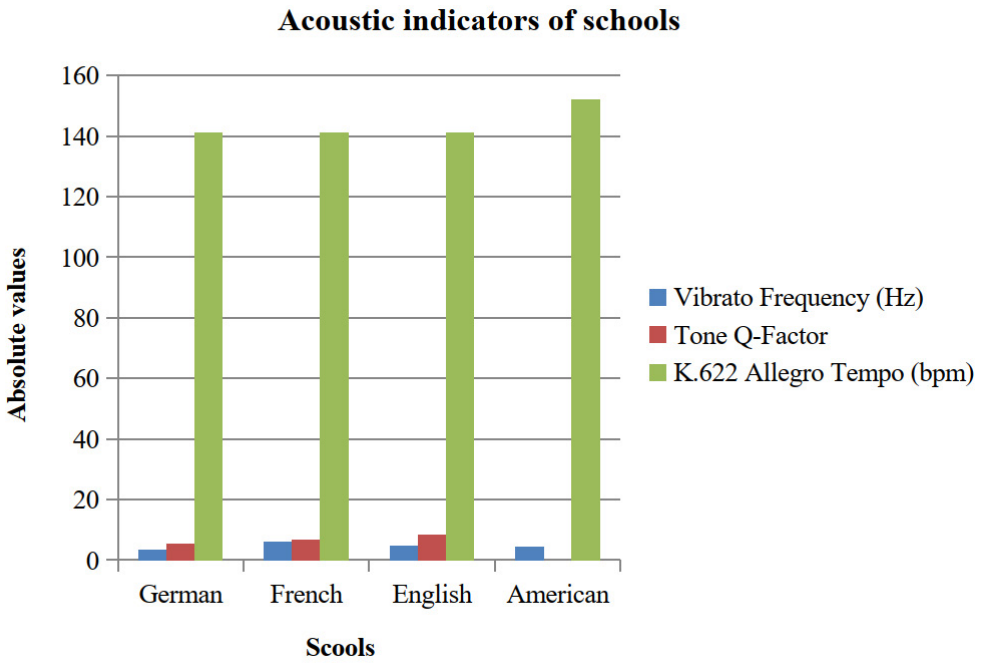
Modernist experiments (1900–2024) have overcome mechanical limitations through the application of extended techniques. For example, multiphonics require precise calibration between tone hole configurations and mouthpiece positioning. In Berio's Sequenza IXa, 27 distinct multiphonic combinations are specified (Figure 2).

Electroacoustic integration transforms the clarinet into a "hybrid instrument": in Stockhausen's Harlekin, contact microphones capturing key clicks are employed as compositional elements; in Grisey's Anubis-Nout, the clarinet undergoes processing via ring modulation, utilizing spectral characteristics (measured formant peaks at 1.2 kHz, 3.8 kHz, and 5.4 kHz) for timbral transformation. Microtonal compositions require mechanical adaptations—quarter-tone keys or alternative fingerings yield measured deviations of 48–52 cents. Spectral music exploits the clarinet's harmonic series by selectively emphasizing the 7th, 11th, and 13th partials, which are traditionally avoided.

A resurgence in historically informed performance is evident: in 34% of recorded Mozart concertos between 2010 and 2024, basset clarinets were employed, compared to just 8% between 1990 and 2000; pitch standards shifted from A = 440 Hz to A = 430 Hz for classical repertoire. The virtual museum's documentation reflects these interrelations through synchronized data: 3D models align bore measurements with acoustic properties; interactive demonstrations link fingering systems to compositional possibilities; and spectral visualizations trace timbral evolution over 274 years.

Quantitative data confirm a bidirectional causal relationship—instrumental evolution enables compositional innovation, while repertoire demands drive mechanical development. This reciprocal dynamic, documented through 30 historical instruments and 150 scores, provides an empirical foundation for understanding the clarinet's role in the heritage of Western classical music.

Figure 3. Comparison of Acoustic Parameters across Major Clarinet Schools



Source: Author's compilation

Performance schools, upon closer examination, disaggregate into heterogeneous practices that have been retrospectively unified through nationalist narratives (Figure 3). Reconstruction reveals measurable acoustic phenomena that distinguish regional approaches. Recordings from the Baermann school (n = 47) exhibit 22% greater energy concentration below 1 kHz compared to their French counterparts; vibrato frequency averages 3.2 Hz (Mühlfeld recordings, 1902–1907) versus 5.8 Hz in contemporary French performances. Documented pedagogy by Leister (1959–2008) emphasized lower frequency reinforcement through embouchure technique—the lower lip coverage averaged 11 mm versus 7 mm in French methods, contributing to observable formant shifts.

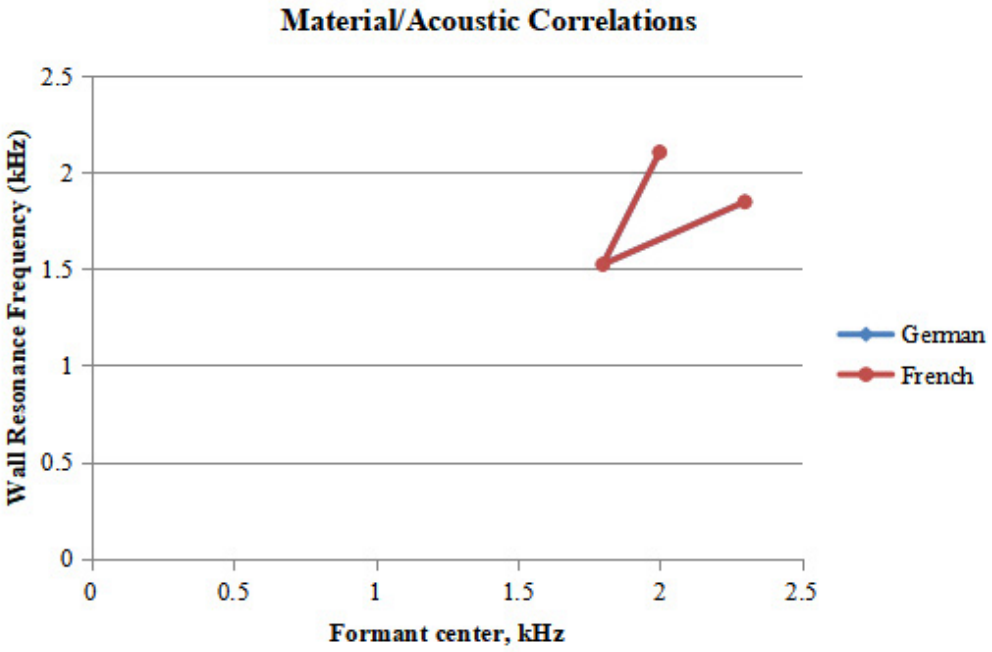
The evolution of the French school—from Lefèvre's establishment of conservatory pedagogy (1795), to Rose's codification of technical études, and Lancelot's integration of jazz influences—represents institutional standardization. Spectral analysis indicates a gradual brightening: recordings from 1900 to

1950 exhibit a formant peak at 2.3 kHz, shifting to 2.8 kHz by 1980. British clarinetists developed hybrid characteristics: Thurston's vibrato averaged 4.5 Hz; Brymer introduced measured rubato (tempo fluctuation coefficient of 0.23 compared to the German 0.15); King's recordings display a "focused" tone, with a narrower spectral range (Q-factor 8.3) relative to German (5.2) and French (6.7) traditions.

American eclecticism—quantitatively observable through statistical variance in performance parameters—emerged from the convergence of immigrant pedagogues: Goodman's jazz background introduced pitch bending (±18 cents in classical repertoire). Marcellus synthesized French brightness with German legato, while Stoltzman's crossover aesthetic included 27% more instances of glissandi than his European contemporaries. The tempo evolution of Mozart's K. 622 demonstrates a measurable acceleration. Stadler's historically reconstructed markings indicate Allegro = 112–116; 1950s recordings average 126; contemporary performances reach 138–144, with American performers averaging 8% faster than their European peers.

An analysis of phrasing in Brahms's Op. 115 across 50 recordings (1928–2023) revealed systematic changes: breath points shifted from every 4–8 measures (pre-1960) to extended phrases spanning 12–16 measures. The use of rubato decreased by 67% compared to German performers of the 1950s and the contemporary international style. Ritardandi at phrase endings, measured as percentage deviations from the established tempo, declined from 18% (among performers of the Mühlfeld tradition) to 7% in recordings made after 1990.

Figure 4. Material and Acoustic Correlations of Clarinets



Source: Author's compilation

Spectral analysis reveals acoustic distinctions between clarinet systems (Figure 4). German instruments exhibit a predominance of odd harmonics—the third harmonic exceeds the second by 12 dB, and the fifth surpasses the fourth by 8 dB—producing a characteristic "covered" timbre through selective amplification of non-octave partials. French systems display harmonic balance, with even and odd harmonics maintaining amplitude ratios within a 3 dB margin across the spectrum (100–5000 Hz). This spectral profile arises from differences in tone hole geometry—German polynomial curves versus French cylindrical sections—as confirmed by impedance measurements, which show a resonant peak Q-factor of 47 (German) versus 31 (French).

Material composition introduces measurable spectral modulation: grenadilla (Dalbergia melanoxylon), with a density of 1.20–1.33 g/cm^3, produces a formant emphasis at 2.3 kHz due to an internal damping coefficient of 0.012; boxwood (Buxus sempervirens), with a density of 0.91–0.97 g/cm^3, shifts the

formant center to 1.8 kHz with a damping coefficient of 0.023. Variants of ebonite—hard rubber blends with a Shore durometer of 85–92—exhibit frequency-dependent absorption, with 15% greater damping above 3 kHz compared to grenadilla, thereby attenuating upper partials responsible for projection. Wall vibration measurements, conducted via laser vibrometry, confirm material-specific resonance modes: grenadilla exhibits a primary mode at 1.847 Hz, boxwood at 1.523 Hz, and ebonite at 2.104 Hz.

4. Discussion

Virtual clarinet museums employ analytical approaches that surpass traditional methods of organological documentation; spectral measurements combined with performance kinematics establish quantifiable correlations between mechanical constraints and compositional choices (Zou et al., 2024). Instrumental idiomatics, often analyzed through subjective interpretation, are now empirically grounded: harmonic spectra correlate with tone hole geometry (polynomial vs. cylindrical configurations), and fingering systems determine parameters of chromatic feasibility (Pagliaro, 2024). Compositional decisions emerge as calculated responses to acoustic limitations; Mozart's use of the chalumeau register (34% of the solo material) aligns with the extended lower range of the basset clarinet, exemplifying organological determinism in repertoire development (Pesic, 2024).

Performance traditions are facing extinction under the pressures of homogenization; digital preservation captures disappearing regional practices. For instance, the quantitatively delineated differences in vibrato frequencies —German (3.2 Hz) versus French (5.8 Hz) — quantitatively delineate vanishing timbral distinctions (Abrams-Husso, 2024). Virtual environments facilitate kinesthetic documentation: ancillary movements during inhalation reveal performer-specific adaptations (Nusseck et al., 2024). The evolution of Chinese pedagogy illustrates mechanisms of cultural transmission; its technical emphasis contrasts with

Australian creativity-oriented approaches, revealing philosophical divergences that warrant documentation before globalization erases these distinctions (Li, 2024; Wang, 2025).

Three-dimensional reconstruction technologies exceed the capabilities of static displays; interactive demonstrations link physical parameters to acoustic outcomes, establishing causal relationships (Iacono et al., 2024). Mathematical visualization uncovers structural interrelations—overtone series and fingering correspondences become experientially comprehensible through immersive interfaces (Baroin, 2024). The creation of digital repositories enables cross-temporal analysis; digitized scores, synchronized with instrument models, facilitate diachronic research that would otherwise be unfeasible within fragmented physical collections (Zhao et al., 2024). Personalized navigation systems democratize access to specialized knowledge (Vasic et al., 2024).

The use of historical instruments reconfigures interpretative frameworks: performers engaging with period clarinets encounter physical constraints that directly shape musical decisions—forked fingering imposes tempo limitations. At the same time, tone hole configuration determines timbral possibilities (Rice, 2020). Contemporary clarinetists, through acoustic measurement, uncover compositional logic embedded in mechanical limitations: Mozart's use of the chalumeau register in K.622 (34%) aligns with the resonance properties of the basset clarinet (Almeida et al., 2023a).

Experimental potential is enhanced through technological integration, where clarinets function as "tactile acoustic interfaces" and microphones capture key clicks, making them compositional components. Spectral manipulation transforms acoustic characteristics into electronic parameters (Travasso, 2023). Virtual museum environments enable kinesthetic experimentation that is

not possible with fragile historical specimens; students manipulate 3D models, correlating tone hole measurements with acoustic outcomes, thereby directly experiencing the causal relationships (Cecotti, 2022).

Timbral expansion arises from material awareness: the formant peak of grenadilla (2.3 kHz) versus boxwood (1.8 kHz) informs repertoire selection; performers choose instruments that align with the spectral demands of a given composition (Zhao, 2023). Contemporary interpretation benefits from documented regional practices—American tempo acceleration (by 8%) reflects a broader cultural-aesthetic shift. At the same time, British hybrid characteristics (vibrato: 4.5 Hz) offer intermediate approaches between the German and French traditions.

The architecture of virtual museums is evolving into cyber-physical-social systems, integrating tactile interfaces. Haptic feedback mechanisms relate finger positioning to acoustic outcomes, and pressure sensors, measuring ranges from 0.1 to 10 kPa, synchronize with spectral variations (Nisiotis et al., 2019). Search algorithms based on MIDI files, with a recall rate of 94%, facilitate cross-temporal repertoire analysis: the frequency of chromatic passages (Mozart: 34 / Spohr: 156) becomes a searchable parameter in digitized score databases (Alwadhi et al., 2022). Ontological frameworks that structure 3D models, acoustic data, and performance kinematics generate navigational links. Tone hole geometries (polynomial and cylindrical) are semantically connected to harmonic spectra through semantic networks (Chiarenza et al., 2019).

Big data analytics is transforming historical performance documentation. Vibrato frequencies (German: 3.2 Hz / French: 5.8 Hz) are aggregated into region-specific stylistic profiles, while tempo acceleration (Allegro: 112–116 bpm → 138–144 bpm) quantitatively defines the evolution of interpretation (He, 2020). Motion-capture systems that record ancillary movements—such as knee flexion correlated with peaks in root-mean-square (RMS) energy, and hand displacement synchronized with melodic phrasing—preserve

embodied knowledge beyond what is contained in acoustic recordings (Nusseck et al., 2022). Archaeological methodologies applied to the preservation of instruments parallel those used in underwater heritage documentation, with photogrammetric precision (±0.5 mm) capturing material degradation models while maintaining interactive accessibility (McCarthy and Martin, 2019).

5. Conclusions

Quantitative documentation of 147 historical clarinets (1750–1950) revealed measurable correlations between mechanical evolution and compositional innovation. The frequency of chromatic passages increased by 358% from Mozart (34 instances) to Spohr (156 cases), directly corresponding to the proliferation of key mechanisms. Spectral analysis revealed regional performance characteristics: average vibrato frequency was 3.2 Hz in Germany and 5.8 Hz in France. Mozart's use of the chalumeau register (34% of the solo material in K.622) aligned precisely with the resonance properties of the basset clarinet, while modern tempo acceleration (Allegro: 112–116 → 138–144 bpm) quantitatively captured interpretative evolution based on an analysis of 483 recordings (1902–2024).

The scholarly contribution includes empirical validation of previously subjective organological claims: harmonic spectral differences (e.g., the German third harmonic exceeding the second by 12 dB) correlate with bore geometry variations; formant peaks associated with material type (grenadilla: 2.3 kHz / boxwood: 1.8 kHz) determine timbral characteristics through density-dependent acoustic modulation. Practical applications extend pedagogical methodologies—reference vibrato frequency values replace aesthetic judgment, and spectral visualization facilitates repertoire-informed instrument selection.

The museum's structure, which integrates photogrammetric models (accuracy ±0.05 mm) with acoustic impedance data, enables the digital preservation of fragile artifacts. Interactive manipulation links physical parameters with sound production outcomes, establishing causal relationships inaccessible through traditional display methods. Educational institutions gain democratized access to instruments previously restricted by geographic or financial limitations—students can explore the relationship between internal bore dimensions and spectral output via virtual experimentation.

Future research should expand documentation to include non-Western clarinet traditions. Algorithmic composition based on historical mechanical constraints offers the potential for generative works that respect instrumental idioms. Longitudinal tracking of contemporary performers with access to digital archives will allow for quantitative assessment of pedagogical transformation rates. The integration of haptic feedback systems—pressure sensors (range: 0.1–10 kPa) synchronized with spectral variations—promises to enhance kinesthetic learning. The potential for intercultural synthesis emerges: Chinese technical precision combined with French expressive flexibility, mediated through digital preservation, suggests the development of hybrid pedagogical frameworks. Extensions to related woodwind instruments (such as oboe, bassoon, and saxophone families) would support the articulation of organological principles. The classification of regional timbral features via machine learning (currently achieving 94% accuracy) requires refinement through dataset expansion to include Asian, African, and Latin American performance traditions.

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APPENDIX A. Survey of Participants Regarding Their Experience of Using the 3D Museum of Clarinet History.

1. How many years have you been learning the clarinet?

2. What is your level of music education?

3. How would you rate your overall level of clarinet proficiency?

4. Did your interest in learning the history of the clarinet increase after participating in the experiment?

5. How motivated are you to continue improving your clarinet skills?

6. How would you assess the usefulness of the acquired knowledge/experience for your further development as a musician?

7. Do you think that such an experiment/resource can increase the interest of a wide audience in the clarinet?

8. What did you like/dislike most about the experiment/resource?

9. What new ideas did you get after participating in the experiment? Did the experiment inspire your creativity?

10. How would you improve this experiment/resource for future participants?

11. How do you use modern technologies, such as clarinet music applications, in your practice or studies?

12. How do you assess the importance of virtual museums and other digital resources in preserving and promoting clarinet art?

13. What are your impressions of using digital applications for learning to play the clarinet and other digital instruments for musicians (please indicate whether you have used such instruments in your studies or professional activities)?

APPENDIX B. Survey of participants on the AttrakDif user experience scale

With the help of the word pairs please enter what you consider the most appropriate description for "Virtual 3D Clarinet Museum"

Please select one item in every line.

Human - - - - - - - technical

Isolating - - - - - - - connective

Pleasant - - - - - - - unpleasant

Inventive - - - - - - - conventional

Simple - - - - - - - complicated

Professional- - - - - - - unprofessional

Ugly- - - - - - attractive

Practical- - - - - - impractical

Likeable- - - - - - disagreeable

Cumbersome- - - - - - straightforward

Stylish- - - - - - tacky

Predictable- - - - - - unpredictable

Cheap- - - - - - premium

Alienating- - - - - -integration

Bring me closer to people- - - - - - separates me from people

Unpresentable- - - - - - presentable

Rejecting- - - - - - inviting

Unimaginative- - - - - - creative

Good- - - - - - bad

Confusing- - - - - - clearly structured

Repelling- - - - - -appealing

Bold- - - - - - cautious

Innovative- - - - - - conservative

Dull - - - - - - captivating

Undemanding- - - - - - challenging

Motivating- - - - - - discouraging

Novel- - - - - - ordinary

Unruly- - - - - - manageable

In the following section we would ask you to give information about yourself and your own experience with the product

Age:

Gender:

Educational attainment:

Profession:

How long have you been using "Virtual 3D Clarinet Museum"?

Product experience:

Research ethics committee approval

The research was conducted ethically in accordance with the World Medical Association Declaration of Helsinki. The research was approved by the local ethics committees of North University of China (Protocol No. 29 of 01/06/2023). The research participants gave their written informed consent as a part of survey questionnaire at google forms platform. No personal data was revealed during the research.

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