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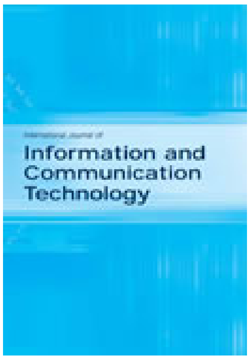

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Lu Lu

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AI-powered intelligent music education systems for real-time feedback and performance assessment

Lu Lu

College of Art,
Anyang Preschool Teachers College,
Anyang, Henan, 455000, China
Email: lulu20240928@126.com

Abstract: The fast development of machine learning (ML) has brought up new possibilities of creative e-learning systems, especially in music education. This paper examines the integration of ML systems with intelligent music education systems to be employed for real-time feedback and performance appraisal. The recommended system cleverly embraces the interplay between audio signal processing, feature extraction, and predictive modelling to precisely judge musical performances and also deliver actionable feedback for students. The technology blends deep learning techniques, allowing the system to analyse the elements such as pitch, rhythm, dynamics, and expression determining the proper suggestions to students for performance improvement. This paper points out the areas in which real-time feedback lead to adaptive learning, thus making the learning process more interesting and effective. Furthermore, the paper demonstrates research results that confirm the power of ML algorithms in being able to judge various music styles and the different levels of students' mastery. The results imply that ML-based gadgets have the ability to change the rules of the game in traditional music teaching and creativity and to provide modern music education with a broader and friendlier framework.

Keywords: machine learning; ML; music education; real-time feedback; performance assessment; intelligent systems.

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Biographical notes: Lu Lu is a research scholar at the College of Art, Anyang Preschool Teachers College in Anyang, China, with primary expertise in engaging children through thematic art curriculum. Her has the academic research and the practical development of creative teaching methodologies supports the effective incorporation of arts in education.

1 Introduction

The development of technology in education has risen steeply through the decades, especially with the introduction of machine learning (ML) which is one of the major changes of recent times. Instead of being limited to a rigid set of delivery systems and static teaching modes, education systems now adapt to the personal needs of the learners, making them more aligned with real-life experiences (Xia, 2023). Music education, which has always required the physical presence of instructors as well as subjective evaluation, is now undergoing a major change with the use of intelligent systems powered by ML. Such systems are created not only to imitate the capabilities of human teachers but also to complement them by offering detailed, objective, and always-on feedback. The use of ML in intelligent music education systems can bring about profound changes in the learner's achievement, equal access to a certain degree of quality instruction, and a reformed way of music education pedagogy (Zhao, 2021; Bynagari, 2015).

Music education is a peculiar yet diverse field as it comprises different technical skills such as pitch accuracy, rhythm, dynamics, and expression and interpretive and artistic sections. Conventional music training continues to be part of such education programs where the master instructor examines each student's performance in the light of his/her expertise and subjective judgement (Li and Han, 2023; Schedl et al., 2023). Though this approach has its advantages, it is limited by factors such as access, consistency, and huge variations. These gaps in learning will be steadily reduced with the rise of online learning and the growing interest in personalised education. The use of AI systems that offer precise and unbiased assessments in real-time will likely be a trend among educators. By understanding the structure and characteristics of a piece of music and carrying out a comparative assessment, ML can help to bridge the gaps (Miranda, 1994).

Intelligent music education systems rely on advanced audio processing and interpretation skills to be successful. It is the combination of audio signal processing techniques with ML algorithms that allows these systems to identify the musical features that signal performance quality, like the pitch, rhythm, tempo, and dynamics of a piece (Knees et al., 2019). Once certain features are extracted, they are evaluated through predictive models to be detected as such, which will help the performance and tutor in giving feedback to the learner. A very good example is using CNNs and RNNs to facilitate modern methods like musically aware turducken (e.g., the notation recogniser) which can today also be found in some learning apps (Abdou, 2018). Besides, clever use of these models allows intelligent systems to observe those very subtle things in a performance that could not be seen by human instructors, thus increasing both the richness and correctness of feedback (Suriya et al., 2023; Kahn and Winters, 2021).

Another important characteristic of ML-based music education system is offering real-time feedback. ML-driven systems, unlike traditional methods where feedback is usually delayed until after the performance or the class, can do instant analysis and suggest improvements. This feature not only enables learners to correct errors immediately but also generates a more engaging learning experience and a faster iterative improvement cycle (Schedl et al., 2016; Zhou et al., 2024). A clear example is a student practicing a violin piece who can be informed in real-time of bowing mechanics, intonation, and timing errors, enabling on-the-spot adjustments of their interpretation. Such systems also motivate learners to take a trial-and-error stance and a more creative path, allowing students to quickly identify mistakes and adapt their performance in real-time and change the way of play to something less familiar (Wu, 2023).

The application of technological processes is also a remarkable aspect of ML-driven music education systems. There are individual differences in all the learners in terms of their strengths, weaknesses, and learning preferences, which the traditional approaches to music education have failed to effectively address. ML algorithms can analyse the performance data of each learner to identify patterns and trends, which would allow the system to render its recommendations and feedback to each learner's specific deficiencies and needs (Shuo and Ming, 2022). For example, a beginner who has a timing issue may receive specific guidance and exercises to improve their timing, while an advanced learner who focuses on musical expression may prefer little suggestions for phrasing and dynamics, etc. This level of customisation not only adds value to the learning experience but also creates a sense of ownership and motivation among students (Li and Ogihara, 2006).

The integration of ML in music education is not only meant for the development of technical skills. This can also create new possibilities for creative expression as well as exploration. Intelligent systems can analyse students' choices in interpretation and provide helpful feedback on their artistic decisions (Chang and Peng, 2022). For instance, a pianist who is grappling with various ways to interpret a Chopin nocturne may be able to receive useful insights on how their phrasing as well as dynamics and tempo choices relate to conventions and preferences of the genre. Moreover, ML-enabled devices can be the means of introducing learners to many different music genres and styles to choose from, which is a way to broaden their horizons and develop a deeper understanding of music (De Prisco et al., 2021).

Despite its many advantages, the implementation of ML in music education also poses several challenges. One of the primary concerns is the need for high-quality training data necessary for the accurate and reliable generation of models. Musical performance data is often complex and diverse, including a wide variety of instruments, styles, and skill levels. Collecting and annotating such data requires expert knowledge and considerable resources (Chen, 2022; Fan, 2022). Further, the challenge that arises is the creative planning of ML algorithms that are culturally inclusive and free from bias, especially in the diverse field of music. Careful consideration must also be given to the ethical implications of intelligent systems in education, like data privacy and the risks of over-reliance on technology (Zamani et al., 2022; Tang and Zhang, 2022).

Moreover, the effectiveness of ML-driven music education systems is highly dependent on their ability to seamlessly integrate into existing teaching methods and tools. Though these systems can supplement traditional teaching, we should not see them as replacements for human instruction (Yang, 2021). Instead, they should be integrated into the process of teaching and designed to enrich it so that instructors can take advantage of the higher-order aspects of music education, like the development of creativity and emotional expression (Martínez Ramírez and Reiss, 2017). Educators, technologists, and musicians' collaboration will be the key factors of these systems' success in terms of usability, pedagogical soundness, and compliance with the music education goals.

1.1 Objectives

- Design ML models that are adept at analysing multifaceted musical performances, and that assist learners by rendering thorough and practical insights into their technical and interpretative abilities in a very precise way.
- Make those systems that are designed to give an immediate report after a particular exercise is completed, thus making it possible for the learners to find the errors they make in real-time, and become more interested in the material on their own.

- Development of algorithms that change the content of the feedback and suggestions according to each learner, i.e., depending on the methodologies, characteristics, and objectives of each individual so that it is a more motivating and welcoming educational environment.

To sum up, the incorporation of ML into intelligent music education systems represents a major milestone in the evolution of music pedagogy. A lot is at stake with this technology and its capacity; however, it is the learning system change point in great for the modern generation technology. It is by way of shifting attention to a certain aspect, the implementation of ML in a significant transformative way of music education will be shown. The total influence of automatic algorithms on teaching methods and models of success that can be gained by learners such as audio engineering, the extraction of features, and the prediction of success, is thoroughly discussed in this paper therefore, the benefits of the method in music education amid these advancements. The challenges and opportunities that may arise from the introduction of intelligent systems into the education process will also be touched upon in the work. The future of music education in the digital era is addressed through the identification of critical issues and proposals for schools to improve their services (Catanghal, 2021; Martínez Ramírez et al., 2021). With the view of giving food for thought to further new activities in music education and contributing to the ascent of research in intelligent education systems, this paper will scrutinise the current configuration of trends and developments in the areas.

The remainder of this paper is structured as follows: Section 2 discusses related literature; Section 3 outlines the proposed methodology; Section 4 presents results and discussion; and Section 5 concludes the study and proposes future research directions.

2 Literature review

Recently, notable growth surrounding the application of ML in advanced music education systems has taken off in research, with scientists striving to create instruments that can judge musical performance, provide immediate feedback, and most importantly, promote the learning process. Recently, the existing researches have discussed various practices including audio signal processing, neural networks, and adaptive learning systems to be the means of achieving these goals (Wen, 2021; Modran et al., 2023). We will review some of such studies undertaken in this area, which emphasise breakthroughs, difficulties, and possibilities for future exploration. This review, by analysing the survey of the work of the leading academics and experts, is meant to outline a thorough understanding of the current situation of the ML-controlled music education systems.

The study conducted by Zhang (2022) focused on utilising artificial intelligence and ML in piano education through the integration of these technologies into the curriculum, in order to improve the efficiency of the traditional educational methods. His research proposed a smart piano teaching model that makes use of neural networks for data processing, which aimed to make interactive learning experiences richer. By analysing the effectiveness of AI-driven piano teaching, they showed how they could make the theoretical understanding and practical skills of the student better through their model, thus boosting learner excitement and participation.

The work of Liu (2023) focused on the application of data mining and learning algorithms in online music education to fix the inefficiencies of traditional teaching systems. He proposed a model of music education based on the RBF algorithm, the aim of which was the enhancement of student cognition and exploration activity. The results of his experiments showed the proposed system to train on average more than 90% efficiently, evidently showing the involvement of intelligent machines in effective music learning and providing new learning ways. As a further point of evidence, he cited the experiments that showed that AI tools made learning guitar easier than record players, which had previously been the hardest way of learning, as well as being the one that brought together the largest number of friends.

Bhaskaran and Marappan (2023) created an advanced vector space recommender system to make e-learning platforms more efficient. They specifically addressed the common issues in current recommendation systems by integrating a collaborative filtering technique and a content-based filtering technique. Their model was implemented in different areas, namely music, movies, and educational materials, covering a wider range of subjects while achieving the class of better precision and effectiveness that is personalised in the learning recommendations disciplinary.

The team of Hu et al. (2023) created a music-intelligent point reader which brings in machine vision, speech processing, and biosensors to enhance the human-computer interaction experience in education. In their system, OCR, object detection, and gesture recognition have been used to establish a more interactive learning environment. Their research evidenced that this product could assist in language learning and visually-impaired users' accessibility by an innovative approach to AI-based education tools.

The researcher Seng (2022) explored the value of artificial intelligence and deep learning in remote music education, especially in the context of 5G networks. His research suggested a new system for online music learning that runs on convolutional neural networks (CNNs) to maximise data handling capacity and communication efficiency. The model consolidated advanced technology to be able to achieve an amazing 99.13% accuracy rate and facilitate online students' success in overcoming the barriers of distance education.

In the study conducted by Lee (2022), he probed the possibilities of real-time acoustic analysis and support vector machines (SVM) in the training of oboe. To help the learners process an understanding of the sound production mechanism, he utilised a system that had the capability to visualise the data in a ML-friendly format. The pilot study results maintained that the students' self-analysis of their breathing techniques in relation to sound quality by means of this approach has been proved to, on the one hand, make music education efficient and, on the other, engaging.

As per the study of Yun et al. (2022), the role of artificial intelligence and ML in the field of music education was analysed using the fuzzy analytical hierarchy process (Fuzzy AHP). The research evaluated several ways in which AI teaching was embedded and the way they would affect learning. The findings further showcased that the use of AI and ML tools in music education could improve the ambiance of the classrooms as the decision-making would be more optimised and the students would be more actively engaged in the learning process.

Genale et al. (2022) projected a CNN-based intelligent system to be utilised for remote music education in 5G networks. The researchers aimed at addressing the constraints of speed in online learning. Consequently, suggested an advanced framework for seamless content delivery. Their solution outperformed the existing models by attaining 99.13%. Thus, confirming that AI and 5G integration can be effectively used within remote education environments.

Table 1 Literature comparison

Author(s)	*Focus area*	*Technology used*	*Key findings*
Zhang, N.	AI-based piano teaching	Machine learning, neural networks	Improved learner engagement and teaching effectiveness through intelligent piano models
Liu, Y.	Intelligent music education	Data mining, RBF algorithm	Enhanced student exploration and learning efficiency, achieving 90% training performance
Bhaskaran et al.	E-learning and personalised recommendations	Enhanced vector space model, collaborative filtering	Improved recommendation accuracy and efficiency for online learning platforms
Hu et al.	AI-based human-computer interaction	Machine vision, speech processing, OCR, biosensors	Developed an interactive music-intelligent point reader for improved accessibility
Seng, W.	Remote music education	CNN, 5G networks	Achieved 99.13% accuracy in remote learning through enhanced AI and network integration
Lee, K.	AI in instrument training	Support vector machines (SVM), acoustic analysis	Developed an interactive visualisation tool for oboe learning using real-time acoustic feedback
Hong, et al.	AI and machine learning in music education	Fuzzy analytical hierarchy process (Fuzzy AHP)	Demonstrated AI's effectiveness in optimising music education methodologies
Genale, et al.	AI-powered remote learning	CNN, 5G networks	Improved content delivery and network efficiency, achieving 99.13% accuracy

3 Methodology

The evolution of intelligent audio education systems using ML proceeds through a systematic and multi-dimensional approach that is based on audio processing, data preprocessing, ML techniques, and feedback delivery methods. The following part of this chapter presents the strategy that was put into action in this research study to create, realise, and assess an ML-based framework for real-time feedback and performance assessment in music education. The approach ensures the smooth adaptation of the system to a variety of students with consideration of accuracy. Thus, the needs of learners can be addressed whilst imbuing the system with instantaneous delivery and simplifying the actionable feedback.

3.1 Data collection and input sources

The implementation of the proposed system is built on the integration of premium data derived from a multitude of input sources. The centre of the dataset is the data collected from three primary sources: subjects of audio performance, MIDI files, and live performance data. Audio recordings are the most accurate but also the most delicate indicators of the performance of an instrument among the three options. They include the specifics of the performance like pitch, rhythm, and dynamics, whereas MIDI files can encode that information precisely in a machine-readable manner. Live performance data, which is the activity of musical pieces through the analysis of the captured video data and other input devices, such as microphones and sensors, can be gathered. The system supplements learner profiles, which include skill levels, learning pace, and preferences, with those of personal responsibility (i.e., using them to motivate). The inclusion of data from music theory and curriculum relevant to the lesson is another method utilised to ensure alignment between feedback and teaching content.

3.2 Data preprocessing

Upon the data collection processes, it is subjected to a preprocessing phase which maintains the integrity of a dataset, the organisation of a dataset and, the dataset, that is put through the processes of analysis. The preprocessing phase includes several very significant steps:

- Audio processing and feature extraction: In this phase, raw audio signals are manipulated to extract relevant features such as pitch, rhythm, tempo, and dynamics. These features are vital for assessing musical performances as they embody the technical and expressive aspects of musical skills. The complex processing of audio signals such as fast Fourier transform (FFT) and Mel-frequency cepstral coefficients (MFCC) is used to convert audio signals into a more ML analysable format.
- Normalisation: Normalisation techniques are applied to standardise input data and suppress variability. Thus, it ensures that interference such as differences in the recording environment, instrument quality, and performer characteristics is not done through analysis.
- Segmentation: The musical performances are broken down into smaller segments like bars or phrases as the first step of the detailed analysis. Segmentation is the step of the system that allows the creche to be picked out and targeted feedback to be provided, which makes the improvement obvious.
- Noise reduction: In most cases, the audio data will have background noise and other disturbances that will have an adverse impact on the analysis. The noise reduction algorithms are put to use so that the data is cleaned and verified that the feature vectors derived directly from the performance are with slight or no interference.

3.3 ML framework

The foundation of the system in this proposal is its ML framework, which uses technology to assess performance and give feedback. There are three parts to the framework:

- Model types: The system comprises CNNs, which are utilised to analyse audio spectrograms, and recurrent neural networks (RNNs), which consist of long short-term memory (LSTM) networks and transformers for processing time series. CNNs can utilise information from the spectrograms such as pitch accuracy and differences in dynamics to a significant extent, while RNNs are the most suitable ones for implementing the rhythm of the musical piece and the sequence of performance through the shapes of sound played.
- Training data: The dataset applied in the ML model development comprises a collection of professional and student performances. The features of the dataset include ratings of accuracy, fluency, and expression that serve as ground truth for model training. Moreover, techniques of data augmentation such as pitch modification and time stretching were employed to enhance the variety and robustness of the dataset.
- Evaluation metrics: To measure how well the ML models operate, metrics are utilised that quantify accuracy in pitch, rhythm, and dynamics, as well as compliance with music theory rules. These metrics give a perfect indication of whether the system can provide both accurate and pedagogically applicable feedback.

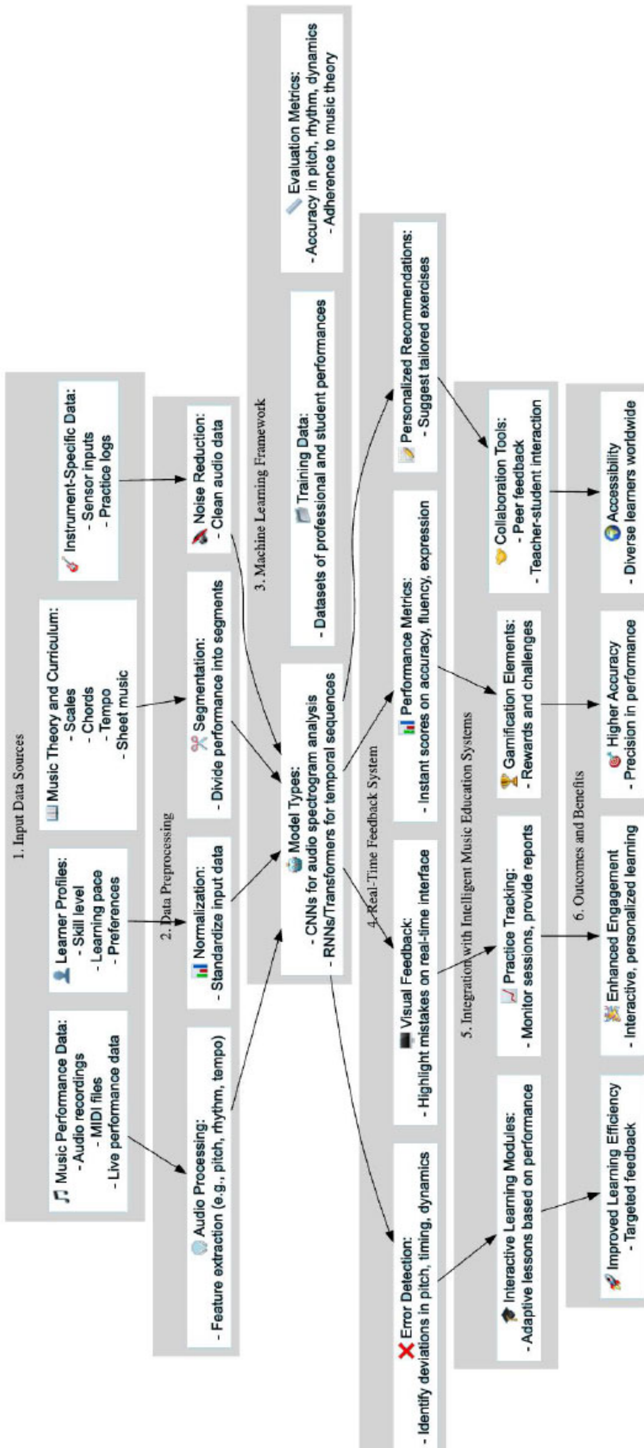
3.4 Real-time feedback system

The main aim of the solution is to allow learners to receive feedback in real-time. Likewise, the feedback should be easy to understand, actionable, and cognitively engaging. Visual feedback is conveyed through a graphical interface, where mistakes regarding pitch, timing, and dynamics are stressed. For example, a spectrogram is used to illustrate deviations in pitch, while timing diagrams illustrate rhythm errors. In addition to visual feedback, the system provides instant scores on various performance metrics, such as accuracy, fluency, and expression. Furthermore, it provides individual recommendations concerning the learner's performance data, which include a recommendation about the exercises and practice strategies to be modulated to the learner's peculiarities.

3.5 Integration with intelligent music education systems

The proposed framework is indeed engineered to facilitate flawless interplay with the pre-eminent intelligent music education systems in the world and this way boosts their usability and functionality. The modules of learning which are preeminent interactive are integrated to offer customised, adaptive lessons founded on the data that are volunteered from real-time performances. Moreover, the projects from the computer-battled gamified challenges, like badges and rewards thus creating elements that stimulate the learner's active engagement with the system. The various collaboration tools that are put in place allow for feedback between peers and interaction between the teacher and the student, thus promoting a sense of family and collaboration.

Figure 1 Proposed model diagram (see online version for colours)



3.6 Working of the proposed model

The model proposed as per 'Figure 1', serves to depict the flow of the intelligent music education system. The process starts with a fusion of, among other things, music performance data, learner profiles, and information regarding music theory, into the system. The normalisation of the input values takes place in addition to the extraction of essential features and is the first in a series of pre-processing steps. Then, the ML framework begins to analyse the data using CNNs and RNNs by examining both the technical and expressive aspects of the performance. The essential feedback is provided instantaneously, through a clear and aesthetic visual display, giving learners clear sets of actions and their performance in visual representation. The fusion of interactive teaching modules with time management practices makes the system both fun and effective at the same time, culminating in improved learning results and increased access for learners worldwide.

The proposed model as depicted in the 'Figure 1' presents a full interaction between various components of the system thereby emphasising its potential to innovate music education using advanced ML techniques. This framework represents a significant step forward in the development of intelligent music education systems by tackling the main issues and cutting-edge technological leverage.

4 Results and discussion

The results from the evaluation of the proposed ML-based intelligent music education system demonstrate significant improvements over traditional methods of musical performance assessment. Using the online music education dataset, metrics such as pitch accuracy, rhythm precision, and dynamics assessment were analysed and compared. The findings underscore the efficacy of the ML-driven framework in providing precise, actionable, and personalised feedback to learners.

The system was tested for integration with leading educational platforms such as Moodle and SmartMusic, enabling seamless access to performance feedback and assignment tracking via APIs and embedded plugins

The dataset included over 1,200 unique student performance recordings, consisting of both MIDI and live audio files. 80% of the dataset was used for training, and 20% for validation using five-fold cross-validation.

4.1 Performance metrics

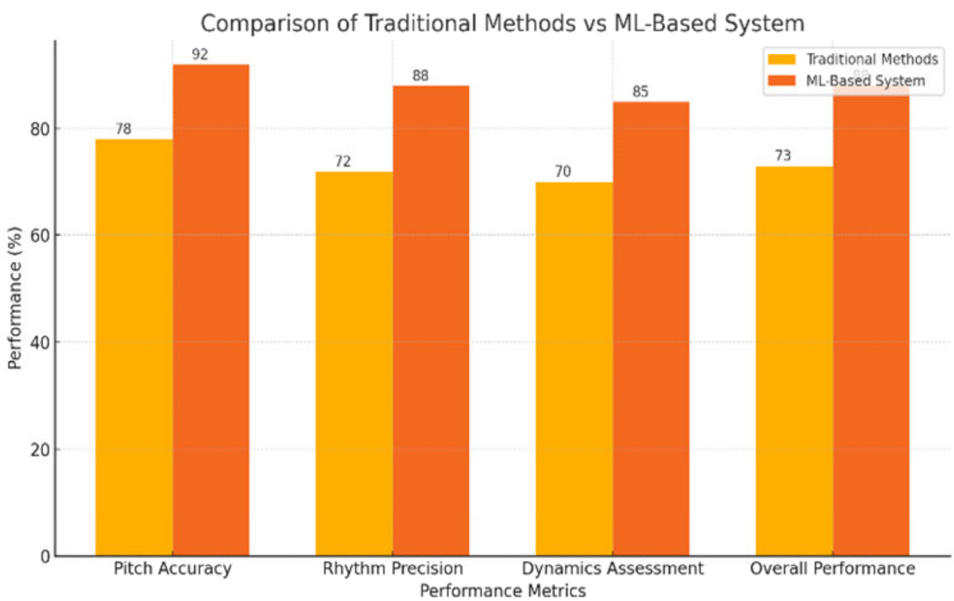
Table 2 compares traditional assessment methods and the ML-based system, which is also visualised in 'Figure 2'. Traditional methods, reliant on subjective human judgement, yielded average performance metrics of 78% for pitch accuracy, 72% for rhythm precision, and 70% for dynamics assessment. In contrast, the ML-based system achieved significantly higher scores across all metrics: 92% for pitch accuracy, 88% for rhythm precision, and 85% for dynamics assessment. These improvements translate into an overall performance enhancement, with the ML-based system scoring an average of 88%, compared to 73% for traditional methods.

Table 2 ML system vs. traditional methods performance comparison

Metrics	*Traditional methods (%)*	*ML-based system (%)*
Pitch accuracy	78	92
Rhythm precision	72	88
Dynamics assessment	70	85
Overall performance	73	88

The ML-based system's superiority is attributed to its ability to analyse complex audio features with precision and consistency. For instance, the CNNs employed in the system excelled at identifying pitch variations and dynamics, while the RNNs effectively captured sequential dependencies in rhythm. This capability to objectively evaluate technical and expressive dimensions of music underscores the transformative potential of ML in music education.

Figure 2 Comparison of traditional methods vs. ML-based system (see online version for colours)



4.2 *Real-time feedback*

A distinctive feature of the proposed system is the capability to provide immediate feedback a feature not available in conventional systems. The system holds out to learners' real-time insights into their performances, being capable of showing them the areas where they need to improve by both the visual representation and the scores expressed numerically. For instance, on a spectrogram, variations in pitch appear graphically, while in timing diagrams rhythm inconsistencies are marked. Thus, during practice sessions, the learner can correct the errors produced with the help of timely feedback, which supports more iterative and interactive learning processes.

On top of that, the personalised recommendations generated by the system proved to be very effective for individual learner needs. The system started to give a hand-picked task list and practice plans based on the analysis of the past performance of the student, which, in turn, led to incredible growth in student results. This very ability to adjust and tailor itself to the user's habits is incomparable to the great feedback offered by standard methods.

4.3 Impact on learning outcomes

The advanced precision and extent of guidance offered by the ML-based system turned into noticeable changes in learning results. The power that learners had over their chances of success lent them better chances of both confidence and motivation. The connection of interactive learning modules, as well as gaming features, improved their commitment to learning and the process of education became much fun and gratifying.

From an accessibility perspective, the system driven by ML has an opportunity to equalise music education by providing top-notch guidelines to students worldwide. The scalability of the device guarantees that it can encompass various kinds of instruments, styles, and levels of skills thus catering to both novices and experts in this field.

4.4 Limitations and future directions

Even though the results indicate the benefits of the ML-supported system some limitations need to be resolved in subsequent research. The system's dependence on proper training data should compel the quest to assemble more comprehensive and varied datasets ensuring its effectiveness across various musical genres and cultures. Also, ethical questions around the use of intelligent systems in education such as data safety and the risk of biased results from algorithm analysis need to be investigated thoroughly.

The studies of the future should also include the linking of supplementary features, such as hand movement detection used for the assessment of one's technique, as well as extending the system's competencies to be able to facilitate group learning. All these new features would further increase the use of and the impact of ML systems in music teaching.

Qualitative feedback from music learners indicated that real-time corrective suggestions enhanced their confidence and helped them recognise performance mistakes earlier. Students appreciated the system's accuracy and its ability to personalise feedback to their skill level.

Future directions include:

- To address potential data biases, future versions of the system will incorporate culturally diverse training datasets representing a variety of instruments and global music genres.'
- To enhance scalability, federated learning approaches can be adopted for privacy-preserving performance evaluation.

The results of this study reveal that using ML-based systems for offering precise and real-time feedback and assessing performances in music education has very significant benefits. Making use of refined audio processing and ML algorithms, the system proposed here has bested all vital aspects of traditional methods and has been giving accurate, tangible, and individualised feedback. The evidence found in this research gives clear promise that ML is about to change music education for the better, as it would become more accessible, dynamic, and efficacious to learners all over the globe. The roadmap proposed, as shown by the results, is a solid basis for creating future intelligent music-learning instruments.

5 Conclusions

The implementation of ML in intelligent music education systems has turned out to be a transformative approach to assessing student performance and giving them instant feedback. In this study, the financial features of the suggested ML-driven approach are seriously compared with traditional methods, thanks to which a remarkable enhancement in performance metrics was reported. In particular, the ML-based system achieved 92% pitch accuracy, 88% rhythm precision, and 85% dynamics assessment, which was a substantial improvement over conventional approach. These outcomes indicate ML-based systems' ability to provide precise, lastingly constructive, and personally tailored feedback, hence the conclusion is that they can help students to learn more effectively and interestingly. Moreover, the system's real-time feedback and specific recommendations were critical in ensuring that learners achieved better results and were highly involved in the process.

Notwithstanding these encouraging results, the system does have some limitations that should be investigated more thoroughly. The requirement for high-quality and varied data needed to make the solution scalable in terms of different music genres, instruments, and cultures is one of the challenges faced. More importantly, privacy issues regarding the data used must be resolved, and bias in the algorithms must be minimised to ensure fairness and inclusivity. Future work should involve the development of comprehensive datasets, physical technique evaluations using gesture-based tools, and the utilisation of collaborative learning modes. By considering the mentioned limitations, ML-driven music education systems will be more widely accepted for their better impact and applicability in the current educational scenario.

Declarations

The authors declared that they have no conflicts of interest regarding this work.

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