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ARTICLE

Interactive Robotic Chess Resource for Basic Education

Recurso Interactivo de Ajedrez Robótico para la Educación Básica

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ABSTRACT

Chess has been recognized as a relevant pedagogical resource for developing cognitive processes associated with logical-strategic thinking, concentration, planning, and problem-solving in basic education. This research aimed to evaluate the technical feasibility of a Robotic Expert System applied to chess instruction and to describe its pedagogical potential as perceived by experts in educational robotics and chess instruction. The study was framed within the pragmatic paradigm, used the technological development method, followed a quantitative approach, and adopted a non-experimental, cross-sectional, projective-descriptive technological design. The unit of analysis was the chess-playing robotic prototype, classified as a technological artifact. The validation process included three teachers who assessed the operating conditions and pedagogical potential of the system, while twenty middle school students tested the developed prototype as users during the interaction process. The methodology was based on the construction and validation of a mechatronic prototype integrating a Minimax-based expert system, computer vision, and a robotic arm with three degrees of freedom. Data collection techniques included technical validation through a requirements and performance checklist and pedagogical evaluation through a questionnaire administered to experts. The results showed 100% compliance with the system's functional specifications, 98% accuracy in move identification through computer vision, and an average response time of 2.5 seconds for the Minimax algorithm. The expert evaluation reported favorable ratings regarding perceived educational effectiveness, motivation, interest, and instructional functionality. It was concluded that the prototype constituted a technically viable system with expert-perceived pedagogical potential for chess instruction in basic education.

KEYWORDS: Educational robotics, expert system, artificial intelligence, strategic thinking, robotic arm.

RESUMEN

El ajedrez se reconoció como un recurso pedagógico relevante para desarrollar procesos cognitivos asociados al pensamiento lógico-estratégico, la concentración, la planificación y la resolución de problemas en la educación básica. La investigación tuvo como objetivo evaluar la viabilidad técnica de un sistema experto robótico aplicado a la enseñanza del ajedrez y describir su potencial pedagógico según la percepción de expertos en robótica educativa y enseñanza del ajedrez. El estudio se enmarcó en el paradigma pragmático, utilizó el método de desarrollo tecnológico, adoptó un enfoque cuantitativo y un diseño tecnológico proyectivo-descriptivo, no experimental y de corte transversal. La unidad de análisis fue el prototipo robótico ajedrecista, clasificado como artefacto tecnológico. El proceso de validación incluyó a tres docentes que valoraron las condiciones operativas y el potencial pedagógico del sistema, mientras que veinte estudiantes de media-básica probaron el prototipo desarrollado como usuarios durante el proceso de interacción. La metodología se basó en la construcción y validación de un prototipo mecatrónico que integró un sistema experto basado en el algoritmo Minimax, una visión computarizada y un brazo robótico con tres grados de libertad. Las técnicas de recolección de datos incluyeron la validación técnica mediante una lista de cotejo de requisitos y desempeño, así como la valoración pedagógica mediante un cuestionario aplicado a expertos. Los resultados evidenciaron un 100% de cumplimiento de las especificaciones funcionales del sistema, un 98% de precisión en la identificación de jugadas mediante visión computarizada y un tiempo promedio de respuesta de 2,5 segundos en el algoritmo Minimax. La evaluación de expertos reportó valoraciones favorables sobre la efectividad educativa percibida, la motivación, el interés y la funcionalidad didáctica. Se concluyó que el prototipo constituyó un sistema técnicamente viable, con potencial pedagógico reconocido por expertos para la enseñanza del ajedrez en la educación básica.

PALABRAS CLAVE: Robótica educativa, sistema experto, inteligencia artificial, pensamiento estratégico, brazo robótico.

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Introduction

Chess is recognized as a relevant pedagogical resource for developing cognitive processes associated with logical-strategic thinking, concentration, planning, and problem-solving in basic education. Its educational value lies in the fact that each move requires analysis, anticipation, decision-making, and the evaluation of possible consequences within a structured system of rules. In school contexts, chess is progressively incorporated as an instructional strategy that supports mathematical reasoning, analytical thinking, and socio-cognitive skills. From this perspective, chess transcends recreational practice and becomes a formative resource that contributes to students' intellectual development and strategic learning processes (Aciago et al., 2016).

Despite these educational benefits, chess instruction in school settings faces challenges related to student motivation, active participation, and adaptation to contemporary digital learning environments. Traditional teaching strategies often rely on explanatory or repetitive approaches that may limit interaction, experimentation, and immediate feedback during the learning process. At the same time, students are increasingly exposed to highly interactive digital resources that transform their ways of accessing information and engaging with knowledge. This situation creates the need to explore technological alternatives capable of making chess instruction more dynamic, interactive, and aligned with the learning expectations of basic education students.

In response to this problem, the integration of information and communication technologies, educational robotics, and artificial intelligence offers possibilities for designing interactive learning resources. Educational robotics supports experimentation, problem-solving, creativity, and computational thinking through physical interaction with technological artifacts (Rosero Calderón, 2024). Similarly, expert systems based on artificial intelligence (AI) can simulate decision-making processes in specific domains, such as chess, and generate responses according to predefined reasoning rules. Atmatzidou & Demetriadis (2016) also emphasize that educational robotics can support the development of computational thinking skills when students interact with robotic systems through structured learning activities. Recent studies suggest that emerging technologies can contribute to expanding access to innovative educational resources and reducing gaps in technology-mediated learning environments (De la Cruz-Veliz et al., 2025).

Within this framework, the present research aims to evaluate the technical feasibility of a Robotic Expert System applied to chess instruction in basic education and to describe its pedagogical potential as perceived by experts in educational robotics and chess instruction. The system integrates a mechatronic prototype, computer vision, a robotic arm with three degrees of freedom, and an expert system based on the Minimax algorithm. Based on this purpose, the following research question is posed: How can an AI-based robotic expert system contribute to the technical and pedagogical design of an interactive resource for chess instruction in basic education?

Methodology

To address the stated objective and contribute to the generation of knowledge in the field of educational robotics applied to chess learning, the research was framed within the pragmatic paradigm, since the study was oriented toward the practical development, evaluation, and validation of a technological solution applicable to an educational context. This paradigm was appropriate because it allows research decisions to be guided by the nature of the problem, the usefulness of the results, and the empirical evidence obtained during the study process (Creswell & Creswell, 2018). Under this approach, the technological development method was adopted, understood as a systematic process focused on the design, construction, testing, and validation of a functional prototype intended to respond to a specific educational need.

The study was developed using a quantitative approach, focusing on the measurement and analysis of observable data through systematic procedures that enable the description of phenomena and the evaluation of results based on numerical information (Hernández-Sampieri & Mendoza Torres, 2018). Regarding research design, a non-experimental technological development design was employed to

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develop and evaluate a mechatronic artificial intelligence-based prototype for educational applications. The study was projective-descriptive, as it involved designing a technological solution to address a specific educational problem and describing the system's performance. Furthermore, the research was conducted using a cross-sectional design, as data collection occurred at a single point in time during the system validation process.

The unit of analysis was the chess-playing robotic prototype, understood as a technological artifact composed of a mechatronic structure, a computer vision subsystem, an expert system based on the Minimax algorithm, and a three-degree-of-freedom robotic arm. The validation process included a panel of three teachers with experience related to educational robotics and chess instruction (hereafter, the expert panel), who assessed the operating conditions and pedagogical potential of the system. In addition, twenty middle school students tested the developed prototype as users during the interaction process. However, student participation was limited to prototype testing; therefore, the study did not measure learning gains, logical-strategic thinking development, or mathematical reasoning through pretest, posttest, experimental comparison, or longitudinal follow-up.

The validation setting corresponded to the prototype testing scenario in which the robotic system interacted with the chessboard, the computer vision module, the artificial intelligence algorithm, and the users. Because no specific school, classroom, laboratory, or institutional environment is reported, the findings were interpreted as evidence of prototype performance and expert-perceived pedagogical potential, rather than as evidence of generalized classroom effectiveness. This delimitation was necessary to avoid extending the conclusions beyond the empirical data collected during the validation stage.

Regarding data collection techniques, technical validation was employed using a checklist, and pedagogical evaluation was conducted using a questionnaire administered to experts. Research techniques are systematic procedures used to obtain relevant information about the phenomenon under study (Arias, 2016). Technical validation was conducted using a requirements and performance checklist designed to verify compliance with the functional specifications of the robotic system. This checklist assessed the integration and operation of the mechanical, electronic, computational, computer vision, and artificial intelligence components. Pedagogical evaluation was conducted through a questionnaire administered to the expert panel, which assessed the perceived educational effectiveness, motivation, interest, and instructional functionality of the prototype as a teaching resource for chess instruction.

The instruments used were a technical checklist and a pedagogical evaluation questionnaire. The checklist was used to verify whether the prototype met the functional specifications established during its design phase. The questionnaire used a three-point rating scale to collect expert assessments of the system’s perceived pedagogical value. The technical indicators analyzed were functional requirements compliance, accuracy in human move identification through computer vision, and average response time of the Minimax algorithm. The pedagogical indicators analyzed were expert ratings related to educational effectiveness, motivation, interest, and instructional functionality.

Statistical analysis was performed using descriptive statistics, which allow the organization, summarization, and presentation of data through numerical indicators that facilitate the understanding and interpretation of the study's results (Hernández-Sampieri & Mendoza Torres, 2018). This type of analysis focuses on describing the main characteristics of the collected information without establishing causal relationships between variables, thereby allowing the identification of trends, frequencies, and levels of compliance with the evaluated indicators. In this research, descriptive statistics were used to analyze the results of the robotic prototype's technical validation and the pedagogical evaluation conducted by experts. Specifically, indicators related to compliance with the system's functional specifications, the accuracy of move identification by the computer vision system, and the response time of the implemented artificial intelligence algorithm were examined. Additionally, the evaluations obtained from the questionnaire administered to experts regarding the educational effectiveness, motivation, and interest generated by the robotic system as a teaching tool were analyzed. The results were summarized as

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percentages and average ratings, demonstrating the extent to which the system met the technical requirements and the specialists' positive perception of the prototype's pedagogical potential.

Regarding ethical considerations, the study was conducted according to principles of scientific integrity, transparency, and responsible use of information. The participation of the expert panel was voluntary, and the information collected was used exclusively for academic and research purposes. Since the prototype was also tested by middle school students, procedures were followed to protect participants' anonymity, confidentiality, and informed participation, as described in the Ethics Statement.

Results

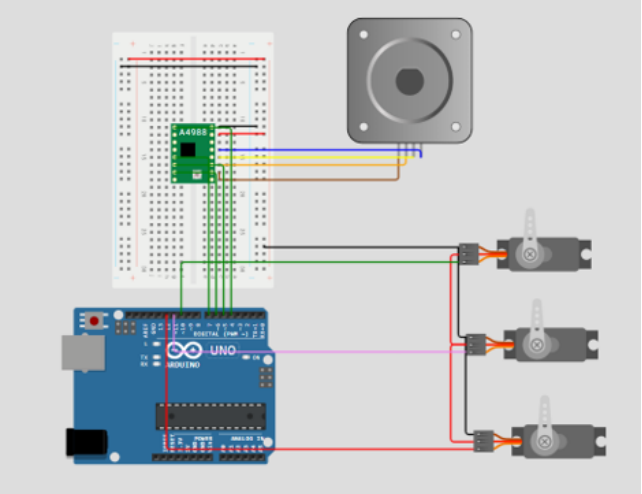
The validation of the Robotic Expert System showed adequate technical performance and favorable expert assessment of its pedagogical potential as a chess-teaching resource. The technical results recorded 100% compliance with the system's functional specifications, 98% accuracy in identifying user moves through the computer vision subsystem, and an average response time of 2.5 seconds for the Minimax algorithm. The pedagogical evaluation, administered to experts in educational robotics and chess instruction, reported average scores above 2.8 on a three-point scale for educational effectiveness and 3.0 for the motivation and interest indicators. These findings reflect the prototype's operational feasibility and expert-perceived instructional value, without establishing causal evidence of learning improvement in students.

Electromechanical Components and Specifications

The developed prototype integrated mechanical, electronic, computational, and control components to execute chess moves on a physical board. The mechatronic architecture included electromechanical actuators, a microcontroller, transmission mechanisms, a computer vision subsystem, and an artificial intelligence module based on the Minimax algorithm. During validation, these components operated as an integrated system for detecting user moves, processing strategic responses, and coordinating the physical displacement of the robotic arm. Figure 1 presents the general architecture of the prototype, while Table 1 summarizes the main electromechanical components and specifications recorded for the robotic system.

Figure 1

Architecture of the Prototype of the Robotic Expert System for Teaching Chess.



Note. Mechatronic prototype integrating a robotic arm, computer vision, and AI-based control for teaching chess. Own elaboration (2026).

Table 1

Electromechanical Components and Specifications of the Robotic System.

Component	Specification	(Approx.)
Linear Motor	NEMA 17 Stepper Motor	-
Transmission	400 mm Linear Lead Screw (15.75 in)	15.75 in
Main Controller	Arduino R4	-
Driver	Stepper Motor Driver	-
Main Arm Servo (L1)	1 × 40 kg·cm Torque	-
Secondary Arm Servo (L2)	1 × 11 kg·cm Torque	-
Gripper Servo	1 × 9 g	-

Note. Electromechanical components and technical specifications of the robotic chess prototype. Own elaboration (2026).

Table 1 identifies the main electromechanical components used in the robotic chess prototype. The horizontal displacement system included a NEMA 17 stepper motor and a 400 mm linear lead screw. The control system used an Arduino R4 microcontroller and a stepper motor driver. The

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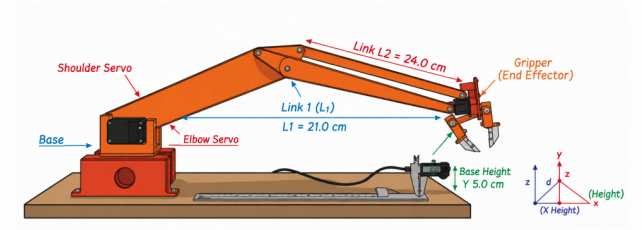
robotic arm incorporated a main servo with 40 kg·cm torque, a secondary servo with 11 kg·cm torque, and a 9 g gripper servo for piece manipulation. These specifications define the hardware configuration evaluated during the technical validation process.

Figure 2

Kinematic Structure of the Robotic Arm of the Chess System.



Note. Mechanical configuration of the parallelogram robotic arm, including links, servomotors, and end effector. Own elaboration (2026).

The robotic system presented three degrees of freedom that enabled controlled movement across the chessboard. Horizontal translation along the X-axis was performed by the NEMA 17 stepper motor coupled to the 400 mm linear lead screw. Articulated movement along the Y and Z axes was generated by two high-torque servomotors arranged in a parallelogram structure.

This configuration allowed the end effector to move toward the board coordinates required for piece manipulation during the validation tests. Figure 2 shows the kinematic structure of the robotic arm used in the prototype.

Figure 3

Graphical Interface of the Chessboard Used in the Robotic System.



Note. Visual interface for identifying and tracking chess moves. Own elaboration (2026).

The robotic system was mounted on a support structure configured to provide mechanical stability during move execution. This structure served as the physical basis of the mechatronic system and delimited the Cartesian workspace in which the robotic arm operated. Figure 3 presents the graphical interface of the chessboard used by the system to identify and track moves during user interaction, while the physical platform defined the operational area of the robotic mechanism.

The support platform measured 20.47 in × 20.47 in and provided the surface required for installing the electromechanical components and the linear displacement system. Within this structure, the usable work area corresponded to the chessboard, with approximate dimensions of 12.60 in × 12.60 in, where interaction between the robotic system and the user was performed.

These dimensions allowed the translation mechanism and the robotic arm to access the board squares during move execution. The workspace configuration supported coordination among the control system, the computer vision subsystem, and the robotic arm's physical motion during the validation process.

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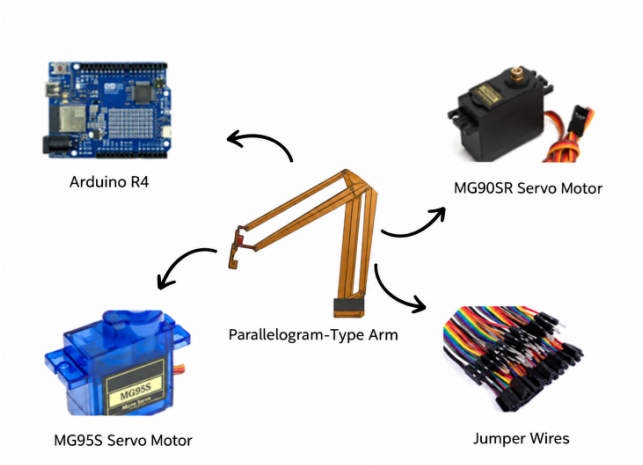
Components of the Parallelogram Arm

The robotic arm implemented in the prototype was composed of electronic and mechanical components configured to support controlled movement and chess-piece manipulation on the board. This configuration was based on a parallelogram-type mechanical structure, which served as the articulated support for the displacement and gripping actions required during system operation.

The system integrated servomotors assigned to the arm's articulated movements, a servomotor for the gripping mechanism, a microcontroller responsible for executing programmed control instructions, and electrical connections used for signal and power transmission between the control board and the actuators. These components allowed the robotic mechanism to perform the physical movements associated with the interaction between the AI module and the chessboard during the prototype validation process.

Since the robotic arm formed part of the mechatronic architecture assessed through the requirements and performance checklist, its description corresponded to the technical validation of the system. Figure 4 presents the main electronic and mechanical components that make up the parallelogram robotic arm used for manipulating chess pieces in the prototype.

Figure 4
Components of the Parallelogram Robotic Arm.



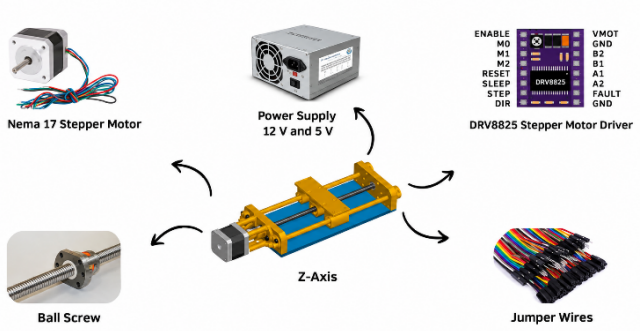
Note. Electronic and mechanical components of the parallelogram robotic arm for chess piece manipulation. Own elaboration (2026).

Linear Rail Components

The robotic system incorporated a linear displacement mechanism designed to support the horizontal movement of the robotic arm across the chessboard. This mechanism formed part of the electromechanical configuration evaluated during the prototype validation process and was used to position the arm within the operational workspace defined for move execution.

The linear rail structure integrated mechanical and electronic components responsible for generating translational motion and transmitting control signals to the movement system. This configuration allowed the robotic arm to move across the board according to the commands associated with the moves generated by the AI module. Figure 5 presents the main mechanical and electronic components of the linear rail system used to provide horizontal motion in the robotic chess prototype.

Figure 5
Linear Rail Components of the Robotic Chess System.



Note. Mechanical and electronic components of the robotic arm's linear rail system. Own elaboration (2026).

The components shown in Figure 5 constituted the linear motion system used to support the robotic arm's horizontal displacement along the chessboard. The NEMA 17 stepper motor, together with the lead screw mechanism, generated the translational motion required to move the arm within the board workspace. The DRV8825 motor driver regulated the electrical signals sent from the control system to the motor, allowing the movement system to operate according to the programmed instructions.

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The system was powered by a 12V/5V computer power supply, which provided the electrical energy required for the actuators and control modules. Jumper cables established electrical connections among the controller, driver, and motor, supporting signal transmission within the mechatronic system. This integration allowed the robotic arm to perform the horizontal displacement required during the execution of chess moves generated by the expert system.

Technical Validation

Verification of the robotic prototype's functional specifications was conducted using the Requirements and Performance Checklist described in the methodology. This instrument was applied to assess the integration and operation of the mechanical, electronic, computational, computer vision, and artificial intelligence components of the system. The validation process allowed the operational performance of the prototype to be reviewed according to the predefined technical parameters established during the design phase. Table 2 summarizes the main technical performance indicators obtained during the validation of the robotic system.

Regarding functional compliance, the results indicated that the prototype achieved 100% fulfillment of the hardware and software specifications established for the robotic system. This result showed that the Minimax decision algorithm, the control architecture, and the kinematic configuration of the parallelogram robotic arm operated according to the functional requirements evaluated in the checklist. Therefore, the technical validation reported full compliance with the design specifications assessed during the prototype validation process.

Table 2

System Performance Indicators.

Performance Indicator	Obtained Value	Minimum Requirement
Functional Requirements Compliance	100%	≥95%
Accuracy in Human Move Identification (Computer Vision)	98%	≥95%
Average AI Response Time (Minimax Algorithm)	2.5 s	≤3.0 s

Note. Robotic system performance indicators: functional compliance, move identification accuracy, and AI response time. Own elaboration (2026).

In relation to system performance, the evaluation focused on two operational indicators: move-identification accuracy and AI response time. The tests recorded 98% accuracy in identifying user moves through the computer vision subsystem and an average response time of 2.5 seconds per move for the Minimax algorithm.

These values were within the minimum requirements established for the prototype, which were ≥95% for move-identification accuracy and ≤3.0 seconds for algorithm response time. The results indicate the system's capacity to process user input and generate robotic responses under the technical conditions evaluated.

Pedagogical Validation

The pedagogical validation of the robotic prototype was conducted using a Pedagogical Evaluation Questionnaire administered to a panel of experts in educational robotics and chess instruction. This instrument assessed the experts' perception of the system as an instructional resource for chess instruction. The evaluated dimensions included perceived educational effectiveness, motivation, interest, and instructional functionality of the prototype within the context of logical-strategic reasoning and mathematical thinking.

The results from the expert evaluation indicated average scores above 2.8 on a three-point scale for items related to perceived educational effectiveness. The indicators associated with motivation and interest obtained an average score of 3.0, corresponding to the maximum value of the instrument's scale. These results showed favorable expert ratings regarding the prototype's instructional potential as a resource for supporting chess-based learning activities. However, the data were interpreted as expert perceptions and not as direct evidence of improvement in students'

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logical-strategic thinking, mathematical reasoning, or academic performance.

The assessment of the system's instructional functionalities, including guided tutorials and interactive practice modes, also obtained favorable evaluations from the expert panel. These results reflect the pedagogical value attributed to the prototype by the evaluators, particularly in relation to its possible use as an interactive resource for chess instruction. Since the methodology did not include pretest-posttest measurements, a control group, or inferential analysis of student learning outcomes, the findings were limited to the descriptive validation of the prototype's perceived pedagogical potential.

Overall, the results showed that the robotic prototype achieved the technical performance indicators established for the validation process and received favorable pedagogical ratings from the expert panel. The functional compliance, move-identification accuracy, and response-time indicators described the operational performance of the mechatronic components, the computer vision subsystem, and the Minimax-based AI algorithm.

The pedagogical evaluation reported positive expert perceptions regarding the prototype's instructional potential, particularly in relation to perceived educational effectiveness, motivation, interest, and instructional functionality. These findings provided descriptive evidence of the prototype's technical feasibility and expert-perceived pedagogical value as a chess-teaching resource. The educational implications, limitations, and relationship with previous studies are addressed in the Discussion.

Discussion

The results answer the research question by indicating that the integration of an artificial intelligence-based robotic expert system in chess instruction is technically feasible and pedagogically promising as an instructional resource for basic education. The technical indicators, represented by 100% functional compliance, 98% accuracy in move identification through computer vision, and an average response time of 2.5 seconds for the Minimax algorithm, show that the prototype operates according to the functional requirements established for validation. From a pedagogical perspective, the expert panel's ratings suggest favorable perceptions of the system's instructional potential. However, these findings must be interpreted as descriptive evidence of technical feasibility and expert-perceived pedagogical value, not as causal evidence of improvement in students' logical-strategic thinking or mathematical reasoning.

The findings are consistent with previous studies that identify chess as a pedagogical resource associated with cognitive processes such as planning, decision-making, problem-solving, and logical reasoning. Gobet & Campitelli (2006) and Kazemi et al. (2012) highlight the educational value of chess in the development of analytical and metacognitive skills. In relation to the present study, these contributions support the selection of chess as the instructional domain for the robotic expert system. Nevertheless, the comparison must be made cautiously, since the present research does not directly measure cognitive gains in students but rather evaluates the technical performance of the prototype and the expert panel's perception of its educational potential.

The results also relate to research on educational robotics, particularly studies that describe robotic systems as resources capable of increasing interaction, motivation, and active participation in learning environments. Benitti (2012) and Eguchi (2014) emphasize that educational robotics can support experiential learning when students interact with technological artifacts designed for problem-solving activities. In the present study, the robotic prototype physically interacts with the chessboard and executes moves generated by an artificial intelligence module, which provides an interactive technological environment. However, the available evidence supports only the possibility of using the system as an instructional resource, because motivation and engagement were assessed through expert perception rather than through direct student measurement.

The interpretation of the results is also consistent with Bers (2018), who argues that educational robotics can promote active learning environments where students interact with programmable systems and develop computational thinking skills. In this research, the integration of a robotic arm, computer vision, and an expert system

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contributes to the construction of a technological environment in which chess instruction may become more interactive. This relationship is relevant because the system does not operate as a merely digital application, but as a physical robotic artifact capable of responding to user moves. Even so, the pedagogical contribution remains exploratory, since the study does not include a pretest-posttest design, a control group, or direct assessment of students' cognitive performance.

Similarly, Atmatzidou & Demetriadis (2016) showed that educational robotics can contribute to the development of computational thinking skills when students interact with robotic systems through structured learning activities. This contribution supports the relevance of integrating robotic artifacts into educational environments; however, unlike that study, the present research did not directly measure computational thinking or student learning outcomes, since its empirical scope was limited to technical validation and expert-perceived pedagogical potential.

The findings also coincide with Holmes et al. (2019), who discuss the role of artificial intelligence in creating adaptive and interactive educational experiences. The use of the Minimax algorithm in the prototype allows the system to process chess positions and generate responses according to programmed decision rules. This characteristic supports the interpretation of the prototype as an intelligent instructional resource for chess instruction. However, the study does not provide evidence of adaptive personalization, differentiated feedback, or individualized learning trajectories. Therefore, the contribution of artificial intelligence in this research is mainly associated with move generation and system interaction, rather than with the full implementation of an adaptive tutoring model.

From the perspective of educational robotics as an active learning environment, the results are related to the approaches of Alimisis (2013) and Scaradozzi et al. (2019). These authors describe robotics as a pedagogical field that connects technological design, experimentation, computational thinking, and problem-solving. The present prototype extends this perspective by integrating a mechatronic system, computer vision, and artificial intelligence in a chess-based instructional context. This integration represents a relevant technological contribution because it connects abstract strategic reasoning with physical robotic execution. Nonetheless, the study cannot claim that the system strengthens students' logical-strategic thinking until future research measures this variable directly with validated instruments.

The results also correspond with the technopedagogical perspective proposed by Mujica-Sequera (2023), since the prototype articulates technological resources, instructional intention, and an instructional activity centered on chess. From this perspective, the robotic expert system may be interpreted as a technopedagogical resource that combines artificial intelligence, robotics, and game-based learning. Similarly, the contribution of Vargas et al. (2019) is relevant because it supports the use of educational robotics as an interactive learning environment in basic education. In the present study, this relationship is observed in the expert panel's favorable assessment of the system's instructional functionality, although the pedagogical effect must still be verified through empirical studies with students.

The main limitation of the study is that pedagogical validation was based on expert perception and not on direct measurement of student learning outcomes. Although twenty middle school students tested the prototype, the results do not report pretest-posttest scores, comparative groups, inferential analysis, or validated instruments for measuring logical-strategic thinking, mathematical reasoning, motivation, or engagement. Another limitation is that the technical results report general indicators, such as 98% move-identification accuracy and 2.5 seconds of response time, but do not provide detailed information about the number of trials, types of board positions, lighting conditions, or error distribution. These aspects limit the generalization of the findings and require more robust empirical validation.

Future research should evaluate the prototype in real classroom conditions through a methodological design that includes direct student assessment. It is necessary to incorporate validated instruments for measuring logical-strategic thinking, mathematical reasoning, motivation, and learning outcomes before and after interaction with the

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robotic system. In addition, future studies should compare the robotic system with traditional chess instruction or digital chess platforms to determine its specific educational contribution. From a technical perspective, subsequent developments may optimize the computer vision subsystem, the gripping mechanism, and the Cartesian positioning of the robotic arm, especially under different lighting conditions, board configurations, and prolonged-use scenarios. These lines of work would strengthen the empirical basis of the prototype and clarify its contribution to educational robotics and artificial intelligence applied to learning.

Conclusions

This study highlights the importance of integrating educational robotics and artificial intelligence into technology-mediated learning environments. The Robotic Expert System designed for chess instruction constitutes a viable technological proposal because the prototype meets the technical indicators established during the validation process. The results show full compliance with the system's functional specifications, 98% accuracy in identifying moves through the computer vision subsystem, and an average response time of 2.5 seconds for the Minimax algorithm. These findings support the operational feasibility of the mechatronic architecture, the control system, and the artificial intelligence module as integrated components of a robotic chess-teaching prototype.

Regarding the research objective, the study shows that the developed prototype has pedagogical potential as an instructional resource for chess instruction in basic education. The expert panel's evaluation reports favorable ratings for perceived educational effectiveness, motivation, interest, and instructional functionality. However, the results do not allow the study to affirm direct improvement in students' logical-strategic thinking, mathematical reasoning, or academic performance, since no pretest-posttest measurement, control group, or inferential analysis was conducted. Therefore, the contribution of the study lies in the technical validation of the prototype and in the expert-perceived pedagogical value of the system as a resource that may support future chess-based learning experiences.

Future research will need to broaden the empirical validation of the robotic system in real educational settings. Subsequent studies should incorporate validated instruments to measure logical-strategic thinking, mathematical reasoning, motivation, engagement, and learning outcomes before and after interaction with the prototype. It will also be necessary to compare the system with traditional chess instruction or digital chess platforms to determine its specific educational contribution.

From a technical perspective, future developments will optimize the computer vision subsystem, the gripping mechanism, the Cartesian positioning of the robotic arm, and the accessibility of the interface for students with diverse educational needs. These improvements will strengthen the scientific basis of the prototype and clarify its contribution to educational robotics and artificial intelligence applied to learning.

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Declaration of Conflicts of Interest

The authors declare that there are no conflicts of interest that could affect the execution of this study, nor do they maintain any personal, academic, or professional relationships that could influence or condition the results obtained and their subsequent interpretation.

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Ethics Statement

The study was conducted in accordance with principles of scientific integrity, transparency, confidentiality, and responsible use of information. The experts and students who participated in the validation and testing of the prototype were informed about the academic purpose of the research, and their participation was voluntary. The information collected was used exclusively for research purposes, without reporting personal or identifiable data. Since the prototype was tested with middle school students, institutional authorization, informed consent from legal representatives, and participant assent were obtained when applicable. Anonymity, confidentiality, and protection of participants were ensured throughout the validation process.

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