



## Enhancing students' understanding of quadrilateral properties through GeoGebra-based instruction

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### Abstract

Understanding geometric properties is fundamental to mathematical reasoning, yet persistent misconceptions in students' classification of quadrilaterals remain a significant concern. Although physical manipulatives and dynamic geometry software have been widely examined, limited research has investigated their integrated use within a structured pedagogical framework to promote inclusive classification and deeper conceptual understanding. This study addresses this gap by exploring the impact of combining physical manipulatives with dynamic geometry software on students' understanding of quadrilateral properties. An eight-hour intervention was implemented using a quasi-experimental pretest-posttest design with a single group of students. The instructional sequence consisted of an initial phase involving hands-on exploration with physical artefacts, followed by digital investigation through dynamic representations. Findings revealed a statistically significant improvement in students' ability to classify and reason about quadrilaterals, indicating enhanced conceptual understanding and active engagement. The study demonstrates that integrating tangible and digital tools strengthens geometric reasoning and supports inclusive mathematical thinking. These findings offer important implications for the design of technology-enriched geometry instruction and highlight the need for more rigorous experimental research.

**Keywords:** Conceptual understanding; dynamic geometry; geometry education; manipulatives; quadrilaterals.

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## 1. INTRODUCTION

In primary education, the use of drawings and geometric definitions is likely widespread among teachers as a means of instruction. However, it is worth asking whether these tools serve as genuine resources or potential obstacles. Drawings, for instance, can represent a key educational support in introducing children to the understanding of spatial aspects of reality. Nonetheless, as noted by Sabena et al., (2019), drawings may also become a hindrance, as they do not always succeed in conveying the underlying geometric concepts beyond their graphic representation.

According to Castelnuovo (2017), drawings do not suggest problems because they present a finite number of cases and restrict learners' freedom of thought. They do not promote observation and therefore cannot facilitate intuitive understanding of truth, as their static nature limits engagement. Additionally, drawings fail to provide realistic representations of spatial situations. The author also highlights that when students create geometric figures, attention tends to focus on the outline while neglecting the interior, and definitions may similarly present obstacles. Sbaragli (2020) further emphasizes these limitations in geometric learning.

In mathematics, definitions have historically always been characterized by containing only the necessary and sufficient information; that is, they must not be redundant. A characteristic that is quite distant from the typical practice of students, who are accustomed to describing the surrounding reality using adjectives, nouns, and overly elaborate descriptions that serve to reinforce the intended message to the listener (Sbaragli, 2020).

To address the limitations of a traditional geometry teaching approach, often overly reliant on abstract definitions and static representations, Castelnuovo (2017) advocated for the use of cognitive artefacts. These are tangible tools designed to support the learning of geometric concepts through physical manipulation and direct engagement. Examples include cardboard strips with holes and brass fasteners, Meccano rods, toothpicks, strings, rubber bands, and similar materials. Such artefacts allow learners to explore geometric properties through motion, thus revealing invariants even as the shapes are transformed.

This dynamic methodology encourages students to construct and physically engage with geometric figures, moving beyond the passive observation of textbook diagrams. In this context, artefacts serve not only as didactic tools but also as instruments for discovering the underlying constraints that define a figure's structure. Castelnuovo (2017) emphasizes that manipulation should not be seen as a mere manual activity, but rather as a cognitively rich process of exploration and reflective reasoning, through which learners can arrive at definitions autonomously.

With the advent of digital technologies, Castelnuovo's (2017) concrete artefacts can be complemented by digital cognitive tools such as dynamic geometry software (Simsek & Clark-Wilson, 2025). One widely used platform is GeoGebra, which enables students to construct and transform geometric figures on screen while preserving their intrinsic properties. In secondary schools, technologies like GeoGebra and augmented reality have shown effectiveness in geometry teaching and learning, but studies on primary schools are rarer (Sunzuma, 2023). A key feature is the dragging functionality, which allows users to move geometric components while maintaining constraints and relationships. This supports the identification of invariants and fosters deeper insight into geometric relationships.

GeoGebra thus provides an interactive and visual environment for exploring geometric concepts and their properties (Yorganci & Subasi, 2025; de Carvalho et al., 2024). As such, it can be considered a powerful digital cognitive artefact for mathematics education. Furthermore, the software integrates multiple mathematical representations, including geometry, algebra, graphs, spreadsheets, and statistics, which enhance students' understanding of mathematical structures and interconnections (Robutti, 2018). Its success is also demonstrated by the fact that it has been translated into many languages (Yohannes & Chen, 2023). Its open-source, freely accessible, and user-friendly nature makes GeoGebra an excellent tool for classroom implementation. This aligns

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well with the recommendations of the Italian national curriculum (dell'Istruzione, 2012), which promotes the use of dynamic geometry environments in school mathematics.

### **1.1. Purpose of study**

This article presents a study in which GeoGebra was used as an educational tool in a Year 3 primary school classroom to support pupils' understanding of the properties of quadrilaterals. Building on the theoretical framework outlined in the previous sections, the study aimed to explore whether this digital artefact, which enables dynamic interaction with geometric figures, could enhance students' understanding of quadrilateral properties when used after a learning experience based on concrete artefacts. The decision to focus on quadrilaterals stemmed from the observation that their classification, based on inclusive definitions, often proves challenging for pupils. Accordingly, the research question guiding the study was: How can the use of GeoGebra, following the use of physical artefacts inspired by the work of Emma Castelnuovo, enhance pupils' understanding of the properties of quadrilaterals? The research hypothesis is that the use of GeoGebra, in combination with prior experience with physical artefacts, may significantly support the learning of quadrilateral classification, fostering a deeper and more dynamic understanding of their properties.

## **2. METHOD AND MATERIALS**

### **2.1. Participants**

The study was carried out as part of a Master's thesis in Primary Teacher Education at the University of Florence. The class teacher was first informed about the study and gave their full consent to proceed. The intervention was then carried out as part of regular classroom instruction, with the assessment activities integrated into ordinary teaching practices. This implementation was in accordance with the professional autonomy granted to teachers under Article 33 of the Italian Constitution and in compliance with national educational guidelines (Legislative Decree 297/1994; Ministerial Decree 294/2012), teaching autonomy laws (Presidential Decree 275/1999; Law 107/2015), and relevant privacy regulations (Legislative Decree 196/2003; EU General Data Protection Regulation 2016/679). Despite being embedded in the regular curriculum, the educational intent and research aims of the project were clearly communicated to both the teacher involved and the students participating in the study. The intervention took place in a Year 3 class at "San Francesco" primary school, part of the "Paolo Borsellino" Comprehensive Institute in Navacchio, in the province of Pisa. This class was chosen because Year 3 is typically the point in the Italian curriculum when pupils begin transitioning from concrete to more abstract mathematical thinking.

The class consisted of 21 pupils, including 11 girls and 10 boys, all of whom took part in the study. Among the group was one pupil with special educational needs, undergoing assessment for suspected dyslexia, who was granted additional time to complete tasks. Despite these challenges, the pupil demonstrated strong logical-mathematical reasoning skills. The intervention was conducted in a classroom equipped with individual desks arranged in three rows. In addition to specific hands-on materials, a range of digital tools was used, including an Interactive Whiteboard (IWB) and tablets.

### **2.2. The intervention**

The teaching intervention, designed to last a total of eight hours, was intended to guide students in exploring the properties of quadrilaterals and classifying them according to an inclusive logic, whereby each category of figures is nested within a broader one. This approach aimed to help students recognize relationships among different categories of quadrilaterals and to overcome the rigidity of exclusive definitions. The main objective was to support students in constructing geometric meaning through the manipulation of both physical and digital artefacts.

The intervention was structured in two main phases:

- Phase 1: Assessing prior knowledge and introducing polygons.

In this initial phase, the plan included administering an interactive quiz using Kahoot! A platform to assess students' understanding of broken, mixed, curved, open, and closed lines. Following the quiz, students were expected to work with polygons using physical cognitive artefacts inspired by Castelnuovo (2017). Specifically, students would begin by observing various shapes projected on the interactive whiteboard and classifying them using their own criteria. They would then be invited to construct polygons using toothpicks to explore the minimum number of sides required to form a polygon. Finally, they would use Emma Castelnuovo's cardboard strips to explore the properties of quadrilaterals, with particular focus on the rhombus and the parallelogram. At the end of this phase, a test was to be administered to assess the knowledge acquired. This test would function as a pre-test for evaluating the hypothesis that the use of GeoGebra, introduced in the following phase, could further enhance students' learning.

- Phase 2: Use of GeoGebra and assessment of learning.

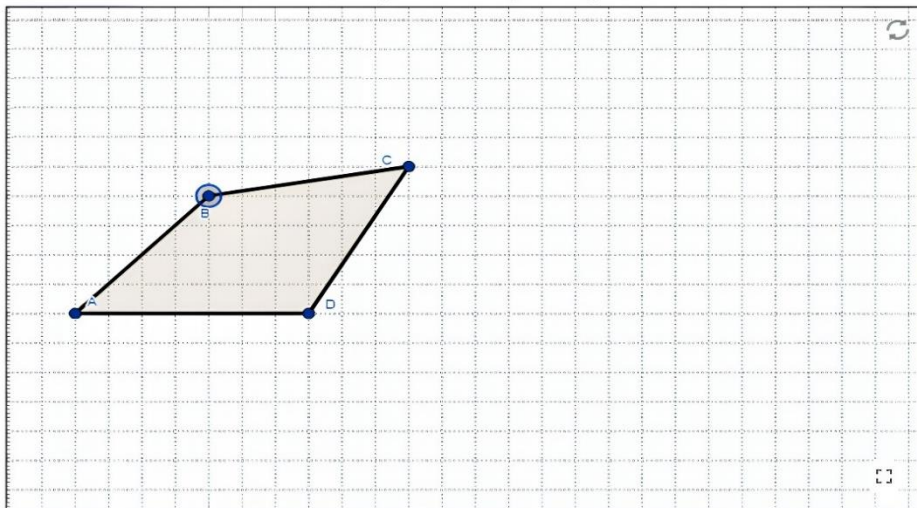
In the second phase, the teaching activity was to focus on the use of GeoGebra to deepen students' understanding of quadrilateral properties and promote classification according to inclusive definitions. Students were expected to work in pairs, each pair using a tablet to manipulate a given quadrilateral (see Figure 1) by dragging its vertices, thereby exploring different types of quadrilaterals and their corresponding properties. This phase was scheduled to conclude with the administration of a second test (post-test) to assess whether students had consolidated their understanding after using GeoGebra.

**Figure 1**

*Initial screen of the GeoGebra activity*

## Discovering Special Quadrilaterals

Move vertices A, B, C, and D to try to create special quadrilaterals.



The overall instructional approach was designed to actively engage pupils in the learning process, encouraging them to explore, manipulate, and reflect upon geometric figures. By integrating both physical and digital artefacts, the intervention aimed to foster conceptual understanding and promote the development of flexible and robust geometric thinking.

### 2.3. Data collection instrument

To test the hypothesis that the use of GeoGebra may support the learning of quadrilateral properties, a quasi-experimental research design was adopted, involving a pre-test and post-test with a single group (Cook et al., 1990). This type of design lacks external validity, meaning the results cannot be generalized to similar classes, and it has limited internal validity, as it does not allow for a causal relationship between the use of GeoGebra and learning outcomes to be established, due to the absence of a control group. Nonetheless, this design enables a comparison between pupils' learning outcomes prior to the use of GeoGebra, as measured by a pre-test, and their outcomes after the intervention, as measured by a post-test. Specifically, the pre-test consisted of two questions aimed at assessing pupils' knowledge of the properties of polygons and quadrilaterals. The post-test included these same two questions, along with a third one designed to measure the ability to recognize the characteristics of quadrilaterals.

In more detail, the first question comprised the following four yes/no items:

1. Is a quadrilateral with all equal sides only a square?
2. Is a rhombus a special kind of rectangle?
3. Is a square a special kind of rectangle?
4. Is a square a special kind of rhombus?

The second question asked students to identify, among four figures (Figure 2), which one was a polygon.

**Figure 2**

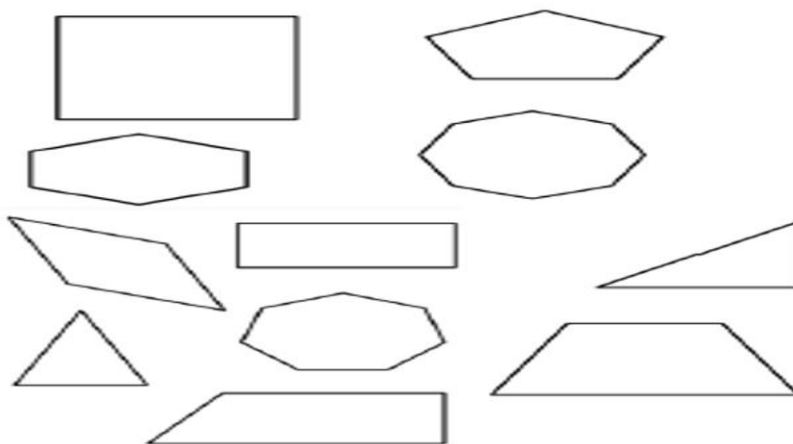
*Second question from the test*



As mentioned, the post-test included a third question, which presented 10 geometric shapes (Figure 3). Students were asked to write the number of sides inside each shape and to color all the quadrilaterals.

**Figure 3**

*Additional question from the post-test*



In addition to the tests, the intervention was documented through field notes following the approach of Corsaro (1985), taken by the student-researcher during the teaching activities after receiving specific training. Corsaro's (1985) method is an unstructured descriptive observation technique used to document in detail the

dynamics and interactions within a research setting. This ethnographic field note model categorizes collected data into four main types of annotation, providing a comprehensive account of the observational experience.

The first category comprises descriptive notes, which focus on a detailed and literal textual account of the observed events, avoiding personal interpretation in order to preserve objectivity. Personal notes record the observer's emotions, reactions, and emotional responses triggered by events or interactions with participants, adding a valuable subjective dimension to the analysis. Methodological notes document procedural decisions, the placement of instruments, and the position of the observer throughout the observation process, ensuring transparency in the conduct of the research. Finally, theoretical notes are used to record hypotheses that emerge directly from the observed situation, with particular attention to participants' behavior and its potential meanings.

The technique involves recording brief observations immediately after an event has occurred. These preliminary annotations are then expanded with further details at the end of the day to deepen and contextualize what was observed. This process facilitates rich and structured data collection, as demonstrated by the use of a fieldwork diary during the teaching intervention described in the sources.

### **Ethical Considerations**

This study adhered to internationally accepted ethical standards for research involving human participants, with particular attention to the protection of minors. The study was conducted within the framework of regular classroom activities, and prior approval was obtained from the class teacher. The research aims and procedures were clearly explained before implementation. All activities complied with national educational policies and data protection regulations. Participation was voluntary, and the study did not involve any procedures that could cause physical or psychological harm to the students. No personal or identifiable data were collected. All data were anonymized and analyzed in aggregate form for research purposes only, ensuring the confidentiality and privacy of participants.

## **3. RESULTS**

### **3.1. Implementation of the intervention**

The teaching intervention took place between March and April 2024. The field notes document how the intervention was carried out. In the first session, students began by observing figures projected on the interactive whiteboard. They were invited to group them according to criteria chosen autonomously, and a discussion was encouraged around the categorization strategies used. The teacher guided the discussion, focusing on the characteristics of the figures, such as the presence of broken, curved, or mixed lines, to introduce the concept of polygons and to distinguish them from non-polygonal shapes.

In the second session, the activity using sticks (or toothpicks) was introduced. Each student received a single stick and was invited to consider it as one side of a potential polygon. The teacher asked reflective questions such as: "Is it possible to form a polygon with just one side?" A second stick was then provided, with the question of whether a polygon could be formed using two sides, aiming to revisit concepts related to broken lines. Finally, a third stick was added, and the students were asked: "Can a polygon be formed with three sides?"

Through these hands-on activities, students arrived at the conclusion that a polygon requires at least three sides. The activity continued with a gradual increase in the number of sticks, allowing children to construct a variety of shapes. With four sticks, for instance, they created a square, which they then manipulated to discover the rhombus. With five and six sticks, they explored the pentagon and the hexagon (Figure 4). The teacher observed the students' constructions, reproduced them on the board, and invited the children to glue the shapes into their notebooks, labelling each with its corresponding name.

### **Figure 4**

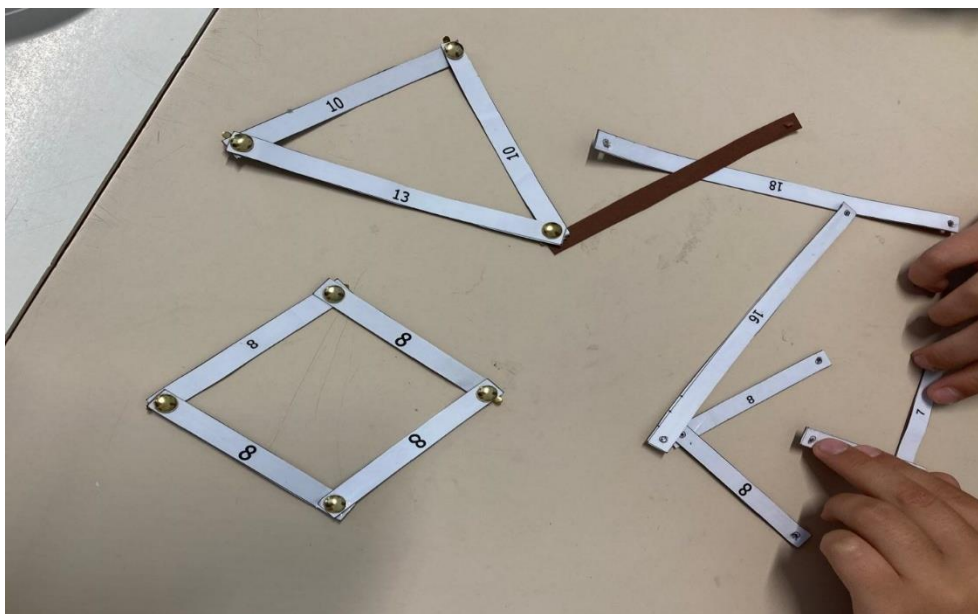
### Activity with toothpicks



In the third session, after summarizing the content from the previous meeting, the strips devised by Castelnuovo (2017) were used with cardboard strips of equal and varying lengths. Students were invited to create shapes with these strips and paper fasteners, and to manipulate them to explore and share their properties (Figure 5). The focus was on quadrilaterals, with targeted questions aimed at distinguishing different types and understanding their relationships: “What distinguishes a square from a rhombus? And can a rhombus be considered a parallelogram?”

**Figure 5**

*Activity with strips and paper fasteners*



These first three sessions were preparatory to the third phase of the intervention, which involved the teaching activity centered on the use of GeoGebra. This part of the intervention represented the independent variable in the quasi-experimental study, aimed at verifying the hypothesis that the use of GeoGebra can support the learning of quadrilateral properties, as measured by a specially designed test. Therefore, at the end of the third session, the pre-test was administered to assess what students had learned before using GeoGebra.

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The fourth session marked the beginning of the third phase of the teaching intervention, designed to deepen the understanding of quadrilateral properties and encourage their classification based on inclusive definitions. Students worked in pairs, each with a tablet. Each pair was provided with a pre-loaded GeoGebra file showing an initial quadrilateral, which they could modify by dragging its vertices.

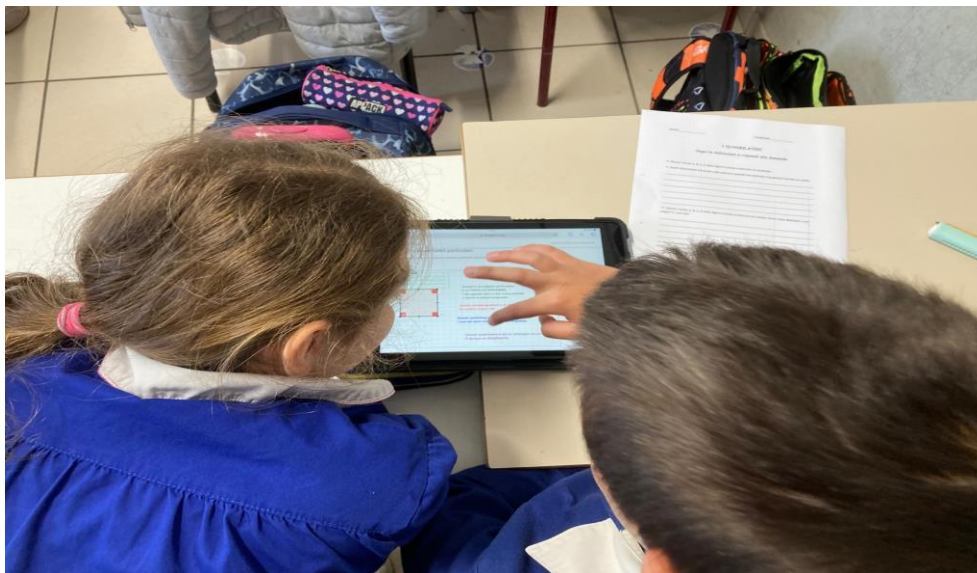
Students were then given a worksheet with guiding questions to answer after manipulating the digital artefact:

- Move the vertices A, B, C, and D of the figure and try to construct a square.
- What information appeared on the screen when you built the square? Write it below.
- Move the vertices A, B, C, and D and try to build a rhombus. What happened to its angles? And its sides?
- Move the vertices A, B, C, and D and try to build a rectangle. Can we call rectangles rhombuses?

While working, students were encouraged to observe how the properties of the figure changed as its shape was manipulated. When a specific case, such as a rectangle, was identified, the relevant properties appeared on the screen (Figure 6).

**Figure 6**

*Properties of a square in GeoGebra*



In the fifth and final session, a concluding discussion was held to reflect on the learning journey. The focus was on the knowledge gained, and each student was allowed to reflect on and share their personal understanding of what they had learned. Finally, the post-test was administered, covering the topics addressed during the intervention.

### **3.2. Learning outcomes and student engagement**

The pre-test, administered before the GeoGebra activity, recorded an average score of 7.61 out of a maximum of 10 points. The post-test, administered after the GeoGebra activity, showed an increase in the average score to 8.85 out of 10. Statistical analysis using the Wilcoxon test confirmed that this improvement is statistically significant, that is, it is not due to chance, but to an actual enhancement in learning outcomes. Furthermore, the standard deviation decreased from 1.47 in the pre-test to 0.96 in the post-test, indicating greater consistency in student performance. Notably, in the post-test, all students were able to correctly identify the quadrilaterals, and

for almost all other items, at least 18 out of 21 students answered correctly. The only exceptions were questions 2 and 3 of the yes/no section, for which 13 and 14 students, respectively, provided the correct answers.

The field notes reflect a high level of student engagement throughout the intervention, with a gradual development of geometric understanding through the use of both physical and digital artefacts. In the initial phase, students showed curiosity in classifying figures based on self-defined criteria and collaborated actively. Later, the use of Emma Castelnuovo's strips enabled students to discover new geometric shapes, so much so that one student exclaimed she had created a rhombus "that moves". The notes also document some initial difficulties with GeoGebra, which were overcome thanks to students' recall of previous activities. The positive feedback at the end of the intervention, along with the students' expressed interest in repeating the activities, is summarized in the following field note: "The activities done in class were very enjoyable, and the children hope to do them again in the future".

#### 4. DISCUSSION

The results of this study support the hypothesis that the introduction of GeoGebra, following a hands-on experience with physical artefacts inspired by Emma Castelnuovo, can enhance students' understanding of the properties of quadrilaterals. The statistically significant increase in the class average from the pre-test (7.61) to the post-test (8.85), along with a decrease in the standard deviation (from 1.47 to 0.96), suggests not only a general improvement in learning outcomes but also a more uniform level of achievement among students. Field notes further revealed strong student engagement, with signs of curiosity, active collaboration, and positive feedback toward the proposed activities.

This approach is fully aligned with the educational principles advocated by Castelnuovo (2017), who criticized traditional instruction based on static drawings and abstract definitions. According to Castelnuovo, static representations do not support intuition or the formulation of problems, restrict students' freedom of thought, and fail to provide a realistic depiction of spatial situations. The combined use of physical manipulatives (such as Castelnuovo's strips) and digital tools (GeoGebra) helped overcome these limitations. Students were able to "build and touch" geometric objects, discovering their properties through movement, a dynamic approach that, according to Castelnuovo (2017), allows learners to understand how shapes preserve their properties even when transformed.

GeoGebra, as a powerful digital cognitive artefact, extended this dynamic experience. Its dragging feature enabled students to explore shape transformations while maintaining geometric constraints, facilitating the discovery of invariants and relationships. This helped overcome the rigidity of static representations and the tendency to focus solely on the outlines of shapes, a limitation of drawing noted by Castelnuovo (2017). Moreover, interaction with GeoGebra supported the development of an inclusive understanding of quadrilateral definitions, counteracting rote memorization and encouraging students to actively construct mathematical meaning, as suggested by Sbaragli (2020). The integration of these artefacts is consistent with the National Guidelines (dell'Istruzione, 2012) and the European Key Competences, which promote the use of geometry software and the development of active digital and mathematical skills.

However, it is important to acknowledge the limitations of the adopted research design. This study employed a quasi-experimental design with a pre-test and post-test administered to a single group. While this design is useful for observing changes within the group, it lacks external validity, making it difficult to generalize the findings to similar classroom contexts. Additionally, its internal validity is limited, meaning that a direct causal link between the use of GeoGebra and the observed learning improvements cannot be established. Uncontrolled external factors, such as the "history" effect (events occurring between tests) or the "maturation" effect (natural student development), may have influenced the results. The "testing" effect, whereby repeating a test may lead to improved scores, also cannot be ruled out (Bailey, 2008). The limited weekly frequency of the intervention may

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have further exposed the results to such variables. While the findings are promising, future research incorporating a control group is necessary to establish a more robust causal relationship.

## 5. CONCLUSION

This study examined how the integration of physical artefacts inspired by Emma Castelnuovo and the dynamic geometry software GeoGebra can enhance students' understanding of the properties of quadrilaterals. The results, which show a statistically significant increase in the average score from the pre-test to the post-test, suggest that this approach strengthened students' geometric knowledge.

This instructional model, based on hands-on manipulation and dynamic exploration, proved effective in overcoming the limitations of traditional teaching methods, which often rely on static drawings and abstract definitions. The opportunity for students to "construct and touch" geometric figures and to observe how their properties are preserved during transformations (enabled by GeoGebra's dragging function) promotes active and intuitive learning. This methodology fosters the development of an inclusive understanding of quadrilateral definitions, which is essential for building solid geometric reasoning. The strong engagement and positive feedback from students highlight the potential of these strategies to make mathematics more accessible and motivating, in line with the National Guidelines and the European Key Competences, which advocate for the use of digital technologies and the development of active mathematical skills.

Despite these encouraging results, the limitations of the quasi-experimental design adopted, lacking a control group, prevent establishing a direct causal link between the use of GeoGebra and the improvement in learning outcomes. Potential influences such as the "testing effect" or "history effect" cannot be excluded. Therefore, future research should include at least one control group to strengthen internal validity. To better isolate the effect of GeoGebra, a factorial study design could be implemented, involving multiple experimental groups: one using both Castelnuovo's physical artefacts and digital tools (GeoGebra), one using only physical artefacts, one using alternative activities aimed at the same learning objectives, and a control group engaged in different geometry-related tasks.

Moreover, to allow for the generalization of findings, it would be necessary to select a representative sample of the student population. Finally, further studies could investigate the effectiveness of this approach across different age groups, with other geometric concepts, or through in-depth qualitative analyses of students' interactions with the artefacts, to gain deeper insights into the underlying cognitive processes.

**Conflict of Interest:** The authors declare no conflict of interest.

**Ethical Approval:** The study adheres to the ethical guidelines for conducting research.

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