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Enhancing mathematical connection skills through animation-supported instruction: an experimental study

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Introduction: The present study aimed to investigate the impact of animation-supported instruction on the development of students' mathematical connection skills. To this end, a conceptual framework was established comprising two main dimensions—internal and external connections—and four sub-dimensions: connections among concepts, among representations, with life contexts, and across disciplines.
Methods: A quasi-experimental design with pretest and posttest applications was employed, involving experimental and control groups. The data were collected using a measurement tool developed in accordance with the proposed framework.
Results: The results indicated that animation-supported instruction had a significant positive effect on students' mathematical connection skills. The most substantial improvements were observed in the sub-dimensions of connections among concepts and among representations. Students demonstrated an enhanced ability to establish relationships between concepts across different learning domains, relate mathematical knowledge to real-life situations, and integrate mathematics within social and cultural contexts.
Discussion: The findings suggest that animation-supported instruction serves as an effective pedagogical approach that strengthens students' mental representations, deepens conceptual understanding, and promotes the transfer and application of mathematical knowledge across various contexts.

KEYWORDS
animation-supported instruction, connection among concepts, connection among representations, connection with life contexts, interdisciplinary connection

1 Introduction

The teaching of mathematical concepts plays an important role in developing students' abstract thinking skills and fostering deeper conceptual understanding (English and Kirshner, 2002; Ncube and Luneta, 2025, Tall, 2013). However, the inherently abstract nature of mathematics often leads students to encounter various difficulties during the learning process. To overcome these challenges, it is essential to diversify instructional methods and employ tools that provide students with more effective learning experiences.

Traditional instructional methods may have limitations in supporting the understanding of abstract mathematical concepts, whereas student-centered and technology-supported approaches have been shown to enhance conceptual understanding and engagement

(Dietrich and Evans, 2022). To address the challenges encountered in the teaching process, it is necessary to go beyond traditional approaches and integrate innovative and technological tools. At this point, technology offers innovative resources that contribute to making instructional processes more effective, interactive, and student-centered, thereby enabling the development of more impactful approaches to teaching (Mayer, 2009). Technology-enhanced learning environments have been reported to support students' cognitive learning outcomes and promote active engagement in learning activities, while also having an effect on learning motivation, although this effect appears to be comparatively limited (Hu et al., 2025). Among the instructional tools designed to present abstract mathematical concepts in a more concrete and comprehensible way, animations are particularly noteworthy, as research has shown that dynamic visualizations can enhance conceptual understanding compared to static representations (Divayani et al., 2024; Höffler and Leutner, 2007). By dynamically and visually representing concepts, animations may facilitate students' ability to establish relationships among mathematical ideas, which is considered a key component of mathematical connection skills (National Council of Teachers of Mathematics [NCTM], 2000). Consequently, it is important to examine the effectiveness of animation-supported instructional processes in mathematics education.

Mathematical connection skills enable students to establish meaningful relationships between concepts and to utilize their knowledge effectively during problem-solving processes (NCTM, 2000). Nevertheless, students may face challenges while developing these skills. Therefore, the present study aims to systematically investigate the differences between animation-supported instruction and traditional methods, examine their effects on students' mathematical connection skills, and provide evidence-based insights to inform the use of more effective strategies in future instructional practices. This study differs from previous research in several important ways. First, it conceptualizes mathematical connection skills as a multidimensional construct rather than treating them as a single outcome. It also examines how animation-supported instruction influences different types of mathematical connections, including conceptual, representational, real-life, and interdisciplinary connections. By addressing these dimensions simultaneously, the study provides both theoretical and empirical contributions, demonstrating how animation-supported instruction can support the development of mathematical understanding and relational thinking through connection skills.

In addition, the study focuses on pre-service teachers, a relatively underexplored group in this context. Pre-service teachers constitute a critical group in mathematics education, as they are future educators who will directly shape how mathematical concepts are taught and understood in classrooms. Developing mathematical connection skills during teacher education is therefore essential, not only for enhancing their own understanding of mathematics but also for supporting effective instructional practices. Teacher education programs also provide structured and controlled learning environments in which innovative instructional approaches can be systematically implemented and examined. This makes them particularly suitable settings for investigating the effects of animation-supported instruction on the development of mathematical connection skills.

2 Background

2.1 Literature review

Mathematical connection skills constitute a fundamental competency that enables students to establish meaningful relationships among concepts, apply their knowledge across different contexts, and utilize it effectively in problem-solving processes (NCTM, 2000, 2014). The literature emphasizes that students encounter various challenges in developing these skills and often struggle to connect mathematics either within itself or with other disciplines (Boaler, 2015; NCTM, 2014). Furthermore, research (e.g., Rohaendi, 2020; Yaniawati et al., 2019) indicates that students predominantly focus on operational and procedural approaches in mathematics learning and fail to sufficiently develop mathematical connection skills, such as connections among concepts. This limitation constrains their ability to comprehend mathematical concepts holistically and to establish links among different representations during problem-solving processes. The findings suggest that both individual competencies and the instructional environment play a critical role in fostering students' mathematical connection skills.

Supporting connection skills in mathematics instruction involves multiple dimensions, such as establishing links among concepts, enabling transitions between different representations, and connecting mathematics with real-life contexts (Bingölbali and Coşkun, 2016). Instructional practices and textbooks predominantly emphasize real-life connections in mathematics learning, whereas connections among mathematical concepts and interdisciplinary connections remain considerably limited (Şimşekler-Dizman and Çakır 2025). In particular, findings indicate that real-life connections are the most frequently used type, while conceptual and interdisciplinary connections are addressed to a much lesser extent. This imbalance suggests that students may have fewer opportunities to engage in deeper relational understanding by linking mathematical ideas within and across domains. Therefore, supporting learners in establishing a broader range of connections—including conceptual, representational, real-life, and interdisciplinary connections—has become an important goal in mathematics education. At this point, animation-supported instruction has been suggested as a promising instructional approach for fostering the development of mathematical connection skills. Research has shown that animations facilitate students' understanding of abstract concepts, assist them in making transitions between different representations, and support their ability to relate mathematical concepts to real-life contexts (Kartika et al., 2025; Liu and Elms, 2019; Rohendi et al., 2019). By providing students with the opportunity to experience concepts dynamically and visually, animations encourage them to form conceptual links during problem-solving and to transfer their knowledge to various contexts (Ainsworth, 2008).

However, the literature contains a limited number of studies that directly examine the interaction between mathematical connection skills and animation-supported instruction. Existing studies predominantly focus on the effects of animations on academic achievement and conceptual understanding, whereas their role in strengthening mathematical connection skills has received comparatively limited attention in the literature

(Boushah-Azzaroulli, 2019). Therefore, investigating the impact of animation-supported instruction on students' mathematical connection skills would make a significant contribution to the literature by empirically examining how animation-supported instruction influences different dimensions of mathematical connection skills.

2.2 Animation-supported instruction

Animation is a visual communication technique that creates the perception of motion by displaying static images, drawings, or digital graphics in a specific sequence and at a certain speed (Eliot and Miller, 1999). This technique enables the dynamic presentation of concepts and often begins with a narrative that evolves into a visual scenario.

Today, animation has increasingly been used as an instructional tool in educational settings. Its capacity to integrate visual and dynamic representations has been reported to support learners' understanding of abstract and complex concepts (Höffler and Leutner, 2007; Mayer, 2009). The combination of visual and auditory elements may enhance students' engagement and facilitate meaningful learning processes by enabling learners to observe conceptual relationships more concretely (Ainsworth, 2008). In classroom contexts, animation-supported materials have been associated with increased attention and participation, particularly when representing temporal changes and relationships among concepts in domains such as mathematics and science (Liu and Elms, 2019; Rohendi et al., 2019).

Based on previous research, animation-supported instruction has been reported as a useful instructional approach for concretizing abstract concepts and making learning more interactive and engaging. This approach not only helps students understand individual concepts but also enables them to visually recognize the relationships among these concepts, thereby transforming them from passive recipients of knowledge into active learners (Höffler and Leutner, 2007). The dynamic and visual support offered by animations allows students not only to grasp mathematical structures at a superficial level but also to understand the deeper connections between them (Ainsworth, 2008; Mayer, 2009). At this point, students' ability to form meaningful relationships between different mathematical concepts—known as mathematical connection—becomes essential (NCTM, 2000). This skill not only supports lasting learning but also facilitates the transfer of knowledge to novel situations. Therefore, effective mathematics instruction is expected to extend beyond the transmission of individual concepts and guide students in establishing meaningful connections among them.

2.3 Mathematical connection

Recent educational research has emphasized the growing importance of mathematical skills, particularly mathematical connection skills, in supporting learners' understanding and problem-solving processes (Boaler, 2015; NCTM, 2000). Mathematical connection is a crucial competency that enables individuals to establish links between different concepts and data, thereby facilitating the understanding of mathematical relationships. This skill not only enhances individuals' mathematical thinking abilities but also allows for the effective resolution of problems and the generation of innovative solutions through informed decision-making (Leikin and Levav-Waynberg, 2007; NCTM, 2000).

Mathematical connection, which lies at the core of mathematics and plays a critical role in its development, is among the fundamental skills that must be cultivated in the teaching process (NCTM, 2000). In education, fostering this skill enables students to gain a deeper understanding of mathematical concepts and to apply this knowledge in daily life and across various domains. Often described in the literature as establishing connections, bridging, or networking between mathematical situations, mathematical connection has been classified in different ways by researchers. For instance, Hau, 1993 initially categorized mathematical connection into internal and external connections and later expanded this classification into five categories: structural internal connections, internal applied connections, cultural or historical internal connections, conceptual/procedural internal connections, and external applied connections. Evitts, 2004 divided mathematical connection into five distinct categories: modeling-based connections, structural connections, representational connections, conceptual-procedural connections, and connections across different mathematical learning domains. Leikin and Levav-Waynberg, 2007 examined connection under three headings: connections based on similarities and differences among various representations of the same concept, connections among different mathematical concepts and operations, and connections across different branches of mathematics. Eli (2009) categorized mathematical connection into five groups: characteristic/feature-based, algebraic/geometric, conceptual/procedural, derivative, and two-/three-dimensional connections. Finally, Bingölbali and Coşkun (2016) proposed four categories: inter-concept connections, connections among different representations of a concept, connections to real-life contexts, and connections across different disciplines. Taken together, these classifications indicate that mathematical connection is a multidimensional construct involving relationships within mathematics as well as connections between mathematics and external contexts.

3 Theoretical framework

Mathematical connection is recognized as a key competency that enables individuals to establish links between mathematical concepts and data, thereby facilitating the understanding of mathematical relationships (Bingölbali and Coşkun, 2016; NCTM, 2000). Researchers note that this competency directly influences individuals' mathematical thinking processes and contributes to the development of their mathematical understanding (Jawad, 2022; Kuzu, 2017). In this study, mathematical connection skills were categorized by synthesizing classifications proposed in previous research (Bingölbali and Coşkun, 2016; Eli, 2009; Evitts, 2004; Hau, 1993; Leikin and Levav-Waynberg, 2007), and a framework consisting of two main dimensions—internal and external connections—was developed. Each type of connection within this framework contributes to the development of mathematical thinking skills and assists individuals in integrating new knowledge with their existing cognitive structures (Leikin and Levav-Waynberg, 2007). The framework comprises four sub-dimensions: connection among concepts, connection among representations, connection with life contexts, and interdisciplinary connection. The components within these sub-dimensions include same learning domain and different learning domains for internal connections; same type and different types for representational connections; daily life and real life for life-context connections; and natural sciences as well as humanities and cultural studies for interdisciplinary connections. Figure 1 presents a framework developed by the authors through a synthesis of classifications in the literature on mathematical connections and their reorganization in line with the purpose of the present study. This framework is conceptually related to Bingölbali and Coşkun (2016) approach; however, it is not a direct repetition of that approach. While Bingölbali and Coşkun (2016) conceptualized mathematical connection in terms of relating mathematics within itself and relating mathematics to other domains, the present study reorganizes this structure under the broader dimensions of internal and external connections. In addition, the sub-dimensions and components were specified in a way that allows a more detailed examination of pre-service teachers' mathematical connection skills in an experimental context. Likewise, whereas Mumcu (2018) discussed mathematical connection mainly within the scope of the derivative concept, the present framework was designed as a broader classification that is not limited to a single mathematical concept.

3.1 Connection among concepts

Mathematics is a discipline with a spiral structure in which newly acquired concepts are built upon prior knowledge, and each concept gains meaning through its integration into the existing network of previously learned ideas during the process of mathematical thinking (Kuzu, 2017). Consequently, establishing connections between mathematical concepts is of paramount importance. Such connections are defined as the linkage of one mathematical concept to another (Bingölbali and Coşkun, 2016). In this context, connections can be examined under two main categories: connections among concepts within the same learning domain and connections among concepts across different learning domains.

3.1.1 Connection among concepts within same learning domain

In mathematics, this type of connection refers to the relationships established among concepts or expressions within the same learning domain, particularly between a concept and its subordinate or superordinate concept. For example, the derivative defines the rate of change of a function at a specific point as the limit value at that point, which illustrates the subordinate relationship of the derivative to the concept of limit. On the other hand, differentiation[1] refers to performing this derivative calculation for all points of the function, and the derivative is the result of the differentiation process. Thus, the derivative is a product of differentiation, and in this context, the derivative is considered a subordinate concept of differentiation, whereas differentiation is regarded as a superordinate concept of the derivative. This example demonstrates the superordinate–subordinate relationship between differentiation and the derivative.

3.1.2 Connection among concepts across different learning domains

In mathematics, this type of connection refers to the relationships established between concepts or expressions belonging to different learning domains, where a concept is related to other mathematical concepts that are neither its subordinate nor its superordinate. For instance, in analytic geometry, the tangent line to a curve at a given point represents the instantaneous direction and slope of the curve at that point. In differential calculus, the derivative expresses the rate of change of a function at a given point. This rate of change is identical to the slope of the tangent line to the curve at that point. Thus, a direct relationship is established between the geometric concept of the tangent line and the calculus concept of the derivative.

3.2 Connection among representations

Mathematical concepts can be expressed through different forms of representation, and establishing connections among these representations enables a deeper understanding of the concept (Goldin, 2002). Representations are also classified as input and output representations according to the roles they play in the problem-solving process. Input representations are descriptive forms used to present the data of a problem, whereas output representations refer to the meanings related to the concept targeted in the solution process (Kendal and Stacey 2003). Input and output representations may be presented in the same or different forms, often involving linguistic, visual, or symbolic representations. In this context, connection among representations is examined under two main categories: connection among the same types of representations and connection across different types of representations. Both forms of connection contribute to the development of mathematical thinking skills and enable individuals to integrate new knowledge with their existing knowledge structures (Bingölbali and Coşkun, 2016; Leikin and Levav-Waynberg, 2007).

3.2.1 Connection among the same types of representations

This refers to interpreting and integrating a concept or piece of knowledge within the same type of representation but in

[1] It refers to the process of deriving the derivative function from a given function.

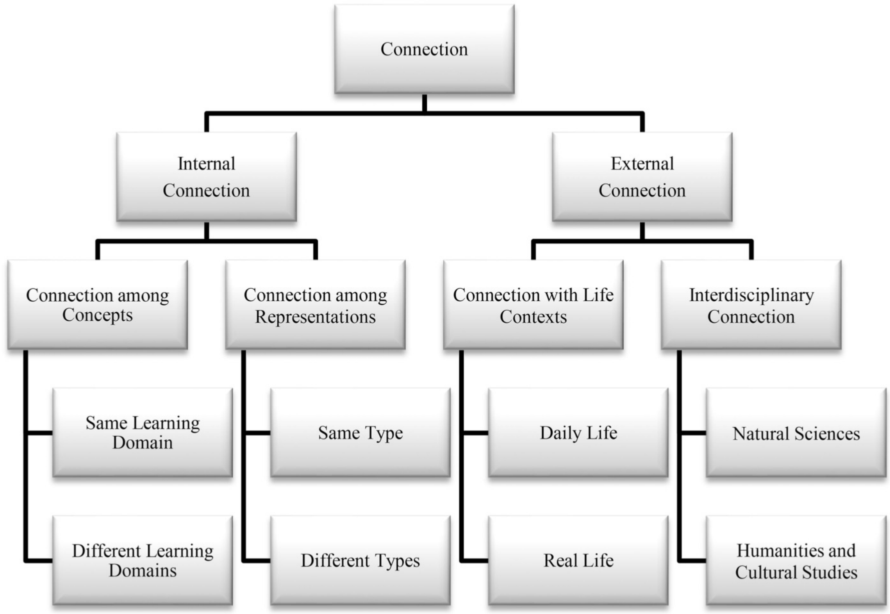

FIGURE 1
Framework for connection skills.

different contexts or at different levels. For example, representing the fraction ¼ using different visual forms, such as an area (region) model and a length model, illustrates the connection within the same type of representation for the concept of fractions.

3.2.2 Connection across different types of representations

This refers to linking a concept or piece of knowledge through distinct types of representation. For example, representing the fraction ¼ both as a visual model (e.g., area or length model) and symbolically as ¼ demonstrates the connection across different types of representations.

3.3 Connection with life contexts

Connection with life contexts refers to linking mathematical concepts or operations beyond the classroom environment to students' own experiences (Bingölbali and Coşkun, 2016; NCTM, 2000). In other words, the student can apply the learned knowledge not only on paper but also in meaningful ways in their own world. This approach aims to illustrate how mathematical knowledge, despite its abstract nature, can be meaningfully applied in everyday and societal contexts. Connection with life contexts can be examined under two main categories: connection with daily life and connection with real-life.

3.3.1 Connection with daily life

This involves relating mathematics to situations that an individual encounters and experiences regularly in their own routine. The goal is to connect mathematics practically and functionally to circumstances that directly occur in the individual's daily life. For example, calculating that a product originally priced at 250 units is reduced to 200 units after a 20% discount illustrates the application of mathematical knowledge in daily life.

3.3.2 Connection with real-life

This involves relating mathematics to situations that exist in life and society, even if they are not part of the individual's routine. This context can be analyzed at two levels: connection with real-life from an individual perspective and connection with real-life from a societal perspective. Connection with real life from an individual perspective refers to relating mathematics to situations that exist in real life but are not part of an individual's daily routine. For example, in a city where a metro system does not exist, using the metro may represent an abstract or simulated situation and can therefore be considered a real-life context. Although this situation is not part of the student's routine, it still constitutes a real-life context because it exists in everyday life. In contrast, in cities where metro systems are widely used, using the metro is a natural part of daily life and can therefore be considered an example of a daily-life context. connection with real life from a societal perspective involves relating mathematics to situations that exist beyond the individual and are embedded within broader social, economic, technological, or environmental contexts. The aim is to move beyond everyday practical experiences and establish connections with phenomena that influence societal functioning. For example, mathematically modeling traffic flow in a city or calculating risks associated with natural disasters represents real-life applications of mathematics that are not necessarily part of an individual's daily routine but contribute to understanding societal processes.

3.4 Interdisciplinary connection

Interdisciplinary connection refers to the application of mathematical concepts and skills in relation to different subjects or fields (Bingölbali and Coşkun, 2016; NCTM, 2000). This approach enables students to understand mathematics not only within its own domain but also in other disciplines. Interdisciplinary connection can be examined under two main categories: connection with the natural sciences and connection with the humanities and cultural sciences.

3.4.1 Connection with the natural sciences

This involves applying mathematical concepts and skills in connection with science subjects and natural phenomena. It allows students to use mathematics not merely as an abstract subject but as a tool for understanding the natural events they observe and experience. For example, students measuring the height of a plant over several days can organize the data into tables and graphs to calculate the average daily growth.

3.4.2 Connection with the humanities and cultural sciences

This approach refers to linking mathematical concepts and skills with social sciences, history, geography, art, and other cultural domains. It helps prevent students from perceiving mathematics solely as a subject of numbers and operations, enabling them to understand it in social, cultural, and historical contexts. For instance, geometric shapes in a traditional carpet or rug pattern can be analyzed to perform area and symmetry calculations.

4 Significance and purpose of the study

It is well established that animations contribute in many ways, such as allowing the slowing down or speeding up of time, demonstrating experiments that are difficult to perform, showing rare events, simplifying complex systems for better understanding, and being practical and cost-effective (Ploetzner et al., 2021; Teplá et al., 2022). The use of animations enhances students' conceptual understanding by presenting mathematical content in a visual and interactive manner, strengthens their learning motivation, and improves learning outcomes (Kartika et al., 2025). Animations, especially by presenting abstract or complex mathematical concepts visually and dynamically, facilitate students' ability to make connections among concepts and across representations. Furthermore, through animations, students can better understand both daily life and real-life contexts. This enables them to learn mathematics not only as formulas but also in relation to life and other disciplines. Therefore, investigating the effect of animations on connection skills is deemed worthwhile.

However, although previous studies have examined the effects of animations on conceptual understanding and academic achievement, limited research has directly investigated their impact on students' mathematical connection skills. Previous studies have shown that instructional materials incorporating animations improve students' conceptual understanding, enhance learning motivation, and develop their ability to apply mathematical knowledge in various contexts (Kartika et al., 2025; Ojo, 2022; Weng and Yang, 2017). Consequently, examining the effect of animation-supported instruction on mathematical connection skills is of significant importance, both for developing innovative teaching strategies in education and for strengthening students' abilities to comprehend abstract mathematical concepts. In this context, the present study investigates the impact of animation-supported instruction on mathematical connection skills and addresses the following research questions:

1. What is the effect of animation-supported instruction on students' mathematical connection skills?
2. What is the effect of animation-supported instruction on different dimensions of students' mathematical connection skills?

5 Method

This study investigates the effect of animation-supported instruction on pre-service teachers' mathematical connection skills. We adopted a quantitative approach and implemented a pretest–posttest quasi-experimental design with a control group. A quasi-experimental design was preferred because the study was conducted in a natural educational setting with pre-existing groups, and random assignment of participants to the experimental and control groups was not feasible under the instructional conditions of the study. Therefore, a pretest-posttest quasi-experimental design with a control group was considered appropriate for comparing the effects of the intervention while preserving the natural structure of the classroom environment. The experimental group received the animation-supported instruction, while the control group underwent the conventional teaching process. We measured the mathematical connection skills of both groups using the Mathematical Connection Skills Test (MCST) before and after the intervention. Table 1 presents the symbolic representation of the experimental design.

5.1 Participants

The participants were 41 pre-service mathematics teachers enrolled in a teacher education program at a public university (33 females and 8 males). Twenty participants were assigned to the experimental group (17 females and 3 males) and twenty-one were in the control group (16 females and 5 males). The

TABLE 1 Pretest–posttest experimental–control group design.

Group	Pretest	Intervention	Posttest
Experimental	MCST	ASI	MCST
Control	MCST	CT	MCST

MCST, mathematical connection skills test; ASI, animation-supported instruction; CT, conventional teaching.

participants were selected using a convenience sampling method based on accessibility and logistical considerations (Creswell and Creswell, 2017). All participants were enrolled in similar coursework within the same program, ensuring comparable academic backgrounds. Participation in the study was voluntary.

5.2 Data collection

Data were collected using the Mathematical Connection Skills Test (MCST), a 10-item instrument developed and validated by Mumcu (2018). In the present study, no modifications were made to the original items. However, in order to provide a more detailed analysis aligned with the conceptual framework of mathematical connection skills adopted in this study, the items were categorized based on their underlying indicators. Specifically, the items were classified into internal and external connections. Internal connections included connections among mathematical concepts (Items 4–6) and connections among representations (Items 1–3). External connections consisted of connections with real-life contexts (Items 7–8) and interdisciplinary connections (Items 9–10). All items were administered as open-ended tasks requiring participants to explain and justify the connections they established. The classification of the items was independently conducted by two researchers based on the conceptual framework. Inter-rater agreement was calculated using the Miles and Huberman, 1994 formula [reliability = consensus/(consensus + dissidence)]. A full agreement was achieved between the coders, indicating a high level of consistency. The agreement was calculated based on the classification of 10 items, each assigned according to its primary indicator.

5.3 Validity and reliability

The Mathematical Connection Skills Test (MCST) used in this study was developed by Mumcu (2018). To support content validity, the instrument was reviewed by four specialists in mathematics education, and the final form of the test was established based on their feedback. In the original study, the reliability of the instrument was assessed through split-half reliability analysis, and the Spearman-Brown reliability coefficient was reported as.70, indicating an acceptable level of reliability. In the present study, the items were aligned with the theoretical framework presented in Figure 1. In addition, because the responses were scored using a rubric, inter-rater reliability was examined. Two mathematics educators independently scored the responses, and the weighted kappa coefficients ranged from .76 to .87, indicating a high level of agreement between raters (Cohen, 1960; Fleiss, 1971; McHugh, 2012).

5.4 Instructional process

The MCST was administered to the participants as a pretest during one class session before the intervention and as a posttest during one class session immediately after the completion of the instructional process. Based on the pretest scores, the participants were distributed into the experimental and control groups to ensure comparable group structures. The instructional process for the experimental group incorporated animation-supported materials, including 18 animations from the literature and seven additional animations created using the Plotagon program. These materials aimed to support students' understanding of derivatives by fostering different types of mathematical connections and included explanatory content and instructional activities. Plotagon was preferred due to its user-friendly interface, its ability to visualize abstract mathematical concepts, and its flexibility in creating customized animations. The instructional content focused on the concept of derivative throughout the four-week intervention. In both the experimental and control groups, the same content was covered; however, the mode of instruction differed. In the experimental group, animations were used to support students in establishing connections among derivative-related concepts, representations, and applications. A typical lesson involved introducing the topic, presenting the animations, discussing the mathematical relationships represented, and completing worksheet-based activities designed to help students explain and interpret these relationships. During the intervention, the experimental group also used three worksheets specifically prepared for this study to reinforce the relationships presented in the animations and to encourage students to explain and interpret these connections. In contrast, the control group received instruction on the same content through conventional teaching methods, primarily including lectures, question-and-answer activities, and classroom discussions. The instructional process was conducted by the researcher during regular course sessions and lasted four weeks. Each week included four class sessions, resulting in a total of 16 class sessions.

5.5 Plotagon

Plotagon is a 3D animation software established in 2013 that allows users to design and animate virtual characters and scenarios. The program features a drag-and-drop interface along with pre-designed characters, scenes, and voice options, enabling animation creation without advanced technical skills. By combining technology and animation, Plotagon enables users to transform ideas into videos. It integrates game technology, classical film production, and screenplay writing techniques to create animations effectively. Plotagon is widely used in education, storytelling, and communication. It allows users to visualize abstract concepts, design interactive scenarios, and engage audiences through animated narratives. Educators, content creators, and corporate trainers use Plotagon to teach and inform students, employees, colleagues, or the general public. Its features make it suitable for creating interactive learning materials, simulations, and digital stories that enhance understanding and engagement.

5.6 Data analysis

We scored the responses to the 10-item MCST according to the criteria presented in Table 2 during the data analysis phase.

TABLE 2 Scoring criteria and connection levels for MCST responses.

Connection level	Scoring criteria	Score
Full Connection + Correct Explanation	Establishes the connection and explains and/or demonstrates it accurately	4
Full Connection + Partial Explanation	Establishes the connection and partially explains or demonstrates it	3
Full Connection + Incomplete Explanation	Establishes the connection but cannot fully explain or demonstrate all aspects	2
Partial Connection + Incomplete Explanation	Partially establishes the connection and cannot fully explain or demonstrate all aspects	1
Blank/Does Not Understand	Provides irrelevant, unclear, or "I do not understand" responses, or leaves it blank	0

For the analysis of the quantitative data obtained from the test, we had two mathematics educators independently score the responses based on the criteria presented in Table 2 and entered the resulting data into SPSS 29 (Statistical Package for the Social Sciences, version 29). To assess inter-rater agreement within this multi-rater scoring rubric, we calculated the weighted Kappa statistic, a variant of the Kappa coefficient. This measure was preferred because the scoring process involved ordered categories, and weighted Kappa provides a more sensitive assessment of agreement in such cases. During the data analysis phase, the normality of the data distribution was examined using both descriptive and inferential methods. We observed that the arithmetic mean, mode, and median values were close to each other for both the experimental and control groups. Additionally, we determined that the skewness and kurtosis coefficients in both groups fell within the acceptable range of −1 to +1 (Morgan et al., 2004). Further analyses using histograms, box plots, and Q–Q plots indicated that the data followed a normal distribution. Finally, the Shapiro–Wilk test was conducted, and the results indicated that the assumption of normality was satisfied (Table 3).

Since the score distributions in the study met the assumptions of parametric tests and exhibited a normal distribution, we concluded that the sample sizes in the groups did not violate these assumptions. In this context, we examined the differences between the pretest and posttest scores of students in the experimental and control groups using a paired-sample *t*-test. The difference between the pretest scores of students in the two groups was analyzed with an independent-sample t-test (Kuzu, 2022). To determine whether there was a statistically significant difference between the posttest achievement scores of the experimental and control groups, we conducted an analysis of covariance (ANCOVA). ANCOVA was preferred because the study employed a pretest-posttest quasi-experimental design with non-randomly assigned groups. In such designs, ANCOVA is commonly recommended as an appropriate technique for comparing posttest scores while statistically controlling for possible initial differences reflected in pretest scores. Therefore, ANCOVA was used to obtain a more accurate estimate of the intervention effect after adjusting for baseline performance (Tabachnick and Fidell, 2013). In addition, we calculated effect sizes to assess the practical significance of changes observed after the animation-supported instruction and traditional teaching processes. We noted that significant differences between mean scores do not necessarily guarantee practical differences; therefore, effect size statistics should be used when interpreting the results. Cohen's d values are interpreted as follows: $.00 \le d < .20$: very small, $.20 \le d < .50$: small, $.50 \le d < .80$: medium, $.80 \le d < 1.20$: large, $1.20 \le d$: very large effect size. Similarly, the η^2 value is interpreted as $.01 \le \eta^2 < .06$: small, $.06 \le \eta^2 < .14$: medium, and $.14 \le \eta^2$: large effect size (Cohen, 1988). Furthermore, we classified achievement levels based on the average test scores as $.00 \le \text{score} \le .80$: Very low; $.80 < \text{score} \le 1.60$: Low; $1.60 < \text{score} \le 2.40$: Moderate; $2.40 < \text{score} \le 3.20$: High; $3.20 < \text{score} \le 4.00$: Very high.

In addition, a sensitivity analysis was conducted using G*Power to evaluate the adequacy of the sample size. Statistical power was set at.80, as this value is widely accepted as a conventional threshold in educational and social science research (Cohen, 1988). With an alpha level of.05, a total sample size of 41, two groups, and one covariate, the analysis indicated that the present sample was sensitive to detect relatively large effects. Furthermore, the large group effect obtained from the ANCOVA analysis ($\eta^2 = .360$; $f = .75$) supports the adequacy of the sample for detecting the main intervention effect observed in this study.

6 Findings

In this section, we examined the effects of animation-supported instruction on students' mathematical connection skills and their different types. The first research problem focused on students' overall mathematical connection skills, while the second addressed specific types, including internal and external connection, connection among concepts, connection among representations, connection with life contexts, and interdisciplinary connection skills. We evaluated the findings through comparisons between the experimental and control groups.

Before starting the instructional process, we examined whether the experimental and control group pre-service teachers differed significantly in terms of their mathematical connection skills. Table 4 presents the findings.

As shown in Table 4, we found no statistically significant difference between the pretest scores of the control and experimental groups, with both groups demonstrating a low level of achievement ($\bar{X}_{experimental} = 1.240$; $\bar{X}_{control} = 1.247$; $t = .034$; $p = .973 > .05$). Following the pretest, the experimental group received animation-supported instruction, whereas the control group received conventional instruction. After the instructional period, we administered the MCST again as a posttest. To determine whether the pretest and posttest achievement scores of the experimental and control groups differed significantly, we conducted a paired sample t-test. Table 5 presents the findings.

As shown in Table 5, we observed a significant difference between the pretest and posttest scores of both the control and experimental group participants. The control group participants improved from low to moderate achievement ($\bar{X}_{pretest} = 1.247$; $\bar{X}_{posttest} = 1.914$; $p < .001$), while the experimental group participants improved from low to high achievement ($\bar{X}_{pretest} = 1.240$; $\bar{X}_{posttest} = 2.650$; $p < .001$). We calculated the effect size as 2.05, indicating a very large effect. To determine whether the difference between the pretest and posttest scores differed significantly between the groups, we conducted an independent samples *t*-test. Table 6 presents the findings.

As shown in Table 6, we observed that the difference scores between the pretest and posttest of the experimental and control group participants regarding their connection skills favored the experimental group, showing a statistically significant difference ($\bar{X}_{experimental} = 1.410$; $\bar{X}_{control} = .666$; $p < .001$). We noted a very large effect size (d = 1.24). To determine whether the difference between the posttest scores of the groups was statistically significant, we conducted an ANCOVA. First, we checked the assumptions of ANCOVA. The tests indicated that the groups met the normality assumption, that there was a linear relationship between pretest and posttest scores ($r = .515$; $p < .001$), and that the homogeneity of variances was satisfied ($F = .199$; $p = .658 > .05$). We also examined whether the difference between the slopes of the regression lines of the groups was significant using the "Group × Pretest" interaction test and found no statistically significant difference ($F = .894$; $p = .351 > .05$). Based on these results, we concluded that we could analyze the difference between the posttest scores of the groups using ANCOVA. Tables 7, 8 present the findings.

Based on the ANCOVA results, we found a significant difference between the groups' posttest scores, adjusted according to their pretest scores on connection skills ($F = 21.397$; $p < .001$). We calculated the effect size for this difference (η^2) as .360, indicating a large effect. The Bonferroni *post-hoc* comparison test results, which we presented in Table 9, also show that the significant difference in adjusted posttest scores is in favor of the experimental group ($p < .001$).

On the other hand, we reported the effects of animation-supported instruction on students' internal and external connection, connection among concepts, connection among representations, connection with life contexts, and interdisciplinary connection skills in Tables 10, 11.

Table 10 shows that students in the experimental group demonstrated significant improvements in most dimensions and components of mathematical connection. We observed very large effect sizes in the dimensions and components from largest to smallest as follows: internal connection ($\bar{X}_{IC-Pretest} = 1.175$; $\bar{X}_{IC-Posttest} = 2.541$; d = 1.89), connection among concepts ($\bar{X}_{CC-Pretest} = 1.166$; $\bar{X}_{CC-Posttest} = 2.483$; d = 1.70), different learning domains ($\bar{X}_{DLD-Pretest} = .750$; $\bar{X}_{DLD-Posttest} = 2.450$; d = 1.68), humanities and cultural studies ($\bar{X}_{HCS-Pretest} = .300$; $\bar{X}_{HCS-Posttest} = 2.200$; d = 1.58), connection among representations ($\bar{X}_{CR-Pretest} = 1.183$; $\bar{X}_{CR-Posttest} = 2.600$; d = 1.45), daily life ($\bar{X}_{DL-Pretest} = .650$; $\bar{X}_{DL-Posttest} = 2.300$; d = 1.41), external connection ($\bar{X}_{EC-Pretest} = 1.337$; $\bar{X}_{EC-Posttest} = 2.812$; d = 1.37), different types ($\bar{X}_{DT-Pretest} = .450$;

TABLE 3 Descriptive statistics results for the distribution.

Group	Test	Mode	Median	$\bar{X}$	SD	Skewness	Kurtosis	Min	Max	Shapiro–Wilk
Experimental	Pretest	.80	1.10	1.240	.749	.977	.853	.30	3.20	.119
	Posttest	2.80	2.70	2.650	.619	−.394	.992	1.10	3.80	.647
Control	Pretest	.40	1.40	1.247	.669	−.137	−1.355	.20	2.30	.187
	Posttest	2.20	2.10	1.914	.645	−.880	.624	.50	3.00	.078

SD, standard deviation.

TABLE 4 Results for the difference between the pretest scores of experimental and control group.

Test	Group	*n*	$\bar{X}$	SD	t	df	*p*
Pretest	Experimental	20	1.240	.769	.034	39	.973
	Control	21	1.247	.669			

SD, standard deviation.

TABLE 5 Results for the difference between the pretest and posttest scores of experimental and control group.

Group	Test	*n*	$\bar{X}$	SD	t	df	d
Experimental	Pretest	20	1.240	.749	−9.363	19	2.05**
	Posttest	20	2.650	.619			
Control	Pretest	21	1.247	.669	−5.812	20	1.02**
	Posttest	21	1.914	.645			

**$p < .001$; SD, standard deviation; df, degrees of freedom.

TABLE 6 Results for the difference between the pretest and posttest scores of the experimental and control group.

Posttest—Pretest Difference Scores	Group	*n*	$\bar{X}$	SD	t	df	d
MCTS	Experimental	20	1.410	.673	−3.951	39	1.24**
	Control	21	.666	.525			

**$p < .001$; SD, standard deviation; df, degrees of freedom.

TABLE 7 Actual posttest scores and adjusted posttest scores based on pretest scores of the groups.

Posttest—Pretest Difference Scores	Group	*n*	$\bar{X}$	SD	$\bar{X}$	SE
MCTS	Experimental	20	2.650	.619	2.652	.114
	Control	21	1.914	.645	1.912	.122

SD, standard deviation; SE, standard error.

TABLE 8 Results for the posttest scores of the groups adjusted according to their pretest scores.

Source	Sum of Squares	df	Mean Square	F	*p*	η^2
Pretest	5.679	1	5.679	21.674	.000**	.360
Groups	5.607	1	5.607	21.397	.000**	
Error	9.957	38	.262			
Corrected Total	21.180	40				

**$p < .001$; df, degrees of freedom.

TABLE 9 Bonferroni test results for the groups' adjusted posttest scores.

Group	*n*	Mean Difference	SE	*p*	Direction of the Difference
Experimental	20	.740	.160	.000**	Experimental > Control
Control	21	−.740			

**$p < .001$; SE, standard error.

$\bar{X}_{DT-Posttest} = 2.300$; $d = 1.29$), and connection with life contexts ($\bar{X}_{CL-Pretest} = 1.375$; $\bar{X}_{CL-Posttest} = 2.850$; $d = 1.28$). We observed large effect sizes in the dimensions and components as follows: interdisciplinary connection ($\bar{X}_{IDC-Pretest} = 1.300$; $\bar{X}_{IDC-Posttest} = 2.775$; $d = 1.15$), and same type ($\bar{X}_{ST-Pretest} = 1.550$; $\bar{X}_{ST-Posttest} = 2.750$; $d = 1.05$). We observed medium effect sizes in the dimensions and components from largest to smallest as follows: real life ($\bar{X}_{RL-Pretest} = 2.100$; $\bar{X}_{RL-Posttest} = 3.400$; $d = .79$), natural sciences ($\bar{X}_{NS-Pretest} = 2.300$; $\bar{X}_{NS-Posttest} = 3.350$; $d = .61$), and same learning domain ($\bar{X}_{SLD-Pretest} = 2.000$; $\bar{X}_{SLD-Posttest} = 2.550$; $d = .58$). The lower effect sizes observed in the same learning domain, real-life, and natural sciences components compared to other dimensions and components may be due to already high initial scores in these skills.

Overall, animation-supported instruction was found to effectively enhance students' mathematical connection skills. When examined across the four sub- dimensions, this effect was particularly pronounced in the sub-dimensions of "Connection among Concepts" and "Connection among Representations", and therefore the highest improvements were observed in "Internal Connection".

Table 11 shows that students in the control group demonstrated improvements across most dimensions and components of mathematical connection, but the effect sizes were generally smaller than those observed in the experimental group. When we examine only the dimensions and components with statistically significant differences, the improvements were very large in connection among concepts ($\bar{X}_{CC-Pretest} = .825$; $\bar{X}_{CC-Posttest} = 1.793$; $d = 1.38$) and different learning domains ($\bar{X}_{DLD-Pretest} = .428$; $\bar{X}_{DLD-Posttest} = 1.642$; $d = 1.29$), large in internal connection ($\bar{X}_{IC-Pretest} = 1.182$; $\bar{X}_{IC-Posttest} = 1.928$; $d = 1.02$), medium in interdisciplinary connection ($\bar{X}_{IDC-Pretest} = 1.023$; $\bar{X}_{IDC-Posttest} = 1.738$; $d = .64$), external connection ($\bar{X}_{EC-Pretest} = 1.345$; $\bar{X}_{EC-Posttest} = 1.892$; $d = .53$), natural sciences (XNS-Pretest = 1.571; XNS-Posttest = 2.428; $d = .45$), and humanities and cultural studies ($\bar{X}_{HCS-Pretest} = .476$; $\bar{X}_{HCS-Posttest} = 1.047$; $d = .44$). On the other hand, we did not observe any statistically significant differences in the other dimensions and components.

Overall, the findings suggest that the control group made measurable progress in mathematical connection, though the gains were generally smaller and less consistent compared to the

TABLE 10 Results for the difference between the pretest and posttest of experimental group in mathematical connection.

Group	Connection Type	Test	n	$\bar{X}$	SD	t	df	d	Effect size
Experimental	IC	Pretest	20	1.175	.826	−8.628	19	1.89**	Very large
		Posttest	20	2.541	.599				
	CC	Pretest	20	1.166	.812	−7.820	19	1.70**	Very large
		Posttest	20	2.483	.737				
	SLD	Pretest	20	2.000	1.123	−2.463	19	.58*	Medium
		Posttest	20	2.550	.759				
	DLD	Pretest	20	.750	.910	−6.807	19	1.68**	Very large
		Posttest	20	2.450	1.110				
	CR	Pretest	20	1.183	1.157	−6.046	19	1.45**	Very large
		Posttest	20	2.600	.784				
	ST	Pretest	20	1.550	1.431	−4.188	19	1.05**	Large
		Posttest	20	2.750	.850				
	DT	Pretest	20	.450	1.145	−4.796	19	1.29**	Very large
		Posttest	20	2.300	1.719				
	EC	Pretest	20	1.337	1.026	−6.392	19	1.37**	Very large
		Posttest	20	2.812	1.123				
	CL	Pretest	20	1.375	1.223	−5.064	19	1.28**	Very large
		Posttest	20	2.850	1.077				
	DL	Pretest	20	.650	1.039	−5.638	19	1.41**	Very large
		Posttest	20	2.300	1.301				
	RL	Pretest	20	2.100	1.997	−3.322	19	.79*	Medium
		Posttest	20	3.400	1.313				
	IDC	Pretest	20	1.300	1.174	−4.914	19	1.15**	Large
		Posttest	20	2.775	1.390				
	NS	Pretest	20	2.300	1.976	−2.580	19	.61*	Medium
		Posttest	20	3.350	1.460				
	HCS	Pretest	20	.300	.732	−4.711	19	1.58**	Very large
		Posttest	20	2.200	1.673				

*$p < .05$; **$p < .001$; SD, standard deviation; df, degrees of freedom; IC, internal connection; CC, connection among concepts; SLD, same learning domain; DLD, different learning domains; CR, connection among representations; ST, same type; DT, different types; EC, external connection; CL, connection with life contexts; DL, daily life; RL, real life; IDC, interdisciplinary connection; NS, natural sciences; HCS, humanities and cultural studies; Main dimensions, IC, EC; Sub-dimensions, CC, CR, CL, IDC; Components, SLD, DLD, ST, DT, DL, RL, NS, HCS.

experimental group. Table 12 presents the comparison of pretest and posttest scores, along with effect sizes, for the experimental and control groups across mathematical connection dimensions and components.

The data presented in Table 12 show the pretest and posttest progress of students in the experimental and control groups across mathematical connection dimensions and components. In the experimental group, most dimensions and components demonstrated high or very high effects; in particular, internal connection ($d_{IC} = 1.89$), connection among concepts ($d_{CC} = 1.70$), different learning domains ($d_{DLD} = 1.68$), connection among representations ($d_{CR} = 1.45$), daily life ($d_{DL} = 1.41$), external connection ($d_{EC} = 1.37$), connection with life contexts ($d_{CL} = 1.28$), and humanities and cultural studies ($d_{HCS} = 1.5$) showed very high effects. Other sub-dimensions with high effects included same type ($d_{ST} = 1.05$), different types ($d_{DT} = 1.29$), and interdisciplinary connection ($d_{IDC} = 1.15$). Moderate effects were observed for same learning domain ($d_{SLD} = .58$), real life ($d_{RL} = .79$), and natural sciences ($d_{NS} = .61$). In the control group, some dimensions and components also showed high or very high effects ($d_{CC} = 1.38$; $d_{DLD} = 1.29$; $d_{IC} = 1.02$); however, most dimensions and components demonstrated moderate or small effects. Moderate effects were observed for $d_{SLD} = .54$, $d_{NS} = .45$; $d_{IDC} = .64$, and $d_{EC} = .53$, while small effects were found for $d_{CR} = .45$, $d_{ST} = .34$, $d_{DT} = .45$, $d_{CL} = .28$, $d_{RL} = .29$, and $d_{HCS} = .44$. Daily life ($d_{DL} = .16$) showed a very small effect.

7 Conclusion and discussion

The findings of the study indicate that animation-supported instruction not only enhanced students' conceptual knowledge but also significantly improved their mathematical connection

TABLE 11 Results for the difference between the pretest and posttest of control group in mathematical connection.

Group	Connection Type	Test	*n*	$\bar{X}$	SD	t	df	d	Effect size
Control	IC	Pretest	21	1.182	.627	−4.626	20	1.02**	Large
		Posttest	21	1.928	.825				
	CC	Pretest	21	.825	.573	−6.582	20	1.38**	Very large
		Posttest	21	1.793	.812				
	SLD	Pretest	21	1.619	.973	−1.943	20	.54	Medium
		Posttest	21	2.095	.768				
	DLD	Pretest	21	.428	.810	−5.271	20	1.29**	Very large
		Posttest	21	1.642	1.050				
	CR	Pretest	21	1.539	1.067	−2.074	20	.45	Medium
		Posttest	21	2.063	1.263				
	ST	Pretest	21	1.952	1.359	−1.558	20	.34	Small
		Posttest	21	2.428	1.468				
	DT	Pretest	21	.714	1.230	−2.087	20	.45	Medium
		Posttest	21	1.333	1.527				
	EC	Pretest	21	1.345	1.047	−3.134	20	.53*	Medium
		Posttest	21	1.892	1.035				
	CL	Pretest	21	1.666	1.511	−1.666	20	.28	Small
		Posttest	21	2.047	1.192				
	DL	Pretest	21	1.238	1.261	−0.658	20	.16	Very small
		Posttest	21	1.428	1.075				
	RL	Pretest	21	2.095	2.047	−1.826	20	.29	Small
		Posttest	21	2.666	1.932				
	IDC	Pretest	21	1.023	1.042	−3.377	20	.64*	Medium
		Posttest	21	1.738	1.200				
	NS	Pretest	21	1.571	1.912	−2.257	20	.45*	Medium
		Posttest	21	2.428	1.859				
	HCS	Pretest	21	.476	1.030	−2.098	20	.44*	Medium
		Posttest	21	1.047	1.499				

*$p < .05$; **$p < .001$; SD, standard deviation; df, degrees of freedom; IC, internal connection; CC, connection among concepts; SLD, same learning domain; DLD, different learning domains; CR, connection among representations; ST, same type; DT, different types; EC, external connection; CL, connection with life contexts; DL, daily life; RL, real life; IDC, interdisciplinary connection; NS, natural sciences; HCS, humanities and cultural studies; Main dimensions, IC, EC; Sub-dimensions, CC, CR, CL, IDC; Components, SLD, DLD, ST, DT, DL, RL, NS, HCS.

skills. Students in the experimental group demonstrated higher levels of progress and greater consistency compared to their peers in the control group. This suggests that integrating animations into the learning process enables students to construct mathematical knowledge more effectively, relate new information to prior experiences, and transfer learned concepts to new contexts more efficiently.

According to the findings, animation-supported instruction emerges as a powerful pedagogical tool that deepens learning by reinforcing students' mental representations, supporting conceptual coherence, and offering a more comprehensive learning experience than traditional teaching methods. This can be directly attributed to the capacity of animations to present abstract mathematical concepts in a more concrete, visualized, and comprehensible manner (Ainsworth, 2008). As emphasized in the literature, visual and dynamic representations strengthen students' mental models, facilitate transitions among concepts, and enhance the retention of learning (Kuzu, 2020). Moreover, animations encourage students to engage actively in the mathematical reasoning and problem-solving process by observing procedural steps rather than passively receiving information (Höffler and Leutner, 2007). This interactive process contributes to the development of mathematical connection skills and the overall growth of mathematical thinking, allowing students to integrate new knowledge more effectively with their existing cognitive structures.

In contrast, although students in the control group also showed some improvement, their progress was relatively limited compared to the experimental group. This can be explained by the reliance of traditional instructional methods primarily on verbal and symbolic representations when conveying mathematical concepts. While such approaches may assist students in recalling information, they often fall short in fostering the core elements of mathematical thinking, such as

TABLE 12 Comparison of pretest-posttest and effect sizes for experimental and control groups in mathematical connection.

Connection Type	Experimental			Control		
	$\bar{X}$ Pretest	$\bar{X}$ Posttest	d	$\bar{X}$ Pretest	$\bar{X}$ Posttest	d
IC	1.175	2.541	1.89**	1.182	1.928	1.02**
CC	1.166	2.483	1.70**	.825	1.793	1.38**
SLD	2.000	2.550	.58*	1.619	2.095	.54
DLD	.750	2.450	1.68**	.428	1.642	1.29**
CR	1.183	2.600	1.45**	1.539	2.063	.45
ST	1.550	2.750	1.05**	1.952	2.428	.34
DT	.450	2.300	1.29**	.714	1.333	.45
EC	1.337	2.812	1.37**	1.345	1.892	.53*
CL	1.375	2.850	1.28**	1.666	2.047	.28
DL	.650	2.300	1.41**	1.238	1.428	.16
RL	2.100	3.400	.79*	2.095	2.666	.29
IDC	1.300	2.775	1.15**	1.023	1.738	.64*
NS	2.300	3.350	.61*	1.571	2.428	.45*
HCS	.300	2.200	1.58**	.476	1.047	.44*

*$p < .05$; **$p < .001$; IC, internal connection; CC, connection among concepts; SLD, same learning domain; DLD, different learning domains; CR, connection among representations; ST, same type; DT, different types; EC, external connection; CL, connection with life contexts; DL, daily life; RL, real life; IDC, interdisciplinary connection; NS, natural sciences; HCS, humanities and cultural studies; Main dimensions, IC, EC; Sub-dimensions, CC, CR, CL, IDC; Components, SLD, DLD, ST, DT, DL, RL, NS, HCS.

forming meaningful connections among concepts, making inferences, and applying knowledge flexibly (Rittle-Johnson et al., 2001). Therefore, the findings highlight the critical role of employing multiple representations, particularly dynamic tools such as animations, in supporting mathematical thinking and consequently enhancing students' mathematical connection skills.

On the other hand, when the findings are examined in terms of the main dimensions of mathematical connection skills, namely internal and external connections, and their corresponding sub-dimensions, it is observed that animation-supported instruction led to higher and more consistent improvements among students in the experimental group compared to their peers in the control group. In the sub-dimension of connection among concepts, animations facilitated students' recognition of hierarchical and logical relationships among mathematical concepts. In particular, connections among concepts constitute one of the cornerstones of mathematical thinking (Kuzu, 2017). Students in the experimental group exhibited markedly greater improvement in these dimensions than those in the control group. This finding suggests that animations help students integrate new knowledge with their existing cognitive structures and build conceptual bridges across different mathematical ideas. Therefore, animation-supported instruction can be regarded as an effective approach for understanding the spiral structure of mathematics and for establishing meaningful connections among concepts.

In the dimension of connection among representations, it was observed that students in the animation-supported instruction process were more effective in transitioning between same-type and different-type representations. Students were able to relate a mathematical concept through tables, graphs, and symbolic expressions, and by viewing different representations together, they were able to grasp the multidimensional nature of the concepts. This process allows students to view concepts from multiple perspectives and establish meaningful connections across representations (Kuzu, 2025). Consequently, students not only repeated information but also enhanced their mathematical reasoning and problem-solving skills by utilizing transitions among representations. This skill helps make abstract mathematical concepts more concrete and comprehensible, enabling students to gain conceptual depth and transfer knowledge to new situations (Ainsworth, 2008; Rittle-Johnson et al., 2015). At this point, the ability to transition and transform among representations directly supports students' mathematical connection skills. As students form connections between different representations and pieces of information, they both organize their internal knowledge structures and integrate new information with existing conceptual frameworks. Therefore, animation-supported instruction not only facilitates the learning of specific concepts but also strengthens students' ability to establish meaningful relationships among concepts and apply knowledge in different contexts. This interactive process demonstrates that mathematical connection and mathematical thinking are mutually reinforcing components of learning.

According to the findings, in the sub-dimension of connection with life context, animation-supported instruction enabled students to relate mathematics to daily life and real-life contexts. In particular, the progress observed in daily life contexts enhanced students' ability to use mathematics not only on paper but also in meaningful and functional ways. This directly supports students' mathematical connection skills, as they organize their knowledge and transfer it to new situations by relating concepts to life (Suardika et al., 2025). Moreover, animations help students render abstract concepts concrete and experiential, thereby integrating mathematical thinking with real-life applications (Kartika et al., 2025). The literature indicates that deficiencies in transferring mathematical knowledge and skills to daily life can hinder meaningful learning and negatively affect student performance (Kuzu et al., 2019). From this perspective, animation-supported instruction contributes to the development of mathematical connection skills by enabling students to actively apply knowledge in real-life contexts. Conducting lessons through technology, supporting daily life activities with technological tools, and using digital games with educational content contribute to increasing students' awareness of technology and promoting meaningful technology use (Kuzu and Sıvacı, 2018). This process allows students to relate their mathematical knowledge to both life and technological tools, thereby supporting the development of mathematical thinking and problem-solving skills.

The findings in the sub-dimension of interdisciplinary connection indicate that animation-supported instruction enhanced students' ability to relate mathematical concepts within both the contexts of natural sciences and the humanities and cultural studies. In the natural sciences component, although students' pretest scores were already high, significant improvement was observed in the experimental group. This suggests that animations enable students to utilize their existing knowledge more effectively across different disciplines and to develop the interdisciplinary aspects of mathematical thinking. In the humanities and cultural studies component, students initially started with low scores, yet the progress achieved through animation support was substantial. This finding demonstrates that students are not only learning mathematics in isolation but can also apply it in broader contexts by connecting it with different disciplines. The literature also emphasizes that students often fail to sufficiently develop their mathematical connection skills and encounter particular difficulties in establishing interdisciplinary links (e.g., Boaler, 2015; Rohaendi, 2020; Yaniawati et al., 2019). From this perspective, animation-supported instruction contributes to overcoming these deficiencies and supports students in developing their mathematical thinking in a more comprehensive manner (Kartika et al., 2025; Liu and Elms, 2019).

Students in the experimental group demonstrated higher and more consistent improvements across all dimensions and components of mathematical connection skills compared to the control group. These findings indicate that animation-supported instruction effectively enhances students' ability to form meaningful connections both within and across mathematical concepts, representations, and disciplines. In particular, students showed substantial progress in areas where initial competence was lower, such as interdisciplinary connections and humanities-related applications, suggesting that animations are especially effective in supporting growth in less developed domains. Even in dimensions and components where students began with higher baseline performance, improvements were observed, reflecting the reinforcing role of animations in consolidating prior knowledge. In contrast, while the control group also exhibited some development, their progress was generally less consistent and pronounced, highlighting the limitations of traditional instructional methods in fostering comprehensive mathematical connection skills. These results underscore the pedagogical value of integrating dynamic and visual representations into mathematics instruction to promote deeper conceptual understanding, flexible reasoning, and the transfer of knowledge to real-life and cross-disciplinary contexts.

Overall, the findings of the study indicate that animation-supported instruction is an effective approach for enhancing students' mathematical connection skills and, consequently, their mathematical thinking abilities. The consistent improvements observed across all dimensions and components among students in the experimental group, compared to those in the control group, suggest that animations contribute to learning by supporting conceptual coherence and strengthening transitions among representations and interdisciplinary connections. This can be explained by the capacity of animations to concretize abstract concepts and enhance students' ability to organize knowledge and transfer it to new situations. Therefore, the strategic use of animations in mathematics instruction not only facilitates the acquisition of mathematical knowledge but also significantly contributes to students' ability to relate this knowledge to life and other disciplines, as well as to develop problem-solving and critical thinking skills. Moreover, animation-supported instruction enabled substantial improvements in areas where students initially demonstrated low performance. This indicates that animations are particularly effective in promoting growth in domains where students show lower initial proficiency. In this context, animation-supported instruction can be regarded as a powerful pedagogical tool that both deepens the learning process and supports the sustainable development of mathematical thinking in mathematics education.

8 Limitations

This study has several limitations. First, the study was conducted with 41 pre-service teachers from a single public university. Therefore, the generalizability of the findings to broader samples and different institutional contexts is limited. Second, the study employed a quasi-experimental design based on intact classroom groups. Since random assignment to the experimental and control groups was not feasible, causal interpretations should be made with caution. Although pretest scores were considered and appropriate statistical procedures were used to reduce initial group differences, the absence of random assignment remains an important limitation. Third, the intervention lasted only four weeks; therefore, the long-term effects and retention of animation-supported instruction could not be examined. Future studies conducted with larger samples, multiple institutions, and longer implementation periods may provide stronger evidence regarding the effectiveness of animation-supported instruction. In addition, the instructional process focused specifically on the concept of derivative; therefore, the findings may be interpreted within the scope of this content area.

9 Recommendations

Based on the findings of this study, several recommendations can be made to guide both educational practice and future research. These recommendations encompass various stakeholders, including teachers, curriculum developers, the educational system and administrators, teacher education programs, and researchers, with the applicability and impact of each recommendation varying according to the role of the stakeholder.

Teachers, particularly when teaching abstract or complex concepts, may integrate animation-supported materials into their instructional processes. Animations can enhance students' engagement, help them focus, and support the establishment of meaningful connections between concepts. Such an approach may increase students' motivation and contribute to the development of their mathematical connection skills.

Curricula and textbooks can be designed to include animation-based instructional materials that support both internal (conceptual and inter-representational) and external (daily life and interdisciplinary) connection skills. The integration of such materials into educational programs may facilitate students' ability to construct mathematical knowledge holistically and apply it across different contexts.

For effective implementation of animation-supported instruction, strengthening the technological infrastructure within the educational system and improving teachers' competencies are essential. Educational administrators can support in-service training programs and make investments to facilitate schools' access to digital resources. This ensures that teachers can use animation tools effectively and that students' learning processes are adequately supported.

Pre-service and in-service teacher education programs should not only focus on the technical use of animation tools but also on pedagogical strategies for their effective application. They can be provided with hands-on experiences to explore how animations can enhance students' mathematical thinking and connection skills.

Future research may examine the long-term effects of animation-supported instruction on mathematical connection skills. Moreover, studies can investigate its outcomes across different educational levels and compare the effectiveness of animation-supported teaching with other digital learning tools such as simulations, augmented reality, or virtual reality. Mixed-methods research, combining quantitative and qualitative approaches, may provide more comprehensive and in-depth insights into this area.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by this study was conducted in accordance with the Declaration of Helsinki and its later amendments. Ethical approval was obtained from the Ethics Committee of Kirsehir Ahi Evran University, Türkiye (Reference No: 2021-5). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

OK: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. ZT: Data curation, Writing – original draft, Writing – review & editing.

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