International Journal of Technology and Design Education
https://doi.org/10.1007/s10798-025-09989-8

Effects of a design-based research approach on fourth-grade students' critical thinking, problem-solving skills, computational thinking, and creativity self-efficacy

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Accepted: 24 April 2025

Abstract
This study examined the effectiveness of a design-based research approach in developing fourth grade students' critical thinking, problem solving, computational thinking, and creative self-efficacy skills. Although previous research has shown how design-based inquiry promotes higher-order thinking among middle and high school students. There is no comprehensive research supporting rural primary school students with this approach. Therefore, this study fills this gap by investigating design-based research (DBR) that can lead students to develop twenty-first century skills through primary science teaching. A quantitative pre-post-test design method was used to collect data over a 7-week period from 431 fourth grade students from two rural schools in Türkiye. Findings showed that the design-thinking model was effective. The findings showed a significant improvement in critical thinking and creative self-efficacy. The effect on problem solving skills and computational thinking was negligible.

Keywords Design thinking · Critical thinking · Problem-solving skills · Computational thinking · Creativity self-efficacy

Introduction

In today's rapidly developing world, twenty-first century skills such as critical thinking, problem solving skills, computational thinking and creativity are gaining importance in all sectors of education (Aflatoony et al., 2018; Luka, 2019). These skills are not only

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Published online: 08 May 2025

necessary for academic success. It is gradually being realised that these competences are essential for one's success in a complex competitive global environment (Guzey & Jung, 2021). Educational systems are challenged to develop competences of students through innovative ways of teaching, which go beyond the traditional. It is therefore looking for ways that can improve students'learning and allow them to develop such twenty-first century skills.

The concept of twenty-first century skills' has gained importance in education as skills that are considered essential for success in the modern era (Kennedy & Sundberg, 2020). The integration of digital skills with twenty-first century skills is particularly important in the knowledge economy and seven core skills have been identified: technical, knowledge management, communication, collaboration, creativity, critical thinking and problem solving (Van Laar et al., 2017). Although there is general agreement on importance of twenty-first century skills, there remains debate about implement and assess these skills in education (Kennedy & Sundberg, 2020; Koenig, 2011). DBR and integrated STEM education have emerged as approaches for developing twenty-first century skills in students. Research shows the implementation of DBR suited to develop such skills, especially if other parameters such as learning objectives, teacher role, and design brief are included (Scheltenaar et al., 2015). Further improvements are needed to produce classroom-ready content to readily support teachers in making DBR materials (Taconis et al., 2018).

Some researchers argue that students should be trained to think like designers (especially doing project-based work in schools), as this will boost creativity among students and help them understand the innovation process (Brown, 2008; Martin, 2009). Among these approaches, DBR, which focuses on iterative learning through real-world problem-solving and active engagement, has emerged as a powerful strategy (Brenner et al., 2016). DBR requires children to think and consider a problem from different aspects. DBR has not any right/wrong answers. However, it has a solution and or solutions that meet the user's needs. This type of learning is best achieved by using student-centred active learning strategies (e.g. peer teaching/discussion; problem and case-based learning; peer tutoring; team-based learning and inquiry-based learning) (Gormally et al., 2009). DBR affirms the active engagement of students in the learning process by the design of solutions to complex problems, which imparts skills of great importance, in keeping with the new educational paradigm (Panke & Harth, 2019).

Beligatamulla et al. (2019) examined the pedagogical applications of DBR in different educational settings, emphasizing its role in developing creativity and problem-solving skills. Papavlasopoulou et al. (2019) used DBR to investigate constructivist-based coding activities for children. Beligatamulla et al. (2019) researched DBR applications and their implementation within various educational frameworks to foster creativity and develop problem-solving approaches. Ladachart et al. (2023) investigated the impact of DBR in developing secondary school students'creative self-confidence and reflective thinking. Zhu et al. (2025) state that it is important to use design thinking in the development of teaching and learning curricula for primary schools to prepare students to work in the twenty-first century workforce. Cochrane et al, (2023) suggested that studies should examine DBR in student learning in the long term. However, there is insufficient research in the literature addressing how DBR affects the critical thinking, computational thinking, and creativity of elementary school students in the context of science education, particularly in under-resourced or socioeconomically disadvantaged settings. This study evaluates the effectiveness of a DBR approach in developing fourth grade students'critical thinking, problem solving, computational thinking and creative self-efficacy skills. We investigated changes on these variables before and after DBR intervention. By assessing these competences, we investigated whether DBR improves basic cognitive and creative abilities in primary school students. The findings of the study will contribute to the integration of DBR and twenty-first century skills in primary education.

Context and background

As a developing country, Türkiye is making changes to education as a means of improving economic and social mobility. However, there are significant differences between different regions, (e.g. Between urban centers and rural) or socioeconomically disadvantaged areas (Çiftçi & Cin, 2018). The province of Muş, where this study was conducted, is located in eastern Türkiye. It has a predominantly rural and low socioeconomic population (BEBKA, 2017). Economic conditions in this region are below the national average (BEBKA, 2017). Access to technology-based educational tools is limited for many students. Most of the students in the participating schools come from families with low socioeconomic status, where parents'education level is limited to primary school. This poses a challenge in equipping students with essential twenty-first century skills such as computational thinking and problem solving. It is conceivable that lack of educational resources, coupled with cultural and linguistic differences, often leads to lower academic performance and reduced self-efficacy in creative and computational skills. This research is all the more important as it aims to examine whether a design-based research approach can bridge educational gaps for children in under-resourced schools.

Literature review

Design-based research

With rapid global developments in the field of technology, design thinking becomes increasingly important. To be successful in today's competitive and technological environment, individuals are expected to possess a variety of modern skills. In science curricula designed to help students find solutions to the problems they encounter in daily life, twenty-first century skills and science literacy are commonly referenced. Guzey and Jung (2021) reported that both in-class and out-of-class educational activities are utilized by schools to increase students' science literacy levels and design skills. Thus, the development of students' design thinking skills is an important topic of interest in educational research (Panke & Harth, 2019; Tran, 2019). Beligatamulla et al. (2019) described the recent emphasis on the pedagogical use of design thinking in educational processes. However, according to Koh et al. (2015), more research that is extensive is needed on students' realization of learning experiences based on design thinking with specific contents and tasks.

Critical thinking

Critical thinking is the ability to think reflectively and independently. The research points out to critical thinking as processes that include conceptualizing, applying, analyzing, synthesizing and evaluating information to arrive at a judgment (Facione, 2011). Critical thinking emphasizes such other skills: interpreting arguments, reasoning for and against a premise and making decisions through logical evidence (Paul & Elder, 2019). The basic components of critical thinking discussed in the literature include analytical thinking (Ennis, 2018), inference (Lai, 2020), explanation (Paul & Elder, 2019), self-regulation and evaluation (Halpern, 2019). Researchers state that promoting critical thinking is important for the development of informed citizens who can make reasoned decisions (Abrami et al., 2015). Critical thinking is also important for students to deal with academic challenges (e.g., identifying and evaluating hypotheses; explaining and interpreting ideas; generating arguments and analyzing different types of arguments, evaluating and making decisions, drawing inferences, etc.) and real-world problems, and has been associated with improved academic performance across disciplines (Fisher, 2020). Such skills are also implied as ways to empower students as they can discern trustworthy information easily (Pithers & Soden, 2010). Various pedagogical approaches concerning inquiry-based and problem-based learning were proposed as able to teach students critical thinking effectively (Jonassen, 2019; Lee, 2020). Good critical thinkers can identify the pertinent problems easily, evaluate several options and implement solutions (Sternberg, 2019). Critical thinking, more and more, is getting associated with creativity, for in it one must discover new solutions (Runco, 2018).

Problem-solving skills

Problem-solving skills reflect the ability of individuals to identify the problems they face, produce solutions, evaluate alternatives, and apply the most appropriate solution. Recent research emphasizes the cognitive, affective, and behavioral elements of problem-solving skills (Jonassen, 2019). Problem-solving skills are also critical for students' academic success and future career success. Such abilities facilitate all individuals in coping with the ambiguity of a problem situation, not to mention treating it more effectively and flexibly (Mayer & Wittrock, 2020). Emphasis on teaching problem-solving skills in education is growing. These include efforts directed toward problem-based learning, project-based learning, and various modes of training and interventions teaching thinking and reasoning skills (Nickerson, 2019; Savery, 2015). Varieties of strategies have been put forward to promote the development of problem-solving ability. Among them, reflective thinking and self-assessment are particularly significant when applying them to the teaching process (Kuhn, 2019). The collaborative learning environment also enhances the development of problem-solving skills of students, allowing them to interact with each other (Johnson & Johnson, 2020).

Computational thinking

Computational thinking allows individuals to approach and solve problems by a commonly shared repertoire of cognitive skills, including abstraction, algorithmic thinking, decomposition, pattern recognition, and debugging (Wing, 2017). Computational thinking as a pedagogical approach equips students, in science educators, with an organized methodology to approach scientific problems by using concepts borrowed from computer science to model, simulate, and analyze complex systems (Weintrop et al., 2019). Under this approach, reasoning and systematic thinking render students capable of adopting the right mindset that will assist them in pursuing careers in the STEM areas (Grover & Pea, 2018). The integration of computational thinking into science education is a growing area of interest for educators and researchers exploring how best to embed computational thinking creatively into the context of science curricula. Recent studies have suggested that it can actually be done through modeling and simulation, data analysis, and algorithmic thinking. Computational models allow students to simulate scientific, explore, and test hypotheses (Imbert, 2017). They build computational thinking skills by analyzing large datasets and trying to identify patterns and derive scientific conclusions (Lee et al., 2020). Students develop step-by-step solutions to scientific problems by utilizing algorithmic processes that guide experiments and investigations (Basu et al., 2017). Researchers espouse intertwining computational thinking with conventional scientific topics to grant a view of both great fields (Shute et al., 2017). Assessing computational thinking within science classes is somewhat difficult and encompasses measuring not only the students'comprehension of the principles of computational thinking. In performance-based assessments, these skills converge multiple task completions-skilling coding projects, simulations, or data analysis and appraisal of students'computational thinking. Rubrics and frameworks developed to standardize the assessment of computational thinking across different scientific disciplines can ensure consistency and comparability (Shute et al., 2017). Curricula are difficult to infuse with computational thinking meaningfully, all while being considerate of existing science standards (Brennan & Resnick, 2012). Another significant burden for education is ensuring that all students receive enough support and resources to develop these skills, regardless of those students'backgrounds (Imbert, 2017).

Creativity self-efficacy

Creative self-efficacy refers to individuals' belief in their competence in creative processes and this concept has an important place in educational environments. However, there are difficulties in including creative thinking in educational environments regardless of the field (Patston et al., 2021). Science curricula prepared in recent years offer various opportunities for creative thinking (De Haan, 2011). In Türkiye, science curricula are being designed to increase students' creative thinking (Ministry of National Education [MoNE], 2018). Especially in the context of science education, creative thinking skills play a critical role in increasing students' success in scientific processes. Research in creative thinking reveals that creativity depends on number of variables (Willemsen et al., 2020). Studies examining the relationship between creative self-efficacy and scientific problem-solving skills in the context of science education showed that students'interaction with creative tasks in science lessons strengthened their self-efficacy perceptions in this area (Orakci, 2023).

Research theory

Dual- coding theory is a learning theory developed by Allan Paivio (1991) which proposes that, visual and verbal representations must be utilized for better learning and retention. The theory stipulates that, people process information through two systems that are separate yet dependent. A visual (image) system and a verbal system (language). Information is better encoded, remembered, and utilized when it is processed through both systems. In DBR, students need both visual and verbal information to solve the problems they face. Critical thinking skills are based on students' abilities to analyze, evaluate, and draw conclusions from information. Dual coding theory can support critical thinking by helping students process events both visually and verbally. Computational thinking includes the processes of creating algorithms, pattern recognition, modeling, and problem-solving. During design-oriented activities, students develop their computational thinking skills with both graphics (modeling and the visualization of algorithms) and verbal explanations.

According to dual coding theory, when students access information through these two different systems, they can process information more easily, recognize algorithms or patterns more effectively, and generate solutions. Creativity is often fueled by a combination of visual and verbal elements. In design-oriented processes, students produce creative solutions using both verbal and visual elements. In our research, most of the materials used during design-oriented activities contain both visual and verbal elements. For example, in the process of solving a scientific problem, students will visualize the experimental results through graphs and verbally explain those results. Using dual-coding strategies to develop students'critical thinking, problem-solving, and creativity can provide an effective learning process. The students learn by linking both visual and verbal information, thus overcoming the limitation of single-source information. It also makes the information somewhat permanent.

Gaps in the literature and the importance of the present research

Despite an increasing emphasis on twenty-first century skills such as critical thinking, problem-solving, computational thinking, and creativity, a limited literature discusses how these skills develop within primary students through DBR methods. Most studies focus on integrating DBR in higher education and its performance effects on adult learners (Brenner et al., 2016; Guzey & Jung, 2021); only a few studies examine the effect on students at the primary school level and preferentially on middle and high schooling as opposed to elementary school (Koh et al., 2015). That created a void in understanding how DBR can leverage younger learners, especially in socioeconomically diverse or low-resourced settings (Panke & Harth, 2019). Moreover, most studies have investigated the impact of DBR on specific cognitive domains, such as problem-solving or creativity, without addressing the connection of these skills to critical thinking and computational thinking. There can be found no comprehensive studies examining how DBR develops these basic skills in elementary school students in the context of science education. It has been realised that the potential of DBR to foster multiple competences such as critical thinking, problem-solving, computational thinking, and creative self-efficacy at the same time has not been investigated in detail.

We conducted a systematic review using databases such as ERIC, Scopus, Web of Science and Google Scholar to identify studies on DBR. Search keywords were'Design-Based Research','DBR in primary education','critical thinking','computational thinking','creativity self-efficacy', and'problem-solving skills in primary schools'. We focused on studies published between 2010 and 2023 for more trends illustrating recently published studies. The number of publications in secondary and higher educational frameworks, although much impressive, is relatively few in studies attended to primary sciences education pupils. This gap is consistent both globally and in Turkey and reinforces the conclusion that the impact of DBR on young learners is under-researched.

This study was carried out in two schools in Muş that is located eastern of Türkiye. The socio-cultural and socio-economic status of the students can be said that they are under the country's average. In line with this information, we can state that these students cannot easily access to technology-based tools at their home, most of them do not have their own personnel computers, lack of private courses and most of their parent's educational statue is primary school. This shows us that those students have not required opportunities to equip themselves with twenty-first century skills. The present study aims to address these gaps by examining the effects of a DBR approach on fourth-grade students' critical thinking, problem-solving skills, computational thinking, and creative self-efficacy. Research suggests that DBR can be beneficial for preschool-aged children, especially through explorative, problem-solving, and hands-on activities (Dorie et al., 2014; Gonzalez & Kuenzi, 2012). It is evident, however, that structured practice in grades early in elementary school (6–9 years), when students are developing the basic cognitive and metacognitive skills for reflective thinking and problem solving, has shown more quantifiable results. According to Noel and Liu (2016), few papers specifically cover design education at the elementary level. This study focuses on fourth-grade students, who also exhibit higher-order thinking abilities that DBR can promote at the ages of 9–10. Further research is needed to explore how DBR affects even younger students and how developmental stages influence its effectiveness.

DBR appears to present an opportunity for a new paradigmatic implementation, spanning design-based learning integrations that foster sure general skills such as innovation, curiosity, critical thinking, empathy, collaboration and facilitation. The research contributes to the understanding of how early exposure to design-based learning can support the development of basic cognitive and creative skills that are important in the modern educational environment. The results of the research may help educators design more targeted interventions for elementary school students by providing insight into the effectiveness of DBR in developing these key skills at an early age. The importance of this research lies in its potential to influence how educators approach the teaching of twenty-first century skills in primary education. As education systems increasingly prioritize the development of critical and creative thinking, it is crucial to explore methods that can effectively nurture these skills from an early age. To achieve this, teachers can use various strategies during the learning process, such as fostering a growth mindset, creating a collaborative learning environment, using real-world problems, providing a safe space for experimentation, and offering opportunities for reflection.

Research questions

The present study was conducted to answer the following research questions:

1. How do critical thinking, problem-solving skills, computational thinking, and creative self-efficacy levels change among fourth-grade students after a DBR intervention?
2. How effective is the DBR approach in developing fourth-grade students' critical thinking, problem-solving, computational thinking, and creative self-efficacy skills?
3. What role does the DBR process play in the development of students' skills in the areas of critical thinking, problem-solving, computational thinking, and creative self-efficacy?

Method

In this study, a pre-test/post-test experimental design without a control group was used among quantitative methods. This design is widely used to evaluate the effects of specific interventions or training programmes. Pre-test (before the intervention) and post-test (after the intervention) measurements are made for an experimental group (Fraenkel et al., 2012). In studies conducted without control groups, assuming that the observed changes are only due to the intervention process may create limitations. However, important information about the effect of the intervention can be obtained by comparing the pre-test and post-test scores of the participants.

Participants

The participants of this study consisted of 431 students (220 for the pretest and 211 for the posttest) from four classrooms within two primary schools. All participants were enrolled in the fourth grade (Fig. 1).

Research process

A series of steps were followed before beginning the research process. First, ethics committee approval was obtained. Research permission was subsequently obtained from the Ministry of National Education. Two schools were selected for conducting the research and a purposive sampling approach was applied for data collection. The two schools participating in the research had a combined 12 fourth-grade classes. The research was carried out with nine teachers who were willing to participate. Teachers were given preliminary information about the DBR process and then documents on design-related workshops for schoolchildren developed by the Scientific and Technological Research Council of Türkiye (TUBITAK) were distributed for use in the teachers' classrooms (https://tubitak.gov.tr/sites/default/files/25506/tasarim_ve_uretim_ortaokul.pdf). From among the possible documents, the researchers considering that it would be suitable for the age group of the students selected an activity named "Journey in My Imagination".

The implementation of the research lasted 7 weeks. The pretest was conducted in the first week. The second week entailed an introduction to design thinking and empathy, the third week was devoted to describing identification, the fourth week involved idea generation, the fifth week was dedicated to prototyping and test generation, and the sixth week-entailed evaluation of test results and production planning. The post-test was conducted at the end of the seventh week. Written permission was obtained from the

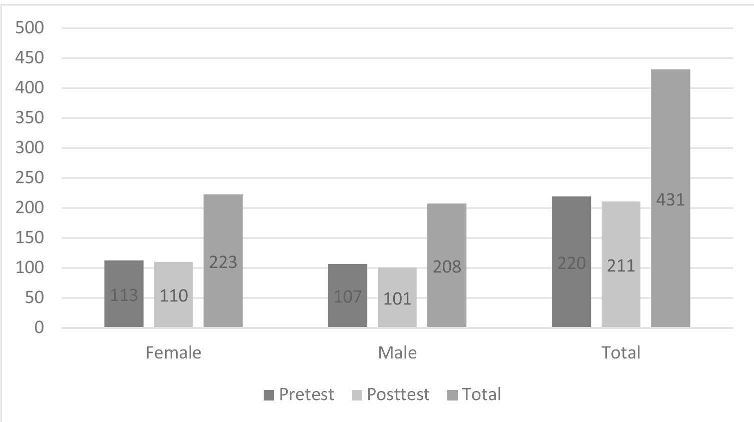


Fig. 1 Gender distribution of pretest and posttest participants

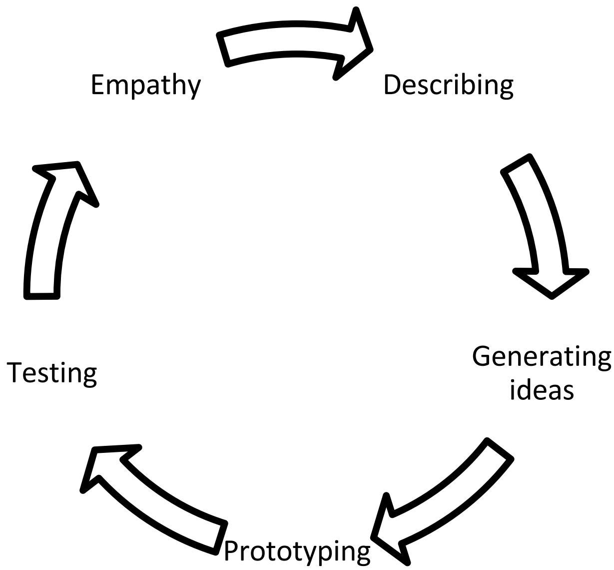
parents of the students participating in the research. The researchers visited the classrooms during the research process and monitored the activities.

Figure 2 illustrates the design thinking process, a framework used for creative problem-solving, especially in fields such as education, business, and product development. In the present study, the design thinking model (Carroll, 2015) was adopted as a pedagogical framework in the process of applying the design thinking approach because this model provides students with a continuous iteration process between different stages, allowing them to develop their final product. The stages in this model are as follows: 'Empathy' is the stage of needing to interact with users or audiences to identify their real problems. This is critical for ensuring that the solutions produced are relevant and human-centered (Brown, 2009). 'Describing' involves analyzing the information gathered in the empathy stage and translating it into a clear, actionable problem statement (Buchanan, 1992). The 'Idea Generation' step constitutes a brainstorming session in which multiple solutions to the identified problem are proposed (Kelley & Kelley, 2013). 'Prototyping' is the stage in which concepts are transformed into physical or digital representations that can be tested (Martin, 2009). Finally, 'Testing' refers to an iterative process whereby the solution is evaluated based on user feedback, helping to refine and improve the prototype (Brown, 2009).

Data collection tools

Within the scope of the study, DBR intervention was applied to fourth grade students and the 'Critical thinking scale', 'Problem solving inventory for children', 'Computational thinking scale' and 'Creativity self-efficacy scale' were used to determine how the students' critical thinking, problem solving skills, computational thinking and creative self-efficacy levels changed, how effective the intervention was and what role it

Fig. 2 Design-based research process



played. Cronbach alpha values were taken into consideration to measure the internal consistency of the scales used. According to Shemwell et al. (2015), Cronbach alpha reliability coefficient values between 0.70 and 0.95 are acceptable.

Critical Thinking Dispositions Scale: This scale was developed by Uluçınar and Akar (2021). It contains a total of 18 items within four subscales: skepticism, curiosity, open-mindedness, and objectivity/bias. The items of the scale are scored on a four-point Likert-type scale (1 = "never," 4 = "always"). The Cronbach alpha reliability coefficient of the scale was found to be 0.81.

Problem Solving Inventory for Children: Data were collected with the Problem Solving Inventory for Children (PSIC) developed by Serin et al. (2010) to evaluate problem-solving skills. The inventory comprises 24 items within the three factors of confidence in problem-solving skills (12 items), self-control (7 items), and avoidance (5 items). When validity and reliability testing of the PSIC was conducted, the Cronbach alpha reliability coefficient was found to be 0.86 and it was stated that all factors of the scale were reliable (Serin et al., 2010).

Computational Thinking Scale: Yıldırım and Uluyol (2023) developed this scale, with one dimension. When the results of exploratory factor analysis were reviewed, it was seen that the factor loadings of the 17 items of this scale varied between 0.56 and 0.86. The Cronbach alpha coefficient of the scale was found to be 0.92.

The Creativity Self-Efficacy Scale: Scale was developed by Koç (2021) to evaluate creative self-efficacy in elementary school students. As a result of exploratory factor analysis, the Cronbach alpha coefficient of the scale was found to be 0.70. The scale consists of 10 items within one factor and all items are scored with a 3-point Likert-type scale as "Suits me," "Suits me a little," or "Does not suit me."

Analyzing the data

The data obtained from the pretest and posttest were analyzed using IBM SPSS Statistics 22.0. First, the data were analyzed for homogeneity.

Table 1 shows the results of the Shapiro–Wilk test performed to evaluate the conformity of the pretest and posttest results to the normal distribution. This test is important to determine the appropriate methods to be used in statistical analyses of the data. According to the results of the Shapiro–Wilk normality test, the critical thinking scores were normally distributed for both the pretest and posttest (Table 1). This confirmed that parametric tests could be used for the variable of critical thinking. However, for problem-solving skills, the pretest scores showed normal distribution but the posttest scores deviated from normal distribution. The variables of computational thinking and creative self-efficacy also failed to

Table 1 Normality test results

	Pretest		Posttest		Pretest	Posttest	Pretest	Posttest
Measure	Statistic	*p*	Statistic	*p*	Skewness	Skewness	Kurtosis	Kurtosis
Critical thinking	0.99	0.43	0.99	0.17	0.07	0.1	−0.22	−0.4
Problem-solving skills	0.99	0.23	0.98	0.01	−0.27	0.45	−0.14	0.43
Computational thinking	0.98	0.00	0.98	0.01	−0.41	−0.41	−0.16	0.18
Creative self-efficacy	0.97	0.00	0.97	0.00	−0.51	0.23	0.97	−0.49

meet the assumption of normal distribution in the pretest or posttest. Therefore, skewness and kurtosis values were analyzed. George and Mallery (2010) stated that skewness and kurtosis values between +2.0 and −2.0 are acceptable. It can be concluded that all data of the present study are normally distributed because all skewness and kurtosis values fall within that range. After the application of parametric tests, t-tests and analysis of variance (ANOVA) were conducted. For the first research question, a boxplot was used to visualize the difference between pretest and posttest results. For the second research question, the independent sample t-test was used. ANOVA was used for the third research question.

Validity and reliability

The pre-test and post-test administered to the participants are the main instruments used to assess the research questions of this study. The internal validity of a study reflects whether the tests administered actually measure the effect of the intervention. The presence of significant differences between the pre-test and post-test results supports the conclusion that the effect of the intervention was accurately measured. However, the absence of a control group is a limitation affecting internal validity. Assuming that participants changed only as a result of the intervention may reduce internal validity. Since the study was limited to the data obtained from two schools, it also has some limitations in terms of external validity. External validity reflects the generalisability of findings from a study to other settings or different groups of participants. Therefore, it was important to determine how well the instruments selected in this study measured the concepts of critical thinking, problem solving, computational thinking and creativity. To ensure the construct validity of these instruments, previously developed and validated scales were used. The construct validity of the scales contributed to their ability to accurately measure the concepts of interest. The reliability of the measurement tools was tested with Cronbach's alpha coefficient. The reliability coefficients of the scales were above 0.70, confirming their internal consistency.

Findings

Changes in levels of critical thinking, problem-solving, computational thinking, and creative self-efficacy

Figure 3 shows the changes in students'critical thinking, problem-solving skills, computational thinking and creativity self-efficacy levels before and after the design-based research (DBR) approach. In the critical thinking results, there is a noticeable increase in the post-test. This situation reveals that students have shown a significant improvement in their analyzing, questioning and evaluating skills with the DBR process. Problem solving skills remained almost at the same level between the pre-test and post-test, indicating that DBR had a limited effect on this skill. A significant increase was observed in creativity self-efficacy scores. This increase reveals that DBR activities were effective in increasing students'creative thinking capacities and strengthening their confidence in own creative potential. While there were differences between the pretests and posttests for critical thinking and creative self-efficacy, there were no significant changes for problem-solving and computational thinking.

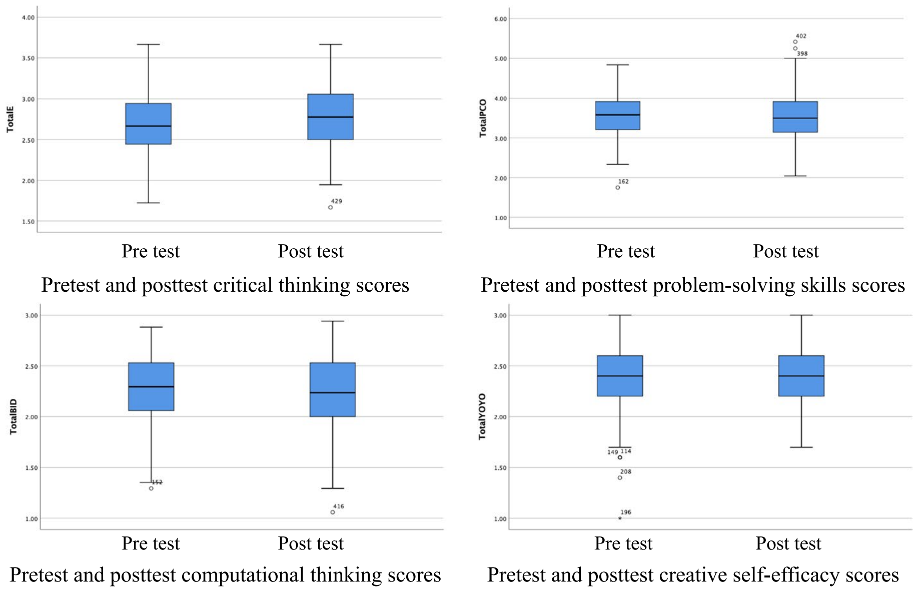


Fig. 3 Changes in critical thinking, problem-solving skills, computational thinking, and creative self-efficacy levels

Effectiveness of the design-based research approach

Table 2 shows the means, standard deviations, t-test results and Cohen's d effect size values of the critical thinking, problem-solving skills, computational thinking and creativity self-efficacy scores of the students before and after the DBR intervention. A significant increase was observed in Critical Thinking scores. DBR fosters students'analytical thinking and questioning skills. In Creativity Self-Efficacy scores, process leads to students feeling more creative and to be more productive. This increases students'confidence in generative processes. No significant change was observed in Problem-Solving scores. This serves as a pointer that structured applications are more needed to develop their problem-solving skills. There was no significant change in Computational Thinking scores before and after the DBR intervention, indicating possible slow growth in this regard requiring more practice and guidance over a timeframe.

Table 2 Comparison of pretest and posttest critical thinking, problem-solving skills, computational thinking, and creative self-efficacy scores

	Pretest		Posttest		*t*	*p*	Cohen's d
Measure	Mean	SD	Mean	SD			
Critical thinking	2.68	0.39	2.78	0.4	−2.84	0.00	0.27
Problem-solving skills	3.57	0.52	3.57	0.55	−0.03	0.98	0.00
Computational thinking	2.28	0.32	2.26	0.35	0.66	0.51	0.06
Creative self-efficacy	2.36	0.32	2.43	0.3	−2.05	0.04	0.2

Table 3 Mean and standard deviation values of students' combined scores for critical thinking, problem-solving, computational thinking, and creative self-efficacy

	N	Mean	SD
Critical thinking	431	2.72	0.39
Problem-solving skills	431	3.56	0.53
Computational thinking	431	2.27	0.33
Creative self-efficacy	431	2.39	0.31

Table 4 Repeated-measures ANOVA for different test cases

Source		Type III sum of squares	df	Mean square	*F*	*p*	η_p^2
Design	Sphericity assumed	460.349	3	153.450	1529.695	0.000	0.781
	Greenhouse–Geisser	460.349	2.567	179.309	1529.695	0.000	0.781
	Huynh–Feldt	460.349	2.584	178.147	1529.695	0.000	0.781
	Lower bound	460.349	1.000	460.349	1529.695	0.000	0.781
Error (design)	Sphericity assumed	129.405	1290	0.100			
	Greenhouse–Geisser	129.405	1103.960	0.117			
	Huynh–Feldt	129.405	1111.162	0.116			
	Lower bound	129.405	430.000	0.301			

* $p < 0.05$

Role of the design-based research process in students' development of critical thinking, problem-solving skills, computational thinking, and creative self-efficacy

Table 3 shows the mean scores and standard deviations of the students in the areas of critical thinking, problem solving skills, computational thinking and creativity self-efficacy. The critical thinking and creativity self-efficacy scores show a general increasing trend among the students. The finding shows the supportive effect of DBR on critical analysis and creative thinking processes. The low standard deviations indicate that this development is consistent among students. No significant difference was found in the mean scores of problem solving and computational thinking. This finding means that DBR was not sufficiently effective in influencing the development of these skills. Standard deviations are relatively large. This means that the skills differ among the students. This suggests that some students may perform better individually, but still not developed enough to generalise.

Table 4 presents the results of repeated measures ANOVA (Analysis of Variance) to assess the change in students'critical thinking, problem solving skills, computational thinking and creativity self-efficacy skills. Analysis was used to measure the overall effect of the DBR intervention on skill development. The results are statistically significant due to the very high F value provided in Table 4 and *p* value which is below 0.05. This shows that the impact of DBR on skills development by students was worth noting. There had been spectacular improvements of self-efficacy skills in critical thinking and creativity. The results support that DBR strengthens students'intellectual and creative processes. Eta square (η^2) value was high. The indicates that DBR explains a large part of the change in skill development. In other words, the DBR process is a strong determining factor in skill development. Although the change in problem-solving and computational thinking skills is statistically significant, the effect size is lower. This indicates that DBR is not sufficient to support these skills and more structured interventions are needed.

The assumption of sphericity is important in repeated measures analysis. Sphericity is violated when the variances for all differences between the combinations of groups of interest (in this case, pre- and post-test scores) are not equal. This is an assumption fundamental for repeated measures ANOVA validity testing. Mauchly's Test of Sphericity tests this assumption. A significant Mauchly's test ($p < 0.05$) indicates the violation of the sphericity assumption, which means the variances of the differences are not equal. Such a violation of sphericity may threaten the very nature an validity of ANOVA results, pushing toward an incorrect conclusion. When sphericity is violated, researchers may apply adjustments such as Greenhouse–Geisser or Huynh–Feldt to adjust for this violation of variances. These adjustments provide corrections in degrees of freedom, making the statistical tests more precise with incalculably fewer chances of Type I errors.

Table 5 presents the results of Mauchly's test of sphericity. Mauchly's W value was calculated as 0.784 at $p < 0.05$, indicating that the assumption of sphericity was violated. In other words, the variances between measurement groups are not equal. Therefore, we applied the Greenhouse–Geisser correction to ensure the robustness of our results. The Greenhouse–Geisser epsilon value is 0.856 and the Huynh–Feldt epsilon value is 0.861. After the corrections, it shows that the effect of DBR on skill development is still statistically significant. This confirms that the effect of DBR is robust and reliable.

The results of pairwise comparison with Bonferroni correction are shown in Table 6. The analysis was conducted to compare the effect of the DBR intervention on students'skill development at various stages of the test. The Bonferroni type is to reduce experimental error in multiple comparisons. According to the table, statistically significant differences were found between all compared measures ($p < 0.05$). This finding shows that the DBR process is effective at different stages of students'skill development. In particular, significant positive differences were observed between the pre-test and post-test. This supports that DBR led to significant improvements in students'skills such as critical thinking and creativity self-efficacy. Mean differences indicate the extent of improvement. The fact that the highest difference was in the areas of critical thinking and creativity shows that these skills were more affected by DBR. Although significant differences were also observed in Problem Solving and Computational Thinking. The size of the change was smaller. This indicates that more structured supportive activities may be needed for the development of these skills. The results show that DBR has a significant impact on the development of students'cognitive and creative skills. Especially the improvements in critical thinking and creativity are remarkable. Findings confirms that DBR is an effective method to support innovative thinking processes.

Table 5 Mauchly's test of sphericity

Within-subjects effect	Mauchly's W	Approx chi-square	df	*p*	Epsilon		
					Greenhouse–Geisser	Huynh–Feldt	Lower bound
Design-based	0.784	104.175	5	0.00	0.856	0.861	0.333

Table 6 Bonferroni post hoc pairwise comparison of significant differences in design scores for four different tests

(I) Design-based	(J) Design-based	Mean difference (I—J)	Std. error	Sig.[b]	95% confidence interval for difference[b]	
					Lower bound	Upper bound
1	2	−0.840*	0.024	0.000	−0.903	−0.776
	3	0.501*	0.020	0.000	0.448	0.553
	4	0.335*	0.018	0.000	0.288	0.383
2	1	0.840*	0.024	0.000	0.776	0.903
	3	1.340*	0.025	0.000	1.273	1.407
	4	1.175*	0.024	0.000	1.112	1.238
3	1	−0.501*	0.020	0.000	−0.553	−0.448
	2	−1.340*	0.025	0.000	−1.407	−1.273
	4	−0.165*	0.017	0.000	−0.211	−0.120
4	1	−0.335*	0.018	0.000	−0.383	−0.288
	2	−1.175*	0.024	0.000	−1.238	−1.112
	3	0.165*	0.017	0.000	0.120	0.211

Discussion and conclusions

This study examined the effectiveness of DBR on fourth grade students'critical thinking, problem solving, computational thinking and creative self-efficacy skills. The impact of the DBR approach on students'cognitive and creative abilities shows some similarities and some differences with previous researches in the literature. Abrami et al. (2015) stated that inquiry-based learning environments might foster the development of critical thinking. Identical to this, the flow of creativity self-efficacy converges with Kaufman and Beghetto's (2020) research on the need for structured designing in enhancing students'creative confidence DBR was found to be an effective approach to support critical thinking and creativity. The evidence supports Principal and Elder's (2019) claim that active questioning and reflective practice strengthen critical thinking. The development of creativity self-efficacy helped students to increase their confidence in the process of generating ideas. Runco (2018) corroborated the findings by stressed the importance of student autonomy therein a creative processing. The improvement in critical thinking and creativity achieved through DBR is consistent with previous research emphasizing the capacity of DBR to support higher-order thinking skills (Koh et al., 2015). DBR may have supported this skill by providing the opportunity to develop ideas through trial and error. However, at the same time, its shortcomings in the ability to develop more procedural or technical skills such as computational thinking should not be overlooked (Panke & Harth, 2019; Tran, 2019). The expected improvement in problem solving and computational thinking skills was not observed. The limited development observed in problem solving and computational thinking skills is consistent with Mayer and Wittrock (2020), who emphasized the importance of structured guidance and hands-on activities for the development of problem solving skills. The results reveal that DBR is a powerful tool in creative processes, but additional support is needed for technical skills. According to Halpern (2019), the skills of critical thinking lead students to make such decisions in their daily lives. The development observed in creativity allows students to develop more flexible and innovative approaches in problem solving processes. On the other hand, the limited change in problem solving and computational thinking supports the findings of Shute et al. (2017) that computational thinking requires constant feedback and repetition for development. This suggests that the learning environment provided by DBR should be strengthened with complementary strategies for specific skills. Other suggestions include other instructional strategies and the establishment of structured support mechanisms for the further consolidation of technical skills.

The results of this study were evaluated in the context of Dual Coding Theory. In the DBR process, students used both visual materials (drawings, prototypes) and verbal explanations. When these two coding systems are used together, learning becomes more permanent. This method is thought to be especially effective in critical thinking and creativity. During the DBR applications, students analysed, discussed and evaluated the problems. In this process, thinking skills were supported with both written and visual data. During the idea generation and prototyping stages, students developed creative solutions through drawing, sketching and narration. The visual-verbal interaction contributed to students seeing themselves as creative. These skills require more systematic and algorithmic thinking. Although the DBR process provided visual-verbal support, there may not have been sufficient repetition and structured guidance in these areas. Dual coding theory can be effective in these areas, but additional support is necessary.

The main focus of this study is on students in socio-economically disadvantaged regions and rural areas. Students in these areas face numerous challenges. Low access to technology, poor educational background of their parents and lack of learning resources. Gormally et al. (2009) state that active learning strategies can be effective in increasing students'learning motivation and academic achievement, especially in disadvantaged groups. In this study, DBR can be considered as an important learning opportunity especially for rural students. The improvement in critical thinking and creativity skills shows how effective structured and student-centred approaches can be in such areas. Moreover, the flexibility of DBR enables active participation of students, sometimes in resource-constrained settings. Beligatamulla et al. (2019) emphasised in their study that student-centred and inquiry-based approaches are very valuable in developing cognitive skills in disadvantaged student groups. In contrast, limited development in problem solving and computational thinking skills suggests that these skills require more support and access to technology. It is clear that investment in teacher training and digital resources is needed to develop these skills, especially in rural areas.

Conclusions

Effectiveness on critical thinking and creative self-efficacy

The design-based research (DBR) approach improved fourth grade students'critical thinking and creative self-efficacy. It shows that DBR promotes analytical reasoning, reflective thinking and creative self-confidence. DBR is an effective approach to nurture higher-order cognitive skills and support the development of key twenty-first century competences in primary education.

Limited impact on problem solving and computational thinking

The impact of DBR on problem-solving skills and computational thinking remains relatively insignificant. This implies that either DBR lacks those systematic features of an algorithm nor has elements for providing executive function required for strategic problem solving. Therefore, additional teaching strategies or extended interventions may be necessary to strengthen these competences.

The role of DBR in skill development and educational implications

An integrated approach that combines DBR with structured, guided activities can increase effectiveness. Teacher training, curriculum development and resource investments should be supported in under-resourced rural contexts to maximize the potential of DBR to develop twenty-first century skills in primary school students.

Limitations

The study faced several limitations. Other variables including classroom dynamics and teacher influence could have contributed to the results. A short duration of the DBR intervention may have limited its potential for sustainable improvements of problem-solving skills and computational thinking, which should be sustained for the long-term with further reinforcement. Finally, even though the sample size is representative of the participating schools, it might not represent the broader diversity of primary school pupils of other socioeconomic and geographical backgrounds.

Suggestions for future research

Future research should include a control group in order to compare the development of skills with DBR interventions. Clear instructional approaches can be developed for primary school students. Comparative studies can be conducted in city center and rural areas. In addition, teacher-student interaction in the DBR process can be investigated. How problem solving skills and computational thinking can be developed in the DBR process can be investigated.

Ethics committee permission information

In order to carry out this study, it was ethically approved in accordance with the decision of the Scientific Research and Publication Ethics Committee of Muş Alparslan University, dated 08.11.2023 and numbered 116,359.

Author contribution First author: collection and analysis of data. Second author: Introduction, methodology, Third author: Designing the study, writing the discussion and conclusions.

Funding Open access funding provided by the Scientific and Technological Research Council of Türkiye (TÜBİTAK). This research has not received any funding.

Declarations

Conflict of interest The authors have no conflict of interest.

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