DOI: 10.46793/STREAM25.061P
UDC: 371.3:5

META-ANALYSIS OF THE EFFECTS OF THE STEM TEACHING APPROACH ON THE DEVELOPMENT OF 21ST-CENTURY COMPETENCIES RELATED TO LEARNING NATURAL SCIENCES[1]

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Abstract: Since the fast scientific growth has a profound impact on life in the 21st century, this research aimed to explore the effects of STEM teaching on the development of key 21st-century competencies for learning natural sciences. Consequently, four research hypotheses were formulated: the STEM approach promotes the development of creativity (H1), critical thinking (H2), problem-solving (H3), and science-processing skills (H4) to a greater extent than the traditional approach to teaching natural sciences. The validity of the hypotheses was assessed through a meta-analysis. The results of 21 studies that examined the effects of the STEM approach on the development of the above-mentioned competencies among both elementary and high-school pupils were used to calculate the corresponding mean Cohen's *d* value for each of the four hypotheses. The mean Cohen's *d* values for the hypotheses related to creativity and science-processing skills range between +0.500 and +0.800 which indicates a moderate positive effect. The mean Cohen's *d* values for the hypotheses referring to critical thinking and problem-solving skills were higher than +0.800, indicating a strong positive effect of the STEM approach on the development of these competencies in comparison to the traditional teaching approach. Consequently, it can be concluded that all four research hypotheses posed here are confirmed. Furthermore, the findings confirm the considerable potential of the STEM teaching approach to contribute to the development of key 21st-century competencies related to learning natural sciences.

Keywords: STEM approach, 21st-century competencies, learning natural sciences, meta-analysis

INTRODUCTION

Life in the 21st century is characterized by constant rapid changes in our social and professional environments (EURYDICE, 2011). Therefore, the competen-

[1] This research is financed by the Ministry of Science, Technological Development and Innovation of Republic of Serbia, Contract number: 451-03-66/2024-03/200288.

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cies pupils need to be equipped with to promptly and successively adapt to these changes have been labeled 21st-century competencies (Partnership for 21st Century Learning, 2016). Since many of the above-mentioned changes are induced by fast scientific growth (EURYDICE, 2011), development of the 21st-century competencies such as creativity, critical thinking, problem-solving, and science-processing skills, which are also essential for learning natural science successfully, is of great importance. One of the novel teaching approaches that have the potential to promote the development of these competencies is known as the Science, Technology, Engineering, and Mathematics (STEM) approach (Binkley et al., 2012). This interdisciplinary teaching approach, which combines the knowledge from the four domains, is student-centered; it prioritizes collaboration and the use of active learning methods such as problem-solving and inquiry-based learning to tackle real-life problems; it is intended for all age groups from pre-school to university and, through facilitating the development of several 21st-century competencies, it also contributes greatly to lifelong learning (Bybee, 2010; Stehle & Peters-Burton, 2019).

By prompting pupils to acquire new knowledge through overcoming real-life problems, the STEM approach actively promotes the development of their problem-solving skills (Tan et al., 2023). To become successful problem solvers, pupils must also be equipped with critical thinking skills, which presuppose the ability to pose questions about the problems of vital importance for themselves and their environment, evaluate the credibility of various data sources, collect trustworthy and relevant information, detect cause-effect relationships, and communicate effectively with individuals in their surroundings while looking for ways to resolve these issues (Ennis, 2018). Successful problem-solving is also facilitated by creativity, i.e. the ability to overcome the challenges in our environment through the generation of innovative products (McWilliams, 2009). In the field of natural sciences, creativity is manifested as the ability to organize new experiments and produce novel theories to solve scientific problems (Hu & Adey, 2002). Hence, it is closely associated with the development of pupils' science-processing skills. The STEM approach teaches pupils how to act and think scientifically by encouraging them to observe various changes in their environment actively, formulate hypotheses that attempt to explain the occurrence of these changes, choose and conduct appropriate experiments to test the proposed hypotheses and use obtained experimental findings to conclude about their correctness (Raj & Devi, 2014). Aside from facilitating the acquisition of new scientific knowledge in educational settings, the development of science-processing skills also helps pupils solve daily-life problems in an organized and systematic manner and make responsible and well-taught decisions regarding complex issues that arise in their social environment (Hodosyova et al., 2015).

RESEARCH METHODOLOGY

The Aim of Research and Research Hypotheses

This research aimed to compare the effects of the traditional disciplinary and the STEM interdisciplinary teaching approach on the development of the key 21st-century competencies in learning natural sciences. By this aim, the four research hypotheses were posed stating that the STEM teaching approach is more effective in promoting the development of pupils' creativity (H1), critical thinking (H2), problem-solving (H3), and science-processing skills (H4) than the traditional disciplinary approach to teaching natural sciences. The correctness of the four research hypotheses was assessed with a meta-analysis.

The Principles of Meta-Analysis

A meta-analysis is a quantitative research technique that assesses the correctness of a research hypothesis by using the findings of the experimental studies that have already evaluated the correctness of that hypothesis (Guzzo et al., 1987). Furthermore, to be included in a meta-analysis, the results of one such study need to enable the calculation of the effect size value of Cohen's *d*. Experimental educational studies typically examine whether a novel, i.e. an experimental teaching approach, produces better results than the approach that has been traditionally applied. By calculating Cohen's *d* values, it can be determined whether, and to what extent, an experimental approach is more effective than the standard one in a certain respect (Guzzo et al., 1987; McGough & Faraone, 2009).

The Cohen's *d* value is obtained with the formula (McGough & Faraone, 2009):

$$d = \frac{\overline{Y}e - \overline{Y}c}{S_p}$$

, where $\overline{Y}_e$ represents the mean achievement of pupils from an experimental group, $\overline{Y}_c$ is the mean achievement of pupils from a control group, and S_p represents a pooled standard deviation of the given research sample. The pooled standard deviation is calculated with the formula:

$$S_p = \sqrt{\frac{(n_e - 1) \cdot S_e^2 + (n_c - 1) \cdot S_c^2}{n_e + n_c - 2}}$$

, where n_e represents a number of pupils in an experimental group, n_c is a number of pupils in a control group, S_e represents the standard deviation of the results of the experimental group, and S_c is the standard deviation of the results obtained for the control group.

The mean Cohen's *d* value for a hypothesis is obtained after the Cohen's *d* values for all studies focusing on the correctness of the given research hypothesis are calculated. Ultimately, based on the sign and numerical value of the mean Cohen's *d*, the proposed hypothesis is either confirmed as correct or rejected as incorrect (Guzzo et al., 1987; McGough & Faraone, 2009).

The mean values of Cohen's *d* can be positive or negative. Positive values imply that the experimental approach produces better results than the traditional approach, while negative values prove the opposite. Additionally, based on the numerical values of the positive mean of Cohen's *d*s, it can be determined to what extent a given experimental approach is more effective than the standard one(McGough & Faraone, 2009). The values between 0 and +0.200 indicate that the positive effects of the experimental approach are negligible and that they are likely to remain as such even after a prolonged period of application. The values ranging from +0.200 to +0.500 are considered low. Consequently, the positive effects of the application of the experimental approach are small, but not negligible. Also, they are expected to become more pronounced as the experimental approach is applied over time. The values ranging from +0.500 to +0.800 are labeled as medium. This implies that the positive effects are greater than in the previous instance and that they become apparent more quickly. The values surpassing +0.800 are labeled as strong and they indicate that the experimental approach produces considerably better results than the traditional approach. The effects are easily observable even after a very short period of application. Ultimately, a hypothesis stating that the given experimental approach is more effective than the traditional approach in a certain respect is confirmed as correct if a corresponding mean Cohen's *d* value is higher than +0.200 (McGough & Faraone, 2009). The identical principles of interpretation of the numerical values of Cohen's *d* apply when the obtained mean values of Cohen's *d* are negative. A hypothesis stating that the traditional approach is more effective than the experimental approach in a certain respect would be considered correct when obtained the mean Cohen's *d* values are lower than -0.200.

Literature Search and Data Analysis

The present meta-analysis includes only the research papers published in the English language in peer-reviewed journals between 2013 and 2023. They present the results of the experimental studies that compared the effects of the STEM approach and traditional disciplinary teaching on pupils' creativity, critical thinking, problem-solving, and science-processing skills. To find such papers, the citation databases Web of Science, Scopus, and Google Scholar were utilized. The search terms referred to the development of 21st-century skills (*development of creativity*, *development of critical thinking skills*, *development of problem-solving skills*, and *development of science-processing skills*) and the educational fields (*STEM education* along with *chemistry education*, *physics education*, or *biology education*). 21 research papers were eligible for the present meta-analysis. Following the computation of individual Cohen's *d* values for all the studies included in this meta-analysis, the mean Cohen's *d* values were calculated for each of the four research hypotheses by using the random-effects model in the JASP software for statistical analysis.

RESULTS AND DISCUSSION

An overview of the research papers included in this meta-analysis is provided in *Table 1* with a special emphasis on Cohen's *d* values calculated based on their finding for the H1–H4.

As can be seen in Table 1, this meta-analysis was conducted on the findings of 21 research papers. 16 papers were published after 2020, while the remaining 5 were published between 2013 and 2020. Their findings enabled the calculation of 24 Cohen's *d* values. Seven values refer to the H1 and H2. Five values are relevant for the H3 and H4. Two studies (P1 and P9) obtained the results that enabled the calculation of Cohen's *d* values for two hypotheses (H1 and H3).On the other hand, one paper (P6) enabled the calculation of two Cohen's *d* values regarding the H4 for two different educational levels. Overall, 12 Cohen's *d* values refer to students in elementary schools, 9 to those attending high schools, 2 to students at universities, and 1 to pre-schoolers.

Table 1 further shows that the mean Cohen's *d* values obtained for the correctness of the H1 and the H4 are +0.594 and +0.672, respectively. Both values are positive and they fall within the range labeled as a moderate effect size (between +0.500 and +0.800). This indicates that the STEM approach had a moderately strong positive effect on the pupils' creativity and science-processing skills in comparison to the traditional disciplinary approach to teaching natural sciences. Furthermore, the effects are expected to become more and more apparent if the application of this approach continues. The mean Cohen's *d* values obtained for the H2 and the H3 are +1.059 and +0.880, respectively. Both values are positive and they can be labeled as high effect size values (>+0.800). It can be concluded that the STEM approach had a very strong positive effect on the development of pupils' critical thinking and problem-solving skills. The effect will be easily observable even after a very short period of application.

Table 1: An overview of the research papers included in the meta-analysis

Paper No.	**Author(s) of the paper**	**Publication year**	**Educational level**	***d*(H1)**	***d*(H2)**	***d*(H3)**	***d*(H4)**
P1	Çalişici & Benzer	2021	Elementary school	+0.076	/	+0.882	/
P2	Cotabish et al.	2013	Elementary school	/	/	/	+0.479
P3	Dewi & Kuswanto	2023	High school	/	+0.780	/	/
P4	Doğan & Kahraman	2021	High school	+1.528	/	/	/
P5	Eroglu & Bektas	2022	High school	+0.781	/	/	/
P6	Gürsoy et al.	2023	Elementary & High school	/	/	/	+0.772; +0.814
P7	Hacioglu & Gulhan	2021	Elementary school	/	+0.470	/	/
P8	Hayuana et al.	2023	University	/	/	+0.870	/
P9	Hebebci & Usta	2022	Elementary school	+0.091	/	+0.920	/
P10	Majeed et al.	2021	Elementary school	+0.685	/	/	/
P11	Mater et al.	2022	Elementary school	/	+1.750	/	/
P12	Noufal	2022	High school	/	+0.435	/	/
P13	Parno et al.	2021	High school	/	+0.757	/	/
P14	Preca et al.	2023	High school	+0.355	/	/	/
P15	Retnowati et al.	2020	High school	/	+1.440	/	/
P16	Şahin	2021	Pre-school	/	/	+0.956	/
P17	Sari et al.	2020	University	/	/	/	+0.700
P18	Siregar et al.	2019	Elementary school	/	+0.720	/	/
P19	Strong	2013	Elementary school	/	/	/	+0.597
P20	Yesildag-Hasancebi et al.	2021	High school	+0.645	/	/	/
P21	Zengin et al.	2022	Elementary school	/	/	+0.774	/
The mean value of Cohen's *d* for each hypothesis				**+0.594**	**+1.059**	**+0.880**	**+0.672**

Following the calculation of a mean Cohen's *d* value for a certain hypothesis within a meta-analysis, it is customary to compare this value with those obtained by other meta-analyses that have addressed the same hypothesis. Given that the STEM approach has been applied in teaching science around the world for only 15 – 20 years, experimental studies and, consequently, meta-analyses regarding the effects of its implementation on the development of the 21st-century competencies are still scarce. Thus, the literature review produced no prior meta-analysis examining the effects of the STEM approach on the development of pupils' creativity, problem-solving, and science-processing skills. Only one previously conducted meta-analysis was found regarding the effects of this approach on the development of pupils' critical thinking. Putra et al. (2023) included 13 research papers published between 2015 and 2021. None of them is included in this meta-analysis since all of them were published in Indonesia in their authors' native language. This meta-analysis is, however, available in the English language. When it comes to the effectiveness of the STEM approach in developing pupils' critical thinking, the study reports the mean Cohen's *d* value of +0.880. This value is lower than the mean value of +1.059 obtained for the H2 in this study, but it still falls into the range of strong effect size values (>+0.800). This provides further confirmation that the STEM approach, compared to the traditional disciplinary teaching of natural sciences, has a considerably stronger positive effect on the development of pupils' critical thinking and that the effect is easily observable even after a relatively short period of application.

CONCLUSION

To examine the effectiveness of the STEM interdisciplinary teaching approach in teaching natural sciences in terms of the development of the key 21st-century competencies, the present study tested four research hypotheses stating that this approach promotes the development of creativity (H1), critical thinking (H2), problem-solving (H3), and science-processing skills (H4) to a greater extent than the traditional disciplinary teaching. The correctness of the hypotheses was assessed with a meta-analysis. 24 Cohen's *d* effect size values were calculated based on the results of the prior experimental studies focusing on the correctness of the given hypotheses. Since the mean Cohen's *d* values obtained for each hypothesis are positive and higher than +0.200, it can be concluded that all four hypotheses are correct. Furthermore, the mean Cohen's *d* values obtained for the H2 and the H3 are within the range of high effect size values (>+0.800). This indicates that the STEM approach promotes the development of critical thinking and problem-solving skills to a considerably greater extent than traditional disciplinary teaching. The effects are easily observable even after a very short period of application. Regarding the H1 and the H4, the mean Cohen's *d* values can be considered medium effect size values (between +0.500 and +0.800). This implies that while the positive effects of the STEM approach on the development of creativity and science-processing skills are not as strong as in the case of the H2 and the H3, they are still far from negligible and will become more and more pronounced as the approach is applied over time.

Given the relative novelty of the STEM teaching approach, the previous research about its effects on the development of the key 21st-century competencies in learning natural sciences is expectedly scarce. Thus, most of the research papers used in this meta-analysis have been published within the last four years. Despite these shortcomings, the mean Cohen's *d* values obtained for the four research hypotheses undeniably indicate that the STEM approach has a far greater potential to contribute to the development of pupils' creativity, critical thinking, problem-solving, and science-processing skills than the traditional disciplinary approach. Disciplinary teaching is dominant in schools throughout Serbia, and this can be linked to the low levels of students' scientific literacy (Putica & Ralević 2022). Consequently, more frequent application of the STEM approach is expected to positively contribute to the development of pupils' 21st-century competencies which are essential for learning natural sciences and the improvement of their scientific literacy.

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