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Meta-Analysis of Cognitive and Affective Effects of Arduino-Based Educational Programs

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Abstract

This study aims to summarize the effects of Arduino-based educational programs through a meta-analysis. Eleven eligible primary studies were obtained through a systematic literature review and coded accordingly. The results are as follows: The meta-analysis revealed that the overall effect size for all the studies was 0.518. Analysis of the moderator variables indicated statistically significant differences between them. Regarding the learning domains, the results were ranked in descending order of the cognitive and affective domains. Within the cognitive domain, the effect sizes were ranked in descending order as follows: logical thinking, content knowledge, convergence competency, self-efficacy, computational thinking, and creative problem-solving skills. In terms of subject areas, the descending order of effect sizes was agriculture, STEAM, environmental science, practical arts, artificial intelligence, informatics, and computers. Regarding school level, the results were ranked in the following descending order: college, elementary school, middle school, and high school.

Index Terms: Arduino, Educational outcomes, Program effectiveness, Meta-analysis

I. INTRODUCTION

With the advent of the Fourth Industrial Revolution, there has been a growing need for changes in school curricula and instructional methods in K-12 education [1]. Educators argue that in this era, where artificial intelligence and big data are becoming essential knowledge, the education system should be restructured to enable students to understand these foundational technologies and continuously learn evolving skills. In particular, educational policymakers emphasize the cultivation of software education and the development of creative and interdisciplinary talent in response to significant societal changes occurring in various professional fields centered on information technology.

Convergence is perceived as an innovative paradigm driving national development in this new era that is rapidly progressing across all sectors of society. Therefore, the direction of education needs to shift towards nurturing experts who can create and utilize information based on convergence capabilities rather than merely having students who can use or manipulate technology.

Countries worldwide are strengthening computer education programs to adapt to social changes. For instance, in 2014, the UK made computer education mandatory for students aged five and above, resulting in improved computational thinking skills through computer science and programming learning [2]. The Republic of Korea made software education compulsory in its revised curriculum, focusing on computing and programming. In the 2022 National Curriculum Update, digital literacy for diverse subjects has been designated as a core competency [3]. Accordingly, the Republic of Korea's Ministry of Education has been developing a national curriculum that incorporates digital literacy tailored to students' diverse characteristics to support practical prob-

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lem solving and social participation.

Within this context, there is increasing interest in software-based integrated education, with educators attempting various methods of combining integrated education and software education. Among these methods, physical computing using Arduino has garnered significant attention [4]. Physical computing involves connecting sensors and programs to a computer, enabling it to function similar to human sensory organs and respond to their surroundings. Physical computing facilitates interactions between objects through actuators and sensors, assisting students with limited computer knowledge or experience in realizing their ideas in various ways. Arduino-based education has been widely reported in the field of physical computing mainly because of its user-friendly interface, strong compatibility, and cost-effectiveness, which makes it easily adoptable in schools. Arduino's versatility, which allows integration with various software packages, has been a significant highlight. Arduino-based educational programs are consistently progressing in many countries worldwide. However, comprehensive research discussing the effects of Arduino-based education is still lacking in the existing literature. Therefore, this study analyzes the effects of Arduino-based education programs on students reported in international databases through a meta-analysis.

The research questions were as follows: First, what is the overall effect size of Arduino-based education programs? Second, are there differences in the effect sizes of Arduino-based education programs based on categorical variables?

II. THEORETICAL BACKGROUNDS

A. Arduino and Education

Arduino is a microcontroller board developed at the Interaction Design Institute Ivrea in Italy in 2004 [4]. Arduino was designed to teach basic programming to students in the fields of design and arts, allowing them to easily design and create output through programming. Conceptually, Arduino encompasses both software and hardware. First, from a software perspective, Arduino is defined as a program development environment for hardware operations, signifying a Java-based integrated development environment that comprises a variety of functions. From a hardware perspective, Arduino refers to an open-source computing platform built with a microcontroller and an integrated development board that performs various functions.

Arduino has garnered worldwide attention since its release, and its advantages recognized in educational institutions include the following [5]. First, when students connect the Arduino board to a computer, it is immediately recognized due to its plug-and-play functionality. Second, it is convenient to use, because the integrated development environment provides many examples to refer to during the process of controlling peripheral devices. Third, the variety of open-source project examples allows students to utilize them easily in the learning process. Fourth, it operates in Windows, Linux, and MacOS environments without any restrictions. Fifth, Arduino hardware is cost-effective, making it affordable, even when purchasing premade products. Sixth, the software is freely available. Seventh, maintenance costs are low and replacing a malfunctioning microcontroller is cost-effective. Eighth, students can quickly create prototypes. Ninth, programming is possible in various languages, including C. These advantages have contributed to the widespread adoption of Arduino in educational settings.

B. META-ANALYSIS

Meta-analysis is a systematic method for summarizing primary study results reported in quantitative research [6]. A significant characteristic of meta-analyses is the use of quantitative indices known as effect sizes. The effect size measures the magnitude and strength of the relationship between variables. In meta-analysis research, comparing effect sizes enables cross-study comparisons and synthesis of research effects.

In this study, the standardized mean difference was used to calculate effect sizes. This involved computing the change in the mean difference between the pre-test and post-test results for both the experimental and control groups.

III. METHODS

A. Methodology

This study comprehensively assessed the effects of Arduino-based educational programs using meta-analysis. This study was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines [7].

B. Search Process

The researcher carefully examined journal articles, theses, and dissertations using a quasi-experimental design. The keywords chosen for the search included "Arduino," "impact," "evaluation," "effect," and "outcome." The following international databases were scrutinized for the literature search: Web of Science, Scopus, Google Scholar, and ProQuest Dissertations & Theses Global. As a result of the search, a total of 90 academic journal articles and 8 theses and dissertations were initially collected. Studies that focused on students as research subjects and included an experimental group in their research methodology were included in the analysis. Consequently, 11 primary studies that demonstrated the effects of Arduino-based educational programs were selected.

C. Exclusion Criteria

Studies that targeted groups other than students in K–12 schools and colleges, operated outside the school, or failed to provide an experimental group were excluded from data analysis (Fig. 1).

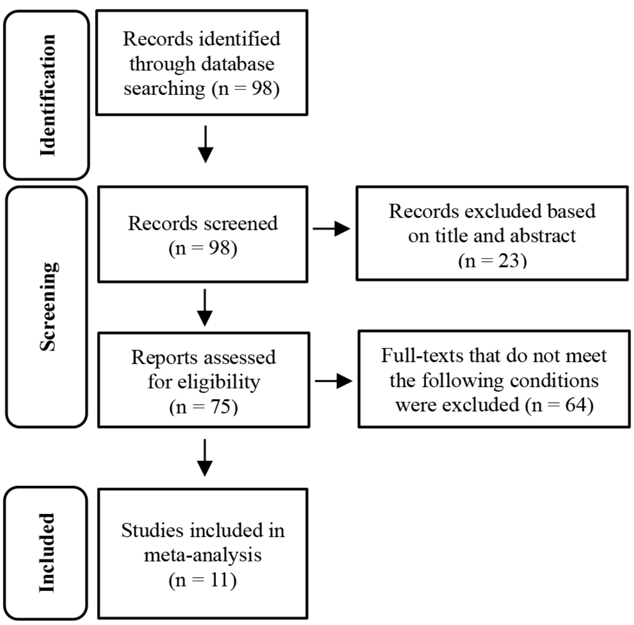

Fig. 1. PRISMA flowchart.

Table 1. Characteristics of Studies

Author	Year	Publica-tion	Level	Domain
Arslan [8]	2021	Journal	College	Cognitive, Affective
Choi [9]	2016	Journal	High	Cognitive
Hong [10]	2020	Journal	High	Affective
Johnson [11]	2022	Journal	College	Cognitive, Affective
Kim [12]	2016	Journal	Elementary	Cognitive
Kim [13]	2016	Journal	Middle	Affective
Kim [14]	2020	Journal	College	Cognitive
Kim [15]	2016	Journal	Middle	Cognitive
Kim [16]	2018	Journal	Elementary	Cognitive, Affective
Lee [17]	2019	Journal	Elementary	Cognitive
Seo [18]	2016	Journal	Elementary	Affective

D. Data Extraction

The characteristics of the 11 papers selected for data analysis are listed in Table 1.

E. Coding

The participants carefully selected categorical variables, such as the type of dependent variable, grade level, and subject area. Subsequently, coding procedures were performed in preparation for the meta-analysis. Before the coding process commenced, the coders collaborated through discussions to create a coding manual. Coding was conducted after deliberation involving one computer education professor, one educational technology professor, and the first author.

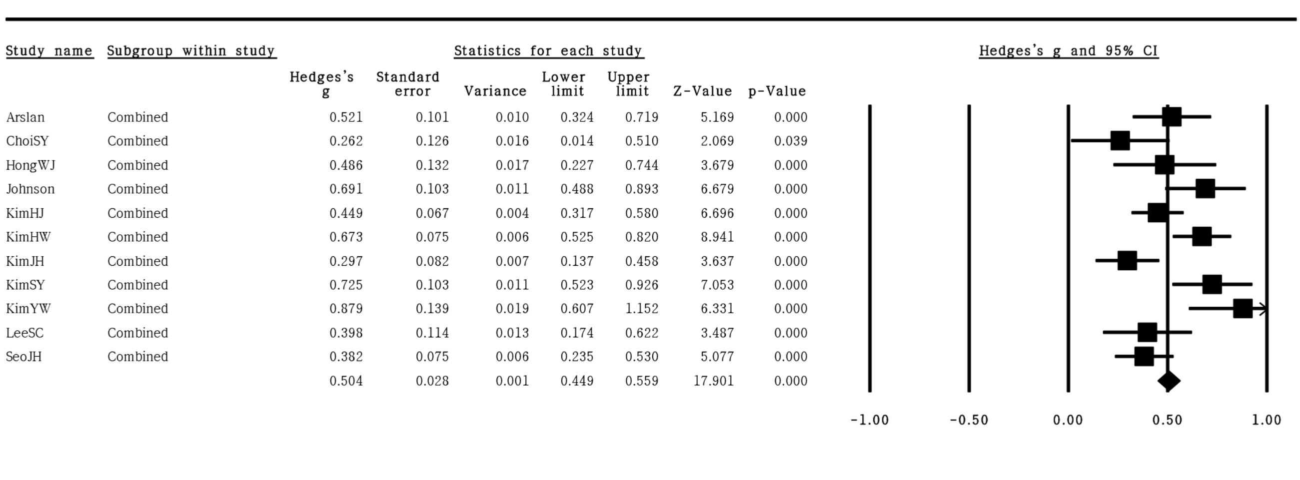

Fig. 2. Forest plot

IV. RESULTS

A. Overall Analysis

Fig. 2 shows the descriptive statistics for all 11 studies, including forest plots, variances, and standard errors.

The results of the homogeneity tests are listed in Table 2. The effect sizes of primary studies were heterogeneous.

The effect of the Arduino-based education program was a standard deviation of 0.518 (Table 3), indicating a moderate effect size.

Table 2. Homogeneity Test

N	ES	SE	-95% CI	+95% CI	Q	P-value
11	0.504	0.028	0.449	0.559	34.468	.000

Table 3. Overall Effect Size

N	ES	SE	-95% CI	+95% CI
11	0.518	0.054	0.412	0.623

B. Moderator Analyses

These analyses were conducted to identify sources of variability and moderating factors [19].

1) Study Characteristics

The variables related to study characteristics were school level, student ability, and publication year. Regarding the school level, the results were ranked as follows: college (0.671), elementary school (0.564), middle school (0.388), and high school (0.369). For student ability, the results were in the order of the full range of students (0.55) and gifted and talented students (0.297). In the publication year category, the results appeared in the order of 2020-2023 (0.64) and 2016-2019 (0.464).

2) Methodological Characteristics

The variables associated with the methodological characteristics included research design and sample size. There were no statistically significant research findings in the moderator analyses based on methodological characteristics.

3) Design Characteristics

The variables related to the research characteristics were treatment duration and session frequency. In the duration of treatment category, the results were observed in the following order: 1-4 weeks (0.557); >5 weeks (0.473).

4) Outcome Characteristics

The variables related to the outcome characteristics included the learning, cognitive, and affective domains, and subject areas. For the learning domains, the results were in the order of cognitive domain (0.585) and affective domain (0.401). For the cognitive domain, the order of effect sizes was logical thinking (0.907), content knowledge (0.896), convergence competency (0.725), self-efficacy (0.655), computational thinking (0.644), and creative problem-solving skills (0.47). The order of effect sizes for the subject areas was as follows: agriculture (0.789), STEAM (0.725), environmental science (0.673), practical arts (0.521), artificial intelligence (0.486), informatics (0.449), and computers (0.362).

C. Publication Bias

To identify publication bias, the researcher adopted a funnel plot and a rank correlation test. These two methods suggested that publication bias was unlikely in this study. First, the funnel plot was considerably symmetrical in Fig. 3. Second, Kendall's tau was 0.109 and p was 0.64 in the rank correlation test [20], which meant that it was difficult to see whether a significant correlation existed.

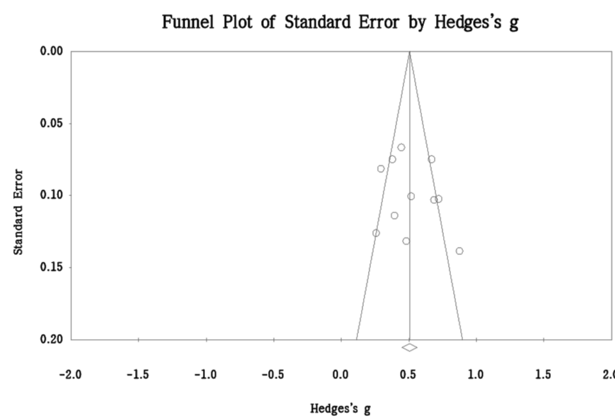

Fig. 3. Funnel plot.

V. DISCUSSION

This study summarizes the effects of Arduino-based educational programs through a meta-analysis. The findings are as follows:

First, the overall effect size of the Arduino-based educational programs was 0.518, which, according to Cohen's (1988) standards, falls into the category of a medium effect size [21]. This finding suggests that Arduino can be effectively utilized in the implementation of school curricula. Additionally, a prior study by Lee (2020), focusing on studies conducted in Korea, reported a meta-analysis of the effects of Arduino-based education in engineering programs targeting elementary and middle school students, which showed an overall effect size of 0.656 [22].

Second, when measuring the effect size based on the dependent variables, the cognitive domain had an effect size of 0.585, whereas the affective domain had an effect size of 0.401. These results align with the findings of Johnson (2022) [11], who argued that students engaging in educational activities involving Arduino could enhance their cognitive abilities by performing programming tasks and addressing problems directly related to the curriculum.

Third, when examining the effect sizes based on the subvariables in the cognitive domain, the order was as follows: logical thinking (0.907), content knowledge (0.896), convergence competency (0.725), self-efficacy (0.655), computational thinking (0.644), and creative problem-solving skills (0.47). The highest effect size, logical thinking, refers to the ability to analyze rules and validity in the relationships between factors. Arduino programming is structured logically, enhancing students' reasoning and problem-solving skills during the learning process [12].

Fourth, when measuring the effect size based on subvariables in the subject area, the order was agriculture (0.789), STEAM (0.725), environmental science (0.673), practical arts (0.521), artificial intelligence (0.486), informatics (0.449), and computers (0.362). These results suggest that Arduino-based educational programs may yield greater effects than computer education when integrated into school curricula. Jamieson (2011) emphasized Arduino's ease of use and strong compatibility in addressing various issues in different curriculum areas [5].

Fifth, at the school level, the results were as follows: college (0.671), elementary school (0.564), middle school (0.388), and high school (0.369). College students are more likely to understand program objectives and processes accurately and engage actively. Their high interest in problem solving and motivation may contribute to the program's positive effects [14].

Regarding student ability, the results were the full range of students (0.55) and gifted and talented students (0.297). This suggests that educators should consider grouping students with different levels of ability when implementing Arduino-based educational programs. Gifted and talented students accurately understand their learning capabilities and grow by incorporating them into their learning processes. Underachieving students can learn problem-solving strategies from gifted and talented students. Thus, Arduino-based educational programs have the potential to foster educational growth for all students, based on interactions among students with different perspectives and abilities.

VI. CONCLUSION

This study systematically analyzes the results of previous research through a meta-analysis to explore the trends and educational significance of Arduino-based educational programs. The findings of this study provide valuable information for educators and researchers interested in developing and implementing effective educational programs utilizing Arduino-based education. In particular, the significant medium effect size observed in the overall effect of Arduino-based education indicates its potential effect on student development when implemented in various forms such as software education or integrated into curriculum-related educational programs at schools.

Based on the research findings, there should be active discussions in schools regarding the recognition and utilization of Arduino-based educational programs as effective teaching and learning methods. Lee (2020) asserts that students can grasp the basic meaning and operational principles of artificial intelligence through Arduino-based education, thereby enhancing teachers' professional competence to nurture the talent required in the Fourth Industrial Revolution [22]. Distributing instructional guides created by experts for classroom use could also be a beneficial approach for activating Arduino-based learning. Therefore, we aspire to the continuous enhancement and expansion of Arduino-based education, with the goal of equipping students with the skills required by future societies.

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