sustainability

MDPI

Article

Innovation of Teaching Tools during Robot Programming Learning to Promote Middle School Students' Critical Thinking

Hehai Liu [1], Jie Sheng [2] and Li Zhao [3,*]

[1] College of Education Science, Anhui Normal University, Wuhu 241000, China; liuhehai1997@163.com
[2] Quality Assurance Department, Anhui Business College, Wuhu 241000, China; s690634891@163.com
[3] School of Education Science, Nanjing Normal University, Nanjing 210097, China
* Correspondence: li.zhao@njnu.edu.cn

Abstract: In the digital age, robotics education has gained much attention for cultivating learners' design thinking, creative thinking, critical thinking, and cooperative abilities. In particular, critical thinking as one of the key competencies in Education for Sustainable Development (ESD) can stimulate imagination and creation. It is of great value to explore critical thinking cultivation in robot programming learning. Therefore, this study applied different teaching tools to take the content of "making a manipulator through programming and construction" in a robotics course as an experimental context to examine the promotion of learners' critical thinking. Before the experiment, a pre-test was conducted to measure students' critical thinking ability. Then, all students were divided randomly into two groups: one as an experimental group with the teaching tool of Construction–Criticism–Migration (CCM) instructional design, and the other as a control group with the traditional teaching tool of demonstrate–practice instructional design. After a 6-week experiment, the measurement of critical thinking was applied as a post-test. SPSS was used to conduct an independent sample *t* test and one-way ANOVA to explore whether students' critical thinking ability had improved and whether differences were found between the experimental group and the control group after the 6-week experiment. The results showed that the experimental group students' critical thinking ability significantly improved, whereas no significant difference was found before and after the experiment for the control group. A significant difference existed between the two groups. This study provides an example of a new instructional design teaching tool for the teaching of robot programming and can provide valuable suggestions for instructors in middle schools.

Keywords: robot programming learning; teaching tools; critical thinking; construction-criticism-migration; instructional design

Citation: Liu, H.; Sheng, J.; Zhao, L. Innovation of Teaching Tools during Robot Programming Learning to Promote Middle School Students' Critical Thinking. *Sustainability* **2022**, *14*, 6625. https://doi.org/10.3390/su14116625

Academic Editor: María Napal

Received: 22 April 2022
Accepted: 26 May 2022
Published: 28 May 2022

1. Introduction

Learning in Education for Sustainable Development (ESD) refers to the gaining of knowledge, values, and theories, and ESD learning can also be interpreted as learning to ask critical questions [1]. Critical thinking, one of the key competencies in ESD, is mainstreamed in ESD in order to promote critical thinking among members of the next generations [2]. Critical thinking is also a vital component of 21st century skills [3]; it refers to students' thinking about a series of interrelated critical questions, their ability to properly raise and answer critical questions, and their desire to utilize their critical thinking ability to solve problems [4]. Many students are unable to understand the relationship between concepts and to connect solutions with problems, which is the embodiment of a lack of critical thinking [5]. Critical thinking ability is an important ability of students which has an impact on their learning, future work, and lives [6]. It is in fact an indispensable ability for learners, and its role in education is increasing with each passing day [7].

Many scholars have carried out relevant studies on how to improve critical thinking. Some studies have shown that critical thinking is closely related to factors such as constructivism, leadership, and education, and is committed to teaching students to think in complex ways [8]. Constructivism, as a theory on learning and knowledge, emphasizes learners' initiative and posits that learning is a process whereby learners generate meaning and construct understanding based on their prior knowledge and experience [9]. The constructivist's learning view is to develop critical thinking ability and habits, skills, and attitudes for the premise of sufficient knowledge construction [10]. Applying constructivist principles in learning models can effectively enhance college students' critical thinking ability [11]. Knowledge transfer is the influence of one kind of learning on another [12]. Using a questionnaire survey and experiment, Lee and Son (2021) [13] found that a significant increase in critical thinking can effectively improve learning transfer.

In addition, Wang et al. (2021) [14] showed that robot education can effectively improve students' critical thinking. This provided an idea for the cultivation of critical thinking in robot education. Robot education refers to the realization of robot programming, construction, and knowledge transfer through robotics teaching [15]. The robot programming course is mainly realized through modular programming and robot practice. In programming and robotics teaching, students' logic, creative thinking, and communication skills are cultivated. Teachers use task guidance to improve students' attention and perseverance [16]. In addition, it also promotes the development of students' cognitive ability and problem-solving ability for complex problems [17], and positively influences students' academic performance [18]. Based on the relationship between knowledge construction, knowledge transfer, and critical thinking, this study puts forward a new construction–criticism–migration (CCM) instructional design teaching tool for application in robotics education.

The combination of appropriate instructional design and robotics education can further amplify the combination of machine teaching models, robotics education, and the influence of robotics education on critical thinking [19]. This study applied the CCM instructional design to robotics learning to explore the improvement in middle school students' critical thinking ability. Many studies on critical thinking have mainly explored students' critical thinking ability in terms of gender or students' characteristics [20]. However, more attention should be paid to the classroom instructional design, focusing on how to teach in a classroom to promote students' critical thinking. Therefore, in this study, two kinds of teaching tools were applied for middle school students to explore whether their critical thinking ability improved and whether there was any difference between the two groups.

2. Literature Review

2.1. Critical Thinking

Critical thinking originated from the dialogues of Socrates about 2500 years ago [21], and there are many different definitions. Paul (1995) [22] proposed that critical thinking, as a disciplined and self-directed learning procedure, exemplifies the perfections of thinking in accordance with a specific subject or area. It is a rational and positive way of thinking [23]. It is also the ability to identify problems, focus on problems, analyze and solve problems, and a skill for judging the reliability and effectiveness of available data and information sources [24]. Critical thinking has gradually gained increasing attention in education, and many studies have stated that critical thinking within subject areas could cultivate students as strong critical thinkers [21]. In addition, critical thinking skills can be instructed, developed, and learned through practice and use in daily life [25].

Previous studies have provided a sufficient theoretical basis for the measurement of critical thinking ability. Kang et al. (2005) [26] studied the critical thinking ability and development strategies of primary school students through a questionnaire survey. Martyaningrum et al. (2021) [27] found that the cognitive level of middle school students promoted the development of critical thinking ability through experiments. Hamid (2017) [28] studied students' critical thinking in chemistry education through a questionnaire survey. Arviana et al. (2018) [29] discussed the impact of teaching style on students' critical thinking in mathematics learning based on later observation and a classroom test. Nirmala et al. (2018) [30] compared students' critical thinking ability by implementing five strategies in students' reading comprehension teaching. On the basis of these studies, this study established an experimental group and a control group to compare the improvements in their critical thinking.

2.2. Robotics Education

Traditional robotics education is the design course of robot components including main control, motor, sensors, and so on. With the development of technology, robotics education has been endowed with new connotations. Robotics education refers to the achievements of basic knowledge and skills in robotics and the development of robotics education theory and practice through robotics teaching and learning [15]. Robotics education usually begins in primary school and is mainly carried out in the upper grades of primary school and middle school [31]. Previous studies have shown that robotics education can reduce cognitive impairment and encourage children to be more engaged in their learning activities [32,33]. Toh et al. (2016) [34] found that robotics education significantly influences children's cognitive, abstract, language, and cooperative abilities. Ioannou et al. (2015) [35] used humanoid robots to cultivate the social communication skills of autistic children. Thus, robotics education has potential value in the education of autistic children. In addition, robotics education can attract students' interest in learning, provide them with a plenty of room for imagination, and cultivate their innovative thinking, practical abilities, and comprehensive application ability [36]. Students are immersed in the authentic context of robot programming while at the same time being presented with great opportunities for meaningful collaboration [37]. Students' problem-solving ability and logical thinking can also be improved in robot programming courses [38,39]. However, although critical thinking is closely related to innovative thinking and creative thinking, cultivating students' critical thinking as the main purpose of robotics education needs further exploration [15]. Therefore, this study explored the impact of two kinds of instructional design in the area of robot programming education on middle school students' critical thinking ability.

2.3. Instructional Design of Robotics Education

Instructional design is a part of instructional development which guides teachers in how to effectively design teaching [40]. Merrill et al. (1990) [41] believed that instructional design adapts to the process of systematically planning the teaching system, which can arrange resources and procedures in a way that is conducive to students' learning. Instructional design includes five principles: guiding activities, reflection, feedback, control, and pretraining [42]. Robot programming courses can be designed based on the interactive teaching of robot form and structure [43]. Teaching strategies developed through teaching design can be applied to robot programming courses. Vicente et al. (2020) [44] believe that learning methods such as flipped classrooms, project-based learning, and cooperative learning can be combined with robotics education to improve students' learning ability. However, these teaching strategies have certain requirements for students and teaching equipment. Nugent et al. (2009) [45] applied the STEM teaching mode to robotics education, which effectively promoted curriculum integration and STEM literacy improvement. The defect of STEM teaching is that it lacks the cultivation of critical thinking. Based on the characteristics of the above teaching strategies, this paper puts forward the CCM instructional design. This strategy focuses on the constructivism theory, critical thinking, and knowledge transfer. This study carried out the experiment in the robot programming course, with the aim of cultivating students' critical thinking.

2.4. Research Questions

Critical thinking ability is a key skill for learners. The cultivation of critical thinking can be conducted in many areas and courses. With the popularization of robotics education, its advantages have gradually attracted more attention than other areas. It is valuable to explore the improvement of critical thinking in robot programming learning. Therefore, this study applied the teaching tools of CCM and the demonstrate–practice instructional design in robot programming learning to explore the improvement of middle students' critical thinking ability and learning performance, as well as the difference between the two kinds of instructional design. The study examined (1) whether both groups' critical thinking was promoted during robot programming learning and (2) whether there was any difference between the two groups.

3. Methods

3.1. Participants

The participants were 103 eighth graders in a middle school. Two classes were randomly selected as the experimental group (50 students), instructed with the CCM instructional design, and the control group (53 students) instructed with the demonstrate–practice instructional design. The two groups were taught by the same teacher with the same learning objectives. Participants were told that they were participating in an experiment, the results of which may be published, and their privacy was guaranteed. All participants agreed to participate in the experiment.

3.2. Experimental Procedure

The experiment lasted for 6 weeks (see Figure 1). Both groups were instructed in the content of "making a robot through programming and construction" in the robotics course. The specific learning objectives of the current robot programming learning course were to make a manipulator, build the foundation of the robot, add programming, and judge the robot's direction and distance during the robot programming learning. Students in both groups were provided with the same robot programming learning environment; they moved to the robot education classroom equipped with blocks, pads, and computers to learn the same content, and their learning objectives and tasks were the same. Students in the same robot programming learning environment had similar experiences to enhance their knowledge of robot education.

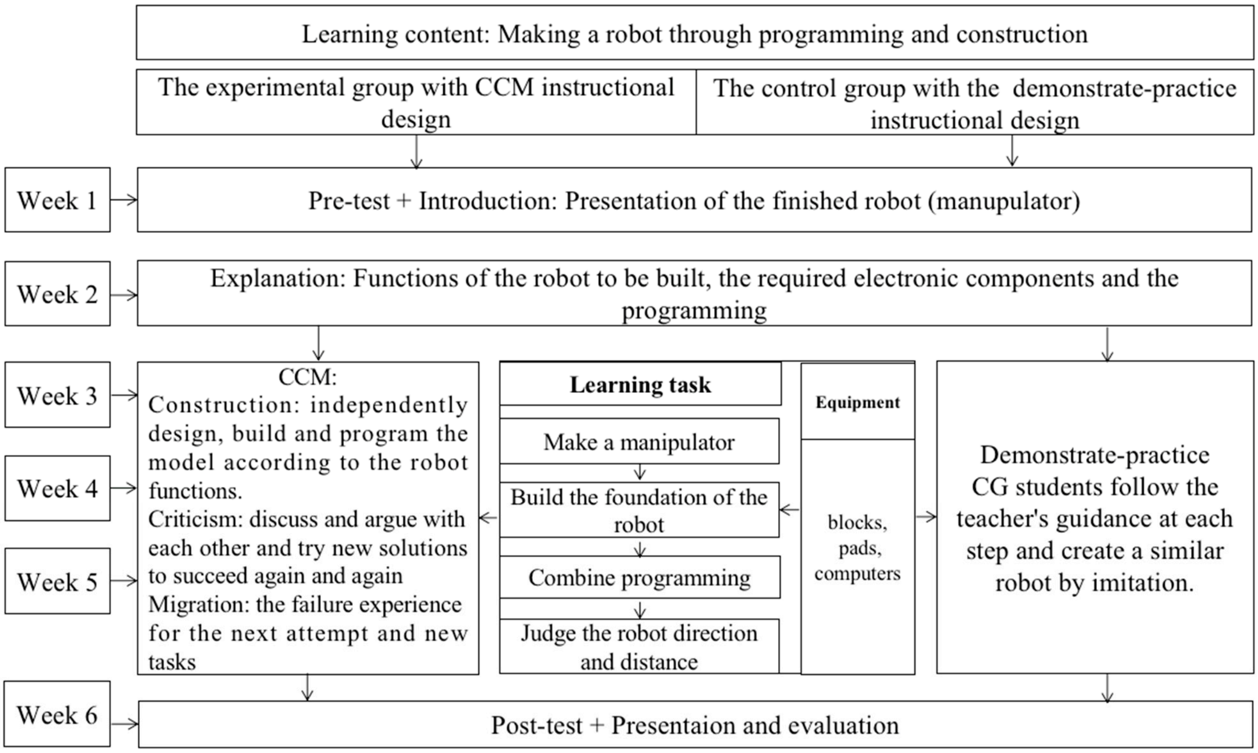

Figure 1. Procedure of the two groups' learning.

In the first week, the teacher conducted the critical thinking pre-test for the two groups and presented the work completed on the robot. In the second week, the teacher explained the functions of the robot, the required electronic components, and the programming for both groups. In the following 3 weeks, the experimental group students independently designed, built, and programmed the model according to the robot's functions, while the control group students followed the teacher's guidance at each step and created a similar robot by imitating the teacher. Students in the experimental group performed independent learning and completed the robot learning task mainly by themselves without the teacher's step-by-step guidance. They encountered many failures. However, they discussed and argued with each other and found new solutions to try again and again. They could ask the teacher for help as well. Their experience of failure could be adapted to produce new ideas for their next attempt. In the last week, the two groups presented and shared their final work. The post-test and evaluation were then conducted (see Figures 1 and 2).

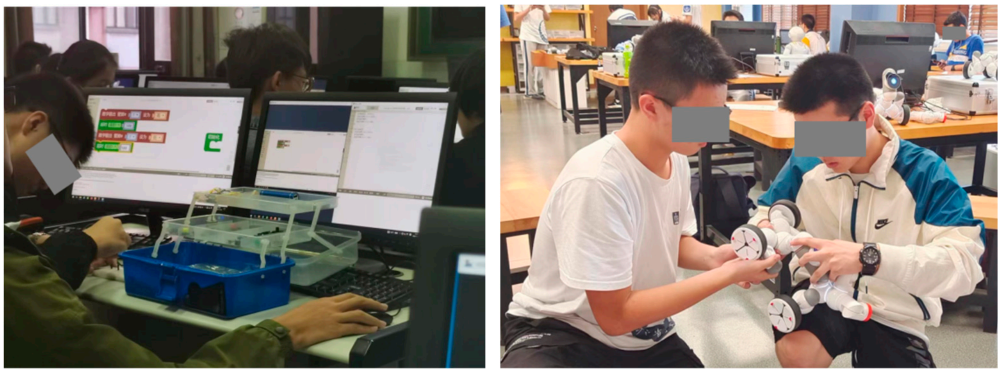

Figure 2. Students' robot programming learning.

3.3. Instrument

The scale for evaluating students' critical thinking was adapted from the critical thinking tendency scale developed by Yu et al. (2017) [46]. Previous studies have shown that a domain-specific critical thinking scale is better at measuring changes in students' critical thinking than a general critical thinking scale [47]. Therefore, this study adapted the scale according to the teaching environment of the robot programming course. Furthermore, in order to ensure the content validity and face validity of the questionnaire, three experts who had studied critical thinking and five teachers who had taught robot programming were invited to review all items and give feedback. The research team compared the similarities and differences in the experts' opinions and made joint decisions. Finally, the scale comprised five dimensions: recognition of assumptions (5 items, e.g., When I do something, I will think about what I really need to learn), induction (5 items, e.g., I can always figure out how to do it in an example), deduction (5 items, e.g., I will choose to think for myself instead of turning to the teacher when I am in trouble), interpretation (5 items, e.g., I can understand the information (icon, text, etc.) provided in the question correctly), and evaluation of arguments (5 items, e.g., I can control myself and keep working towards my goals; see Appendix A).

Confirmatory factor analysis (CFA) and exploratory factor analysis (EFA) were applied to test the reliability and validity of the scale. A total of 485 questionnaires from eighth graders were collected before the experiment. The Cronbach's alpha value was 0.955, the KMO value was 0.955 (>0.7), the Bartlett's test approximate Chi-square was 11,384.868, the degree of freedom was 300, and the significance was less than 0.001. These values indicated that the scale was suitable for the EFA.

This study applied principal component analysis to extract factors. The maximum variance rotation method was utilized for exploratory factor analysis. Factors with eigenvalues of more than 1 were obtained. After many orthogonal rotations, items with factor loadings lower than 0.5 and inconsistent content were deleted. Finally, 25 items with eigenvalues greater than 1 and independent factor loadings greater than 0.5 were selected [48]. According to Conway and Huffcutt's (2016) criteria [49], six factors were extracted, and the cumulative variance contribution rate was 79.633%. Table 1 shows the variance contribution rate, the eigenvalues, and the cumulative variance contribution rate of the six factors. The factor load after rotation is shown in Table 2.

Table 1. The characteristic values and contribution rates of the six factors in the model.

Component	Eigenvalue	Percentage of Variance	Cumulative Variance Contribution Rate
1	12.328	49.312	49.312
2	2.939	11.755	61.067
3	1.943	7.771	68.838
4	1.602	6.408	75.245
5	1.097	4.388	79.633

Table 2. Factor loading of each item in the six-factor model.

Item	Factor1	Factor2	Factor3	Factor4	Factor5
RA1				0.816	
RA2				0.818	
RA3				0.767	
RA4				0.736	
RA5				0.784	
Induction1					0.699
Induction2					0.708
Induction3					0.683
Induction4					0.691
Induction5					0.742
Deduction1		0.724			
Deduction2		0.818			
Deduction3		0.829			
Deduction4		0.781			
Deduction5		0.809			
Interpretation1			0.786		
Interpretation2			0.784		
Interpretation3			0.807		
Interpretation4			0.823		
Interpretation5			0.799		
EA1	0.853				
EA2	0.878				
EA3	0.901				
EA4	0.852				
EA5	0.867				

The reliability and validity of items in each dimension and the internal consistency were both acceptable (Cronbach's alpha range is 0.920–0.951; see Table 3). According to Fornell and Larcker (1981) [50], if the average variance extracted (AVE) of all the factors is greater than 0.5 (0.7014–0.7953), the convergence effectiveness of the potential variables is better. The comprehensive reliability value was greater than 0.6 (0.9212–0.951), slightly higher than the Cronbach's alpha. Thus, the scale was very reliable. In addition, first-order CFA was applied to test the degree of internal fitting of the scale. The results showed that the questionnaire fit well [51]. This scale is therefore suitable for testing critical thinking (GFI = 0.916; f2/df = 2.091; CFI = 0.974; NFI = 0.952; IFI = 0.975; RMSEA = 0.047).

Table 3. Reliability and validity test of the scale.

Latent Variable	Measure Item	Standardized Factor Loading	Composite Reliability (CR)	AVE	Cronbach's α
Recognition of Assumptions	RA1	0.885	0.9212	0.7014	0.920
	RA2	0.877			
	RA3	0.870			
	RA4	0.738			
	RA5	0.808			
Induction	Induction1	0.844	0.9315	0.7313	0.931
	Induction2	0.857			
	Induction3	0.810			
	Induction4	0.857			
	Induction5	0.905			
Deduction	Deduction1	0.800	0.9277	0.7198	0.927
	Deduction2	0.856			
	Deduction3	0.871			
	Deduction4	0.842			
	Deduction5	0.871			
Interpretation	Interpretation1	0.768	0.9354	0.7449	0.934
	Interpretation2	0.913			
	Interpretation3	0.940			
	Interpretation4	0.908			
	Interpretation5	0.770			
Evaluation of Arguments	EA1	0.872	0.951	0.7953	0.951
	EA2	0.889			
	EA3	0.922			
	EA4	0.876			
	EA5	0.899			

3.4. Data Analysis

The critical thinking test scale was distributed in the form of a paper version, and the data were entered and coded with the help of SPSS 24.0. One-way ANOVA and the independent sample t test were used to explore the difference between the two groups and within single groups before and after the experiment, respectively.

4. Results

4.1. All Students' Critical Thinking Improved after the Six-Week Experiment

The independent sample t test was applied to the pre- and post-test results to determine whether students' critical thinking improved after the 6-week experiment. The results indicated that all students' critical thinking improved; furthermore, compared to the control group, the experimental group students' critical thinking significantly improved. Specific descriptions follow:

As shown in Table 4, after the 6-week experiment, the pre- and post-test results of the experimental group showed that five dimensions of critical thinking all significantly improved, and that there were significant differences between the results before and after the experiment (Recognition of Assumptions: $t = -5.085$, $p < 0.001$; Induction: $t = -6.157$, $p < 0.001$; Deduction: $t = -5.191$, $p < 0.001$; Interpretation: $t = -5.131$, $p < 0.001$; Evaluation of Arguments: $t = -2.824$, $p < 0.01$). Cohen's d is commonly used as a standardization effect in the t test [52]. Cohen's d provides the evaluation criteria. When the value is $\geq$0.2 and <0.5, it shows a small effect, $\geq$0.5 and <0.8 indicates a moderate effect, while $\geq$0.8 represents a large effect [53]. The differences before and after the robot learning in the experimental group showed large effect sizes, except in the evaluation of arguments (Recognition of Assumptions: Cohen's $d = 1.016 > 0.8$; Induction: Cohen's $d = 1.241 > 0.8$; Deduction: Cohen's $d = 1.035 > 0.8$; Interpretation: Cohen's $d = 1.030 > 0.8$; Evaluation of Arguments: Cohen's $d = 0.569 > 0.5$).

Table 4. Independent sample *t*-test results (Experimental group $N = 50$).

Test	Dimension	Pre-Test		Post-Test		*t*	*p*	Cohen's *d*	Effect Sizes
		M	*SD*	*M*	*SD*				
Critical Thinking	Recognition of Assumptions	3.24	0.98	4.14	0.78	−5.085	0.000 ***	1.016	0.453
	Induction	3.74	0.72	4.49	0.46	−6.157	0.000 ***	1.241	0.527
	Deduction	2.87	0.97	3.89	1.00	−5.191	0.000 ***	1.035	0.046
	Interpretation	3.71	0.89	4.45	0.49	−5.131	0.000 ***	1.030	0.046
	Evaluation of Arguments	3.90	1.11	4.47	0.88	−2.824	0.006 **	0.569	0.274

Note: ** $p < 0.01$; *** $p < 0.001$.

As for the control group, the average score for critical thinking in the control group increased (see Table 5), but no significant difference was found between the pre-test and post-test (Recognition of Assumptions: $t = -0.114$, $p > 0.05$; Induction: $t = -1.422$, $p > 0.05$; Deduction: $t = -0.781$, $p > 0.05$; Interpretation: $t = -0.320$, $p > 0.05$; Evaluation of Arguments: $t = -0.479$, $p > 0.05$), which shows that there was no change in critical thinking with the demonstrate–practice instructional design.

Table 5. Independent sample *t*-test results (Control group $N = 53$).

Test	Dimension	Pre-Test		Post-Test		*t*	*p*
		M	*SD*	*M*	*SD*		
Critical Thinking	Recognition of Assumptions	3.32	0.95	3.34	0.75	−0.114	0.910
	Induction	3.74	0.70	3.92	0.57	−1.422	0.158
	Deduction	2.89	0.77	3.01	0.87	−0.781	0.436
	Interpretation	3.74	0.84	3.79	0.86	−0.320	0.749
	Evaluation of Arguments	3.97	0.95	4.06	1.00	−0.479	0.633

4.2. Significant Differences in Students' Critical Thinking Existed between the Two Groups

One-way ANOVA was applied to test the differences between the two groups before and after the experiment. Before the experiment, no significant difference in critical thinking ability existed between the two groups (see Table 6). The result showed that the critical thinking ability of the two groups was similar before the experiment (Recognition of Assumptions: $F = 0.164$, $p = 0.686 > 0.05$; Induction: $F = 0.000$, $p = 0.97 > 0.05$; Deduction: $F = 0.012$, $p = 0.913 > 0.05$; Interpretation: $F = 0.026$, $p = 0.872 > 0.05$; Evaluation of Arguments: $F = 0.104$, $p = 0.747 > 0.05$). As showed in Table 7, after the 6-week teaching practice, a significant difference existed between the two groups (Recognition of Assumptions: $F = 28.377$, $p < 0.001$; Induction: $F = 30.516$, $p < 0.001$; Deduction: $F = 22.827$, $p < 0.001$; Interpretation: $F = 22.365$, $p < 0.001$; Evaluation of Arguments: $F = 4.904$, $p < 0.05$).

Table 6. Results of the pre-test.

Test	Dimension	EG		CG		*F*	*p*
		M	*SD*	*M*	*SD*		
Critical Thinking	Recognition of Assumptions	3.24	0.98	3.32	0.95	0.164	0.686
	Induction	3.74	0.72	3.74	0.70	0.000	0.97
	Deduction	2.87	0.97	2.89	0.77	0.012	0.913
	Interpretation	3.71	0.89	3.74	0.84	0.026	0.872
	Evaluation of Arguments	3.90	1.11	3.97	0.95	0.104	0.747

Table 7. Results of the post-test.

Test	Dimension	EG		CG		*F*	*p*	Partial η^2
		M	*SD*	*M*	*SD*			
Critical Thinking	Recognition of Assumptions	4.14	0.78	3.34	0.75	28.377	0.000 ***	0.219
	Induction	4.49	0.46	3.92	0.57	30.516	0.000 ***	0.232
	Deduction	3.89	1.00	3.01	0.87	22.827	0.000 ***	0.184
	Interpretation	4.45	0.49	3.79	0.86	22.365	0.000 ***	0.181
	Evaluation of Arguments	4.47	0.88	4.06	1.00	4.904	0.029 *	0.046

Note: * $p < 0.05$; *** $p < 0.001$.

Moreover, Partial η^2 was applied to test the effect size of the one-way ANOVA analysis, which demonstrated the strength of the relationship between the dependent and independent variables (Small effect size: $\geq$0.01 and <0.06, Moderate effect size: $\geq$0.06 and <0.14, Large effect size: $\geq$0.14) [54]. In this study, the effect size of the two groups was small in the evaluation of arguments and large in the other dimensions (Recognition of Assumptions: Partial $\eta^2 = 0.219 > 0.14$; Induction: Partial $\eta^2 = 0.232 > 0.14$; Deduction: Partial $\eta^2 = 0.184 > 0.14$; Interpretation: Partial $\eta^2 = 0.181 > 0.14$; Evaluation of Arguments: Partial $\eta^2 = 0.046 > 0.01$). This suggests that the CCM model was most effective in terms of developing recognition of assumptions, induction, deduction, and interpretation.

5. Discussion

This study explored the cultivation of students' critical thinking in robotics education. The Construction–Criticism–Migration (CCM) Instructional Design was applied in the experimental group to assess its effectiveness in terms of improving students' critical thinking. Some significant findings were achieved. In the study, empirical evidence and data analysis showed that the critical thinking ability was improved in both groups after the six-week robot programming learning (answering RQ1). Meanwhile, the critical thinking of students in the experimental group applying the CCM Instructional Design was significantly improved. However, there was no significant improvement in the control group (answering RQ2).

5.1. Robotics Education Positively Influences Students' Critical Thinking Ability

According to the results, the five dimensions of the critical thinking abilities of all students improved after the 6-week robot programming learning. This finding was consistent with Rim et al.'s (2014) [39] conclusion, which stated that the application of robot programming in mathematics education can effectively promote students' critical thinking abilities. Meanwhile, in robot programming, students' attitudes towards critical thinking becomes more positive, which stimulates them to think critically.

In this study, students' critical thinking abilities included the five sub-dimensions of the recognition of assumptions, induction, deduction, interpretation, and the evaluation of arguments. After the 6-week experiment, the five abilities of critical thinking had all improved. Regarding the recognition of assumptions, this means the ability to recognize hidden premises. In the 6-week robot programming learning, the functions of the robot to be built were imparted to students, which could help give them the prerequisite experience [55] for developing their recognition of assumptions ability ($M = 4.14$, $p = 0.000$). Induction refers to the ability to draw conclusions from results according to known information. Robotics education can attract students' interest in learning, provide them with plenty of room for imagination, and cultivate their innovative thinking, practical abilities, and comprehensive application ability [36]. Therefore, their induction ability also improved during the robot programming education ($M = 4.49$, $p = 0.000$). Deduction ability can help learners to identify the latent relationships between descriptions and previous descriptions and to extrapolate from general principles to conclusions in special cases. In the 6-week experiment, students were allowed to construct the program model according to the robot's functions and to constantly deepen their understanding of the robot program, so as to cultivate their deduction ability ($M = 3.89$, $p = 0.000$). Interpretation is the ability to find evidence from statements and to evaluate the possibility of induction. The learning objective of the 6-week robot programming learning was to make a manipulator based on the robot program. The objective required students to design and construct the robot based on an understanding of the program. Therefore, students needed to interpret the meaning of the robot program so that their interpretation ability could be developed ($M = 4.45$, $p = 0.000$). Regarding the evaluation of arguments, this means the ability to evaluate the support level of arguments in a question. In the 6-week robot programming education, Construction–Criticism–Migration (CCM) was applied by students in the experimental group. They were allowed to independently construct the robot, discuss and argue with each other, and draw lessons from their experiences of failure for migration purposes. During this process, students' evaluation of arguments ability improved ($M = 4.47$, $p = 0.006$).

Robotics education can attract students' interest in learning, provide students with plenty of room for imagination, and cultivate their innovative thinking, practical abilities, and comprehensive application ability [34]. Furthermore, not only does the application of robots in an educational setting construct 21st century competencies in the learning process [56], but at the same time, promotes a range of additional skills such as initiative, creativity, responsibility, and teamwork [57]. Therefore, students can actively participate in robot programming courses to improve their critical thinking ability. In addition, the quality of the designed robot programming course is also very important to the cultivation of students' different kinds of abilities. Bers et al.'s (2014) [58] research pointed out that a high-quality robot programming curriculum was able to improve students' learning in terms of computational thinking and problem solving. Therefore, a high-quality robotics curriculum should be constructed for students to cultivate their critical thinking ability.

5.2. CCM Significantly Positively Affects Students' Critical Thinking Skills

The results indicated that although both groups' critical thinking abilities improved as a result of the 6-week robot programming learning, compared with the control group ($p > 0.05$), students' critical thinking ability in the experimental group ($p < 0.01$) adopting the CCM instructional design significantly improved. Specifically speaking, students' critical thinking in terms of the recognition of assumptions ($p = 0.000$), induction ($p = 0.000$), deduction ($p = 0.000$), interpretation ($p = 0.000$), and the evaluation of arguments ($p = 0.006$) all improved significantly. Therefore, applying the CCM instructional design in robot programming had a significant positive impact on students' critical thinking ability and learning.

The Construction–Criticism–Migration (CCM) instructional design was devised based on the constructivism theory to develop students' critical thinking and knowledge transfer abilities. Constructivism, as a learning theory, defines learning as a process of constructing knowledge based on learning experience [59]. In robotics education, it is vital to provide students with room for imagination [36], and to help them build their knowledge. Furthermore, migration ability is important in robotics education. Migration background has a significant influence on the mastery of knowledge [60]. According to the results of the experimental group, we learned that one of the critical thinking abilities, the deduction ability ($p = 0.000$), improved significantly after the 6-week robotics course. Thus, the adoption of the migration module in the CCM instructional design also played an important role in the cultivation of students' deductive ability. Therefore, in robotics education, CCM instructional design is an effective teaching mode that can be widely used in robot programming education and could be further applied in other course learning.

6. Conclusions

In traditional robot programming curriculum teaching, teachers usually play the main role, and indoctrination education is adopted, which leads to a lack of students' learning ability and critical thinking ability. In order to solve these problems, this study designed a new teaching tool—CCM—which may be beneficial for the improvement of students' critical thinking abilities in the robot programming subject. Therefore, whether students' critical thinking could be promoted during robot programming learning, and the effectiveness of CCM in terms of improving students' critical thinking abilities, were explored in this study.

The results of the study showed that in robotics education, the experimental group students' critical thinking was significantly improved, while that of the control group showed only a slight improvement. Therefore, the robotics education had a significant and positive influence on the cultivation of students' critical thinking ability. Students' active participation in robot programming learning is very beneficial for cultivating their critical thinking ability. In the course of the experiment, the experimental group instructed with the CCM instructional design for robot teaching exhibited significant differences in critical thinking and learning performance compared with the control group. The application of CCM instructional design in robotics education had a significant positive impact on students' critical thinking and learning performance. Thus, in future robot programming education, it would be worth considering adopting Construction–Criticism–Migration (CCM) as a common teaching tool to help students develop their various abilities.

6.1. Implications

The theoretical significance of this research is as follows: first, this research discusses the impact of robotics education on students' critical thinking ability. The results showed that robot programming learning significantly positively influenced students' critical thinking ability, which is helpful for improving students' critical thinking. Furthermore, differing from previous robotics education research, this research creatively adopted the CCM instruction design in robotics education—initially to explore its impact on the development of students' critical thinking ability. This study revealed the advantages of applying the CCM instructional design in a robot programming course. The adoption of the CCM teaching mode in the robotics course promoted the improvement of students' critical thinking ability. Therefore, the application of the CCM teaching mode in robotics education positively influenced students' critical thinking ability significantly.

The practical significance of this study is, firstly, that the conclusions of this study can be used to expand students' and teachers' understanding in robotics education and can popularize robotics education. Secondly, these findings can promote the wide application of CCM instructional design in robot programming learning and promote the transfer of instructional design. CCM instructional design can be used in other courses by teachers, and its effectiveness can be explored in future studies.

6.2. Limitations and Future Work

Although this study enriches the relevant theories of robotics education and CCM instructional design, there are still some defects to be improved in follow-up research. First of all, the data of students in one school do not take into account other schools or areas. Therefore, future studies should be expanded to a larger number of schools or areas. More extensive and representative samples should be collected to verify the conclusions of this study. Secondly, the study ignores the influence of teachers, family, and other factors on students' critical thinking ability during the process of the experiment. In the future, factors affecting students' critical thinking should be considered from multiple dimensions. Finally, since scientific literacy and cognitive load would affect learning effectiveness in robotics education, whether students learning with different teaching tools show enhancements in different aspects of their scientific literacy or have different cognitive loads may be explored in future studies.

Author Contributions: Conceptualization, H.L.; methodology, L.Z.; writing—original draft preparation, L.Z. and J.S.; writing—review and editing, H.L. and L.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This study was supported by the Higher Education Teaching Reform Research Project in Jiangsu (No. 2021JSJG028).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Some or all data and models that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Critical thinking scale.

Component	Items
Recognition of assumptions	1. When I do something, I will think about what I really need to learn. 2. I can make plans and goals independently before I do anything. 3. I will take the initiative to find knowledge information related to learning. 4. I understand what the teacher wants me to learn. 5. I can figure out what I am thinking.
Induction	6. I don't find textbook knowledge abstract. 7. I can always figure out how to do it in an example. 8. I can make accurate inferences and judgments about a situation. 9. I can find out the exact relationship between variables in a problem. 10. I can organize my thinking in an orderly fashion.
Deduction	11. If the last page of a book was torn out, I would invent an ending. 12. I get more excited when I face a challenge. 13. I will choose to think for myself instead of turning to the teacher when I am in trouble. 14. I'm more interested in guessing about the unknown. 15. I come up with novel ideas.
Interpretation	16. I can analyze and explain things logically. 17. I dare to raise my doubts. 18. I am able to understand and accept different points of view from others. 19. I can understand the information (icon, text, etc.) provided in the question correctly. 20. I can say the same thing in different ways to different people.
Evaluation of arguments	21. I can control myself and keep working towards my goals. 22. I can reflect on myself after making a mistake. 23. I can collect learning information through various channels. 24. I often grade my academic performance or grades. 25. I've always been a good judge of conflict.

References

1. UNESCO. *Education for Sustainable Development: An Expert Review of Processes and Learning*; UNESCO: Paris, France, 2018; p. 8.
2. Taimur, S.; Sattar, H. *Education for Sustainable Development and Critical Thinking Competency. Quality Education*; Springer: Cham, Switzerland, 2019.
3. Bie, H.D.; Wilhelm, P.; Hans, V. The halpern critical thinking assessment: Toward a dutch appraisal of critical thinking. *Think. Ski. Creat.* **2015**, *17*, 33–44. [CrossRef]
4. Alwali, A.K. Benefits of using critical thinking in high education. In Proceedings of the 5th International Technology, Education and Development Conference, Valencia, Spain, 7–9 March 2011; pp. 2527–2532.
5. Arini, W.; Juliadi, F. Analisis kemampuan berpikir kritis pada mata pelajaran fisika untuk pokok bahasan Vektor siswa kelas X SMA Negeri 4 lubuklinggau, Sumatera Selatan. *Berk. Fis. Indones. J. Ilm. Fis. Pembelajaran Dan Apl.* **2018**, *10*, 1–11.
6. Bermingham, M. Clearing up "critical thinking": Its four formidable features. *Creat. Educ.* **2015**, *6*, 421–427. [CrossRef]
7. Allagui, B. Ted talk comments to enhance critical thinking skills in an undergraduate reading and writing course. *Educ. Inf. Technol.* **2020**, *26*, 2941–2960. [CrossRef]

8. Flores, K.L.; Matkin, G.S.; Burbach, M.E.; Quinn, C.E.; Harding, H. Deficient critical thinking skills among college graduates: Implications for leadership. *Educ. Philos. Theory* **2010**, *44*, 212–230. [CrossRef]
9. Kroiče, I. Critical communicative approach in the vocational secondary education. In Proceedings of the International Scientific Conference, Rezekne, Latvia, 27–28 May 2016; Volume 2, p. 131.
10. Puolimatka, T. Constructivism and critical thinking. *Inq. Crit. Think. Across Discip.* **2003**, *22*, 5–12. [CrossRef]
11. Al-Fadhli, S.; Khalfan, A. Developing critical thinking in e-learning environment: Kuwait university as a case study. *Assess. Eval. High. Educ.* **2009**, *5*, 529–536. [CrossRef]
12. Karanikić, P.; Bezić, H. Measuring the knowledge transfer performance at universities. *Econ. Thought Pract.* **2021**, *30*, 189–203. [CrossRef]
13. Lee, J.; Son, H.K. Comparison of learning transfer using simulation problem-based learning and demonstration: An application of Papanicolaou smear nursing education. *Int. J. Environ. Res. Public Health* **2021**, *18*, 1765. [CrossRef]
14. Wang, S.; Jiang, L.; Meng, J.; Xie, Y.; Ding, H. Training for smart manufacturing using a mobile robot-based production line. *Front. Mech. Eng.* **2021**, *16*, 249–270. [CrossRef]
15. Xu, R. Research on Robot Education in Primary School. In Proceedings of the 2018 6th International Education, Economics, Social Science, Arts, Sports and Management Engineering Conference (IEESASM 2018), Qingdao, China, 29–30 December 2019.
16. Cheng, Y.H.; Hsiao, J.M. Exploring the intention to continuance of learning programming at elementary school of rural area by the mbot robot. In Proceedings of the International Conference on Artificial Life and Robotics, Online, Japan, 21–24 January 2021; pp. 61–64.
17. Lee, E.; Lee, Y. The effect of a robot programming learning on problem solving ability. *J. Korean Assoc. Comput. Educ.* **2007**, *10*, 19–27.
18. Yoo, I.H. The effects on flow at using robots of introductory programming course. *J. Korean Assoc. Comput. Educ.* **2013**, *17*, 329–337. [CrossRef]
19. Kim, S.W.; Park, H.; Lee, Y. Development of project-based robot education program for enhancing interest toward robots and computational thinking of elementary school students. *J. Korea Soc. Comput. Inf.* **2019**, *24*, 247–255.
20. Zetriuslita, H.; Ariawan, R.; Nufus, H. Students' critical thinking ability: Description based on academic level and gender. *J. Educ. Pract.* **2016**, *7*, 154–164.
21. Arisoy, B.; Aybek, B. The Effects of Subject-Based Critical Thinking Education in Mathematics on Students' Critical Thinking Skills and Virtues. *Eurasian J. Educ. Res.* **2021**, *92*, 99–120. [CrossRef]
22. Paul, R. *Critical Thinking: How to Prepare Students for a Rapidly Changing World*; Foundation for Critical Thinking: Santa Rosa, CA, USA, 1995.
23. Polat, E.; Kutlu, L.; Ay, F.; Pursa, S.; Erkan, H.A. Decision-making styles, anxiety levels, and critical thinking levels of nurses. *Jpn. J. Nurs. Sci.* **2019**, *16*, 309–321. [CrossRef]
24. Kennedy, M.; Fisher, M.B.; Ennis, R.H. Critical Thinking: Literature Review and Needed Research. In *Educational Values and Sognitive Instruction: Implications for Reform*; Idol, L., Fly Jones, B., Eds.; Lawrence Erlbaum: Hillsdale, NJ, USA, 1991; pp. 11–40.
25. Jackson, L. Increasing Critical Thinking Dkills to Improve Problem-Solving Ability in Mathematics. Master's Thesis, Saint Xavier University, Chicago, IL, USA, 2000.
26. Kang, S.H.; Yoon, S.J.; Shin, S.J. The relationships of critical thinking dispositions with critical thinking abilities, creative dispositions and thinking styles in elementary school students. *J. Yeolin Educ.* **2005**, *13*, 33–45.
27. Martyaningrum, I.D.; Juandi, D.; Jupri, A. The impact of problem based learning model through e-learning on students' critical thinking ability. *J. Phys. Conf. Ser.* **2021**, *1806*, 012085. [CrossRef]
28. Hamid, A. Analysis of students' critical and creative thinking style and cognitive ability on chemistry. In Proceedings of the 5th SEA-DR (South East Asia Development Research) International Conference 2017 (SEADRIC 2017), Banjarmasin, Indonesia, 3–4 May 2017; pp. 302–304.
29. Arviana, R.; Irwan; Dewi, M.P. Problem based learning in mathematics education and its effect on student's critical thinking. *J. Comput. Theor. Nanosci.* **2018**, *24*, 211–213. [CrossRef]
30. Nirmala, S.D.; Rahman, R.; Musthafa, B. Comparing students' critical thinking elementary school in different area with utilizing fives strategy. *Adv. Sci. Lett.* **2018**, *24*, 8357–8360. [CrossRef]
31. Kim, J.H.; Moon, S.H. A survey on after-school robot teacher's perception of robot education in elementary school. *J. Korean Elem. Educ.* **2010**, *21*, 117–133.
32. Wei, C.W.; Hung, I.C.; Lee, L.; Chen, N.S. A Joyful classroom learning system with robot learning companion for children to learn mathematics multiplication. *Turk. Online J. Educ. Technol.* **2011**, *10*, 11–23.
33. Kahn, P.H., Jr.; Kanda, T.; Ishiguro, H.; Freier, N.G.; Severson, R.L.; Gill, B.T.; Ruckert, J.H.; Shen, S. "Robovie, you'll have to go into the closet now": Children's social and moral relationships with a humanoid robot. *Dev. Psychol.* **2012**, *48*, 303–314. [CrossRef] [PubMed]
34. Toh, L.P.E.; Causo, A.; Tzuo, P.W.; Chen, I.M.; Yeo, S.H. A review on the use of robots in education and young children. *Educ. Technol. Soc.* **2016**, *19*, 148–163.
35. Ioannou, A.; Kartapanis, I.; Zaphiris, P. *Social Robots as Co-Therapists in Autism Therapy Sessions: A Single-Case Study*; Tapus, A., André, E., Martin, J.C., Ferland, F., Ammi, M., Eds.; Lecture Notes in Computer Science; Springer: Cham, Switzerland, 2015; pp. 255–263.

36. Yeun, K.T. Effect of Education Program using ICT based SW Education Robot System on Academic Interest. *Asia-Pac. J. Multimed. Serv. Converg. Art Humanit. Sociol.* **2019**, *9*, 833–844.
37. Kopcha, T.J.; McGregor, J.; Shin, S.; Qian, Y.; Choi, J.; Hill, R.; Mativo, J.; Choi, I. Developing an integrative STEM curriculum for robotics education through educational design research. *J. Form. Des. Learn.* **2017**, *1*, 31–44. [CrossRef]
38. Bae, Y.K.; Nam, J.W. Impact of robot programming education in application of web 2.0 on improving problem solving ability. *J. Korea Contents Assoc.* **2010**, *10*, 468–475. [CrossRef]
39. Rim, H.; Choi, I.; Noh, S. A study on the application of robotic programming to promote logical and critical thinking in mathematics education. *Math. Educ.* **2014**, *53*, 413–434. [CrossRef]
40. Innwoo, P. A conceptual analysis on teaching and instruction, instructional theory, and instructional design theory. *J. Educ. Technol.* **2015**, *31*, 633–653. [CrossRef]
41. Merrill, M.D.; Li, Z.; Jones, M.K. Limitations of first generation instructional design (ID1). *Educ. Technol.* **1990**, *30*, 7–11.
42. Moreno, R.; Mayer, M.R. Interactive multimodal learning environments. *Educ. Psychol. Rev.* **2007**, *19*, 309–326. [CrossRef]
43. Stein, C. Botball: Autonomous students engineering autonomous robots. In Proceedings of the 2002 Annual Conference, Montreal, QC, Canada, 16–19 June 2002.
44. Vicente, F.R.; Zapatera, A.; Montes, N.; Rosillo, N. STEAM Robotic Puzzles to Teach in Primary School. A Sustainable City Project Case. *Robot. Educ.* **2020**, *1023*, 65–76. [CrossRef]
45. Nugent, G.; Barker, B.; Toland, M.; Grandgenett, N.; Hampton, A.; Adamchuk, V. *Measuring the Impact of Robotics and Geospatial Technologies on Youth Science, Technology, Engineering and Mathematics Attitudes*; Association for the Advancement of Computing in Education (AACE): Waynesville, NC, USA, 2009.
46. Yu, K.C.; Lin, K.Y.; Chang, S.F. The development and validation of a mechanical critical thinking scale for high school students The development and validation of a mechanical critical thinking scale for high school students. *EURASIA J. Math. Sci. Technol. Educ.* **2017**, *13*, 1361–1376.
47. Renaud, R.D.; Murray, H.G. A comparison of a subject-specific and a general measure of critical thinking. *Think. Ski. Creat.* **2008**, *3*, 85–93. [CrossRef]
48. Fabrigar, L.R.; Wegener, D.T.; MacCallum, R.C.; Strahan, E.J. Evaluating the use of exploratory factor analysis in psychological research. *Psychol. Methods* **1999**, *4*, 272. [CrossRef]
49. Conway, J.M.; Huffcutt, A.I. A review and evaluation of exploratory factor analysis practices in organizational research. *Organ. Res. Methods* **2016**, *6*, 147–168. [CrossRef]
50. Fornell, C.; Larcker, D.F. Evaluating structural equation models with unobservable variables and measurement error. *J. Mark. Res.* **1981**, *18*, 39–50. [CrossRef]
51. Abbas, A.; Sunguh, K.K.; Arrona-Palacios, A.; Hosseini, S. Can we have trust in host government? Self-esteem, work attitudes and prejudice of low-status expatriates living in China. *Econ. Sociol.* **2021**, *14*, 11–31.
52. Nakagawa, S.; Cuthill, I.C. Effect size, confidence intervals and statistical significance: A practical guide for biologists. *Biol. Rev.* **2007**, *82*, 591–605. [CrossRef]
53. Cohen, J. *Statistical Power Analysis for the Behavioral Sciences*, 2nd ed.; Erlbaum: Hillsdale, NJ, USA, 1988.
54. Dörnyei, Z. *Research Methods in Applied Linguistics: Quantitative, Qualitative, and Mixed Methodologies*; Oxford University Press: Oxford, UK, 2007.
55. Podvoyskiy, D. Knowledge and Consciousness as a "World-Constructing" Tool: A Multidisciplinary Perspective. *Sociol. Obozr.* **2018**, *17*, 274–301. [CrossRef]
56. Stork, M.G. Supporting Twenty-First Century Competencies Using Robots and Digital Storytelling. *J. Form. Des. Learn.* **2020**, *4*, 43–50. [CrossRef]
57. Kandlhofer, M.; Steinbauer, G. Evaluating the impact of educational robotics on pupils' technical- and social-skills and science related attitudes. *Robot. Auton. Syst.* **2016**, *75*, 679–685. [CrossRef]
58. Bers, M.U.; Flannery, L.; Kazakoff, E.R.; Sulivan, A. Computational thinking and tinkering: Exploration of an early childhood robotics curriculum. *Comput. Educ.* **2014**, *72*, 145–157. [CrossRef]
59. Jumaat, N.F.; Tasir, Z.; Abd Halim, N.D.; Ashari, Z.M. Project-based learning from constructivism point of view. *Adv. Sci. Lett.* **2018**, *23*, 7904–7906. [CrossRef]
60. Happ, R.; Nagel, M.T.; Zlatkin-Troitschanskaia, O.; Schmidt, S. How migration background affects master degree students' knowledge of business and economics. *Stud. Higher Educ.* **2019**, *46*, 457–472. [CrossRef]