Circuits Kit K–12 Outreach: Impact of Circuit Element Representation and Student Gender

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***Abstract*—Outreach to K–12 schools is important for attracting students to electrical engineering. Circuits kits provide K–12 students hands-on interactions with electrical circuits. The goal of this experimental study was to investigate the effects of two types of electrical circuit element representations on the self-reported perceptions of the outreach activity and learning of elementary and high school students. In the abstract representation type, the circuit elements were marked with the standard engineering symbols. In the concrete representation type, the circuit elements, such as batteries and light bulbs, were familiar to the students. Perceived student enjoyment, understanding, and cognitive load were assessed through surveys. Student learning was measured with a post-test. The impacts of student gender and developmental level were also analyzed. Results indicate that for elementary school students, the concrete representation led to higher understanding ratings and lower cognitive load ratings than the abstract representation, while there was no difference in student learning between the two representation conditions. For high school students, there were no significant differences in student perceptions or learning between the two representation conditions. However, male high school students gave significantly higher interest and understanding ratings as well as lower cognitive load ratings than their female counterparts, even though there was no significant difference in student learning between the genders. Elementary school students reported higher enjoyment for the circuits kit activity and higher cognitive load than the high school students.**

***Index Terms*—Circuit element representation, developmental level, electrical circuits kit, K–12 outreach, student gender.**

I. Introduction

A. K–12 Outreach With Circuits Kits

A NUMBER of recent initiatives have identified outreach to K–12 schools as a key mechanism for educating K–12 students about basic electrical engineering and raising awareness of electrical engineering as a field of study and a career choice [1]–[6]. Electrical circuits kits, such as Snap Circuits, allow hands-on experimentation with electrical circuits during outreach programs to K–12 schools. A critical open question in designing circuits kit activities for K–12 students is how circuit elements should be represented in the circuits. Should concrete circuit elements that are familiar to students from everyday life, such as batteries and light bulbs, be used? Or should abstract circuit elements characterized by engineering symbols (e.g., the symbol for a dc voltage source) be used? Which of the two representations leads to higher enjoyment of the outreach activity, higher understanding of electrical circuits, and lower cognitive load during the circuits activity?

This study examined the effects of the abstract and concrete representation of circuit elements on self-reported enjoyment, understanding, and cognitive load ratings and post-test performance of elementary and high school students. The impact of student gender and developmental level on the ratings of the outreach activity and the post-test performance was also analyzed. This study was conducted with a circuits-kits-based hands-on lesson that introduces a basic resistive circuit to novice students without any prior knowledge of engineering or electricity. The lesson is well suited for integration into the science curricula of K–12 schools.

B. Background and Related Work

1) Engineering Outreach Activities: A wide range of outreach activities for increasing awareness of electrical engineering among K–12 students have been reported in the literature. The outreach activities range from elementary schools [7]–[10] to middle schools [11], [12] and high schools [13]–[16]. Outreach summer programs have also received significant attention [17], [18]. The evaluation results in these studies indicate that students participating in the outreach activities generally reported positive attitudes toward electrical engineering at the conclusion of the activities. Hands-on activities are included in many of these outreach programs. The present study is complementary to the existing literature on outreach programs in that it examines the effects of the representation of circuit elements in a hands-on circuit outreach activity.

2) Representation of Circuit Components: Abstract representations can assist learners to focus on the underlying structure of a system or concept and avoid distractions due to superficial system aspects [19]. Therefore, abstract representations may reduce the cognitive load for understanding a circuit [20], [21]. On the other hand, concrete representations can help novices relate new concepts to their prior knowledge and experiences, and thus can promote learning [22].

Effects of the representation type of electrical circuit components have previously only been studied for a computer-based instructional module [23] with middle school students; the present study examines hands-on circuit instruction for both elementary and high school students. The study [23] found that abstract representation led to improved learning of the

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circuit analysis principles compared to concrete representation for the middle school population. In addition to learning, the present study examines perceived student enjoyment and understanding that were not addressed by the previous computer-based experiment [23].

The related issue of representation through graphics or equations has been examined in [24] and [25], while the study [26] explored the impact of learning from hands-on activities or computer-based simulations.

3) Gender Stereotypes of Engineering: In elementary school, male and female students typically have equivalent positive attitudes toward science and technology [27]. However, among older students, there is a profound tendency for females to avoid science- and technology-oriented courses and careers [28]. Negative stereotypes toward science and technology are considered a critical foundation for this tendency [29]. In particular, science and engineering are stereotyped as masculine study areas and occupations that are unsuitable for females [30]. Since these stereotypical views of engineering have a profound impact on career choices [31]–[33], a number of electrical engineering outreach efforts have specifically focused on female K–12 students [34]–[38].

A few studies have revealed that female students tend to have more negative attitudes toward math and science and perceive their math and engineering capabilities as lower than those of their male counterparts, even though objective tests indicate equivalent math and engineering capabilities [39], [40]. The present study adds to these existing studies by examining the impact of gender on attitudes and learning in a hands-on circuit outreach activity for two distinct age groups, namely elementary and high school students.

II. Study Methodology

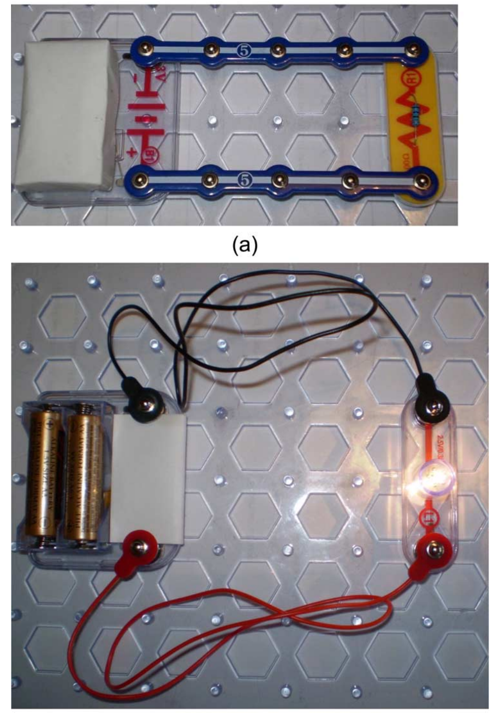
A. Participants and Design

The elementary school participants were a total of 41 students (25 males and 16 females; four African Americans, 30 Hispanics, four Native Americans, and three Caucasians) in the fourth grade at a public elementary school in the southwestern US. The high school participants were a total of 91 students (48 males and 43 females; 10 African Americans, four Asian Americans, 30 Hispanics, seven Native Americans, 26 Caucasians, and 14 who indicated their ethnicity as Other) in grades 9–12 at a public high school in the southwestern United States. The students had no school instruction on electrical circuits prior to participating in the outreach activity.

The students of each class were randomly divided into groups of three to four students. Each group was randomly assigned to either the abstract or the concrete representation condition. The circuit instructional activity was facilitated by one instructor for each student group. The instructors were three males and three females in the age range from 24 to 36 years old. Instructors were experts in the domain of elementary electrical circuits. All instructors wore casual clothing, namely blue jeans pants and university logo T-shirts.

B. Circuits Kit Instructional Lesson

1) Instructional Materials: The instructional materials for each group consisted of one Snap Circuits JR. SC-100 kit. Each group was provided with a photograph showing a single resistor circuit completed with the kit parts. The photograph showed either a circuit with abstract representation, see Fig. 1(a), or concrete representation, see Fig. 1(b). The abstract circuit was built with the 100-Ω resistor, the solid connectors, and a modified voltage source element that had the batteries covered up such that only the standard symbol for a dc voltage source was visible. The concrete circuit was built with a light bulb, wires, and a voltage source element with visible batteries.



(a)

(b)

Fig. 1. Photograph of single resistor circuit. (a) Abstract representation. (b) Concrete representation.

2) Instructional Sequence: Each group's instructor first informed the students about the objectives of the lesson, namely building an electric circuit, measuring current, and learning about Ohm's law. The instructor provided the group with one set of instructional materials, i.e., one unconstructed circuits kit and one photograph of the completed electrical circuit, see Fig. 1 (abstract or concrete, depending on the representation condition). The instructor asked the group to build the circuit displayed in the photograph, and then assisted as needed. Once the circuit had been built, the instructor explained voltage, current, and resistance and how they are mathematically related with Ohm's law. This explanation followed a prescribed script, specific to the representation condition; it used abstract terminology (e.g., voltage source and resistor) in the abstract representation condition or concrete terminology (e.g., battery and light bulb) in the concrete representation condition. At predefined passages in the script narration, the instructor pointed with the index finger to the circuit element corresponding to the narrated passage, e.g., the voltage source (or battery in the other representation) when narrating the explanation of voltage.

Next, the instructor guided the students in measuring the current through the circuit with a multimeter. The students read

TABLE I
DESCRIPTIVE STATISTICS MEAN M AND STANDARD DEVIATION SD FOR ENJOYMENT, UNDERSTANDING, AND COGNITIVE LOAD RATINGS (PERCEPTIONS), AS WELL AS POST-TEST SCORE, BY DEVELOPMENTAL LEVEL AND REPRESENTATION CONDITION WITH N DENOTING STUDENT NUMBERS. SUPERSCRIPT ^{r} INDICATES STATISTICALLY SIGNIFICANT DIFFERENCES BETWEEN REPRESENTATION CONDITIONS. SUPERSCRIPT ^{d} INDICATES STATISTICALLY SIGNIFICANT DIFFERENCES BETWEEN DEVELOPMENTAL LEVELS

Developmental Level / Representation Condition		Student Perceptions: Enjoyment (max: 5)		Understanding (max: 5)		Cognitive Load (max: 5)		Post-test (max: 4)	
Elementary School	*N*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Abstract	21	4.52	0.46	3.33^r	0.80	3.43^r	0.60	3.71	0.56
Concrete	20	4.48	0.64	3.88^r	0.78	2.88^r	0.67	3.65	0.67
Total	41	4.50^d	0.55	3.60	0.82	3.16^d	0.68	3.68	0.61
High School									
Abstract	47	3.84	0.77	3.81	0.86	2.16	0.82	3.79	0.75
Concrete	44	3.85	0.80	3.86	0.70	1.93	0.68	3.86	0.35
Total	91	3.85^d	0.78	3.84	0.78	2.05^d	0.76	3.82	0.59

off the current value. Then, the instructor requested the students to calculate the resistance of the circuit using the voltage value displayed on the voltage source element (battery) and the measured current. The instructor provided feedback and assistance as needed to ensure that the group completed the circuit and arrived at the correct resistance value.

C. Evaluation Instruments

At the conclusion of the instructional sequence, the effects of the instructional lesson were evaluated using a paper-based survey and a paper-based post-test. The survey was a six-item Likert instrument asking students to independently rate their perceptions on a five-point scale that ranged from 1—strongly disagree to 5—strongly agree. Two survey items, "I liked the circuit activity" and "I enjoyed learning using the circuits," related to learner perceived enjoyment of the circuits kit activity; this enjoyment subscale had a high level of internal reliability as indicated by a Cronbach $\alpha = 0.86$ [41]. Two survey items, "The circuit parts looked confusing" and "I understood the function of the circuit parts," related to the perceived level of understanding of the circuit components (Cronbach $\alpha = 0.70$). Two survey items, "Learning Ohm's Law was difficult" and "Learning Ohm's Law required a lot of effort," adapted from [38] related to the perceived cognitive load (Cronbach $\alpha = 0.80$).

The post-test consisted of four single-resistor circuit problems posed in abstract form. Two questions asked learners to independently evaluate the resistance from given voltage and current values. One question provided the voltage and resistance values and asked for the current value, while another question provided resistance and current values and asked for the voltage value. Two engineering instructors, who were blind to the representation condition and student demographics, scored the post-test questions by assigning one point to each correctly solved problem. The two instructors had an interrater reliability (agreement) of 98.5%.

III. RESULTS

To verify that the instructor did not have a significant impact on student perceptions or learning, a preliminary set of one-way analyses of variance (ANOVA) was conducted, with instructor name as independent variable and each of the evaluation measures (perceived enjoyment, perceived understanding, perceived cognitive load, and post-test score) as dependent variable. These analyses indicated that instructor did not have a significant impact on enjoyment, $F(6,125) = 0.62, p = 0.71$, understanding, $F(6,125) = 0.65, p = 0.69$, cognitive load, $F(6,125) = 1.74, p = 0.12$, or post-test score, $F(6,125) = 0.68, p = 0.67$. Also, when split into developmental groups, none of these dependent variables were significantly impacted by experimenter for elementary students (all $F'\text{s} < 1$) or for high school students (all $F'\text{s} < 1$).

A. Impact of Circuit Element Representation

To determine the effect of the representation type on the evaluation measures, a series of independent (unpaired) samples t-tests were conducted, using representation type (abstract or concrete) as independent variable, and each of the evaluation measures as dependent variables. For elementary school students, results did not indicate a significant difference between abstract and concrete representations on perceived enjoyment, $t(39) = 0.28, p = 0.78$. However, there were significant differences between representation conditions on perceived understanding, $t(39) = 2.21, p < 0.05$, and perceived cognitive load, $t(39) = 2.80, p < 0.01$. Students in the concrete representation condition reported significantly higher perceived understanding compared to the students in the abstract condition; see Table I for the descriptive statistics. Perceived cognitive load was higher for the students in the abstract condition compared to the concrete condition. No significant difference was found between representation types for post-test scores, $t(39) = 0.33, p = 0.74$.

For high school students, the analyses indicated no significant differences between representation types for perceived enjoyment, $t(89) = 0.07, p = 0.94$, perceived understanding, $t(89) = 0.33, p = 0.74$, perceived cognitive load, $t(89) = 1.44, p = 0.15$, or post-test score, $t(89) = 0.62, p = 0.54$.

B. Impact of Student Gender

A series of independent samples t-tests were conducted, with student gender as the independent variable and each of the evaluation measures as dependent variables. For elementary school students, there were no significant differences between male and female students on perceived enjoyment, understanding, cognitive load, or post-test scores (all $F'\text{s} < 1$). High school males reported significantly higher enjoyment, $t(89) = 2.02, p < 0.05$,

TABLE II
DESCRIPTIVE STATISTICS MEAN M AND STANDARD DEVIATION *SD* FOR ENJOYMENT, UNDERSTANDING, AND COGNITIVE LOAD RATINGS (PERCEPTIONS), AS WELL AS POST-TEST SCORE, BY DEVELOPMENTAL LEVEL AND GENDER WITH N DENOTING STUDENT NUMBERS. SUPERSCRIPT g INDICATES STATISTICALLY SIGNIFICANT DIFFERENCES BETWEEN GENDERS

Developmental Level / Representation Condition		Student Perceptions						Post-test (max: 4)	
		Enjoyment (max: 5)		Understanding (max: 5)		Cognitive Load (max: 5)			
Elementary School	*N*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Male	25	4.54	0.61	3.62	0.86	3.18	0.72	3.64	0.70
Female	16	4.44	0.44	3.56	0.79	3.13	0.65	3.75	0.45
High School									
Male	48	4.00^{g}	0.71	3.99^{g}	0.73	1.90^{g}	0.71	3.85	0.62
Female	43	3.67^{g}	0.83	3.66^{g}	0.81	2.22^{g}	0.79	3.79	0.56

and understanding, $t(89) = 2.02, p < 0.05$, than their female counterparts; see Table II for the descriptive statistics. Also, high school males reported significantly lower perceived cognitive load than the female students, $t(89) = 2.07, p < 0.05$. No significant difference was detected between male and female performance on the post-test, $t(89) = 0.51, p = 0.61$.

C. Impact of Developmental Level

Independent samples t-tests revealed that the elementary school students had significantly higher perceived enjoyment, $t(130) = 4.85, p < 0.001$, and significantly higher cognitive load, $t(130) = 7.99, p < 0.001$, compared to the high school students; see Table I for descriptive statistics. No significant differences were detected between developmental levels for perceived understanding, $t(130) = 1.26, p = 0.21$, or performance on post-test, $t(130) = 1.59, p = 0.11$.

IV. DISCUSSION

A. Impact of Circuit Element Representation

Among the elementary school students, the self-reported understanding ratings of the circuit components were significantly higher with the concrete representation than with the abstract representation. At the same time, the elementary school students' cognitive load ratings were significantly lower with the concrete representation. In contrast, for the high school students, the representation type did not significantly influence any of the ratings. Furthermore, the representation type did not influence the post-test performance, neither for the elementary school students nor the high school students.

The fourth grade elementary school students had little or no prior experience with abstract symbols representing components of a physical or engineering system. Thus, they probably perceived the abstract circuit elements as confusing, as the lower ratings for level of understanding indicate. Concomitantly, they perceived higher levels of cognitive load working with the unfamiliar abstract components. On the other hand, elementary school students are familiar with batteries and light bulbs from everyday use. Building and measuring a simple circuit with these familiar components led to higher perceived levels of understanding and lower perceived cognitive load. The enjoyment ratings were uniformly high, indicating that the elementary school students derived great enjoyment from the hands-on circuit activity irrespective of the circuit component representation. Interestingly, the differences in the elementary students' understanding and cognitive load perceptions did not carry over to their performance on the post-test.

This result has two implications. The first implication is that the elementary school students in the concrete condition were successful in transitioning from working and learning with concrete circuit components—see Fig. 1(b)—to solving the post-test problems posed in abstract form. The abstract-only format of the post-test is a limitation of this study. Future studies could examine the performance of students who learned with abstract or concrete representations on post-tests posed in abstract or concrete form. The second implication is that despite the self-reported lower levels of understanding, the students in the abstract condition successfully learned the basic circuit concepts and did not differ significantly in post-test performance from the students in the concrete representation condition. This second result on the effectiveness of the abstract representation is complementary to earlier results for electric circuit learning with a computer-based instructional module [23]. In the study [23], middle school students without prior exposure to abstract electrical engineering symbols who learned with abstract representations, and subsequently solved post-test problems posed in concrete form, scored higher than students who learned with concrete representations.

In contrast to the elementary school students, the high school students in this present experiment were not significantly influenced in their self-reported ratings, or their post-test performance, by the different representations. High school students are cognitively more developed than elementary school students and, thus, can more readily engage in abstract thinking [43], [44].

In summary, the results on the representations from this study indicate that for electrical circuit outreach to elementary schools, the concrete representation is preferable, as it leads to more favorable student perceptions of the outreach activity compared to the abstract representation. For high school students, there was not a statistically significant difference between representation types in student ratings or learning. However, for these students, the abstract representation is preferable, as it better prepares the students for further studies in electrical engineering, which mainly employ abstract circuit symbols.

B. Impact of Student Gender

At the elementary school level, enjoyment, understanding, and cognitive load ratings as well as post-test scores did not differ significantly between males and females. On the other hand, for high school students, males reported significantly higher enjoyment and understanding as well as significantly lower cognitive load than females. However, females performed equivalently to males on the post-test, i.e., there was no significant difference between the mean post-test scores of females and males. The widely held negative stereotypes of females toward engineering [29], [30] may have influenced the perceptions of the female high school students. The stereotype is that engineering is a hard and male-dominated discipline; therefore females may have had a preconceived notion that the circuit activity was supposed to provide little enjoyment and be difficult for them to understand.

The results for the elementary school students indicate that these stereotypical perceptions of engineering had not yet permeated in these younger females. This finding is consistent with extensive statistics [27], [45] that indicate that both sexes have equally positive attitudes toward math and science at the elementary school age.

Overall, the gender results indicate that while female students at the high school age gain equivalent knowledge from a circuits kit outreach activity to their male counterparts, they perceive the activity as less enjoyable and more challenging. This discrepancy between actual knowledge (as measured with a test) and perceptions (as rated by the students on a survey) was not observed at the elementary school level. Thus, the findings from this study provide further evidence that preconceived negative notions of engineering develop over the K–12 education process and support early outreach interventions to help curb the formation of negative attributions to electrical engineering by female students. Moreover, examining strategies to address the discrepancy between actual knowledge and perceptions in older students is an important direction for future research.

C. Impact of Developmental Level

Despite experiencing significantly higher cognitive load during the lesson on electrical circuits, the elementary school students reported significantly higher levels of enjoyment compared to the high school students. In particular, the average enjoyment rating by the elementary school students was 4.5, where a rating of 4 corresponds to students saying they "Agree," and 5 corresponds to "Strongly Agree," with the positive survey statements about having enjoyed the circuit outreach activity. The significant drop observed in the average enjoyment rating for the circuit outreach activity from 4.5 for the elementary school age to 3.85 for the high school age complements the observation reported in [46] that interest in mathematics drops as students advance from elementary to high school.

In order to allow for a comparison of developmental levels, this study employed the same outreach activity with a basic electrical circuit for novice elementary and high school students. The high school students may have perceived the basic electrical circuit as overly simplistic, which may have contributed to their lower enjoyment ratings. Examining the effects of more complex outreach activities on high school students is an important direction for future research.

V. Conclusion

This study examined the effects of abstract and concrete representations of electrical circuit elements in a circuits kit-based outreach activity to elementary and high school students. The study results indicate that elementary school students perceive the concrete circuits as easier to understand. The test performance of elementary school students as well as the perceptions and test performance of high school students are independent of the representation. The study revealed a significant gender effect on perceptions of the outreach activity among high school students. Female high school students perceived the activity as less enjoyable and more challenging, while achieving equivalent test scores to their male counterparts. Overall, elementary school students enjoyed the outreach activity significantly more than the high school students despite experiencing higher cognitive load. This result together with the findings that the perceived understanding levels and post-test scores of the elementary school students were equivalent to the high school students, underscores the importance and potential of electrical circuit outreach at the elementary school level.

One direction for future research is to examine strategies to increase positive engineering perceptions by female high school students to bring these perceptions in line with their actual demonstrated knowledge level. For instance, follow-up outreach visits could review the test results of the previous visits, demonstrating the equivalent test performance of males and females so that the self-efficacy of female students is increased. Another direction is to examine how regular outreach activities that begin in elementary school and continue through middle and high school could mitigate the permeation of negative engineering stereotypes among female students.

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