Introductory Circuit Analysis Learning From Abstract and Contextualized Circuit Representations: Effects of Diagram Labels

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***Abstract*—Novice learners are typically unfamiliar with abstract engineering symbols. They are also often unaccustomed to instructional materials consisting of a combination of text, diagrams, and equations. This raises the question of whether instruction on elementary electrical circuit analysis for novice learners should employ contextualized representations of the circuits with familiar components, such as batteries, or employ abstract representations with the abstract engineering terms and symbols. A further question is if text labels in the circuit diagrams would aid these learners. This study examined these research questions with a "2 × 3" experimental design, in which the two forms of representation (abstract or contextualized) were considered under three types of diagram labeling (no labels, static labels, or interactive labels). The design was implemented in an instructional module on elementary circuit analysis for novice learners. Results indicated that abstract representations led to higher near- and far-transfer post-test scores, and that interactive (student-generated) labeling resulted in higher near-transfer scores than either the no-labels or static-labels conditions. These findings suggest that abstract representations promote the development of deep, transferrable knowledge and that generative methods of integration, such as interactive diagram labeling, can facilitate learning with multiple external representations.**

***Index Terms*—Circuit analysis instruction, circuit diagram, diagram label, electrical circuit analysis, multiple external representations, novice learner.**

I. Introduction

A. Challenges of Circuit Representations for Novice Learners

REPRESENTING engineering content to effectively support learning of engineering concepts and problem solving is a significant challenge in engineering education [1]–[3]. Content representation is particularly challenging in electrical engineering due to the abstract, intangible nature of many electrical concepts and quantities; for example, an electrical current cannot (safely or directly) be felt by hand, whereas, say, in teaching mechanical engineering, the force exerted by a spring can readily be felt. Also, the abstract conventional symbols of electrical circuit elements bear little visual resemblance to their real-life counterparts, posing significant learning difficulties and cognitive processing demands [4], [5].

The challenges for effective circuit representation are especially pronounced for novice learners who have not previously been exposed to formal instruction in electrical circuits. These novice learners are unfamiliar with the abstract electrical circuit (model) components, such as voltage sources and resistive electrical devices (resistors), and their abstract standard symbols, such as the zigzag line symbol for a resistor. However, most novice learners are familiar with basic electrical components from everyday life, such as batteries and light bulbs.

B. Research Questions Examined in Present Study

A fundamental research question is whether introductory instruction in electrical circuit analysis for novice learners should employ contextualized representations using contextualized terms from everyday life, such as "battery" or "light bulb," and real-life illustrations (images) of these everyday electrical components. Or, instead, would abstract representations using abstract terms and symbols result in better learning of elementary electrical circuit analysis? In the context of this research question on electrical circuit representations, this study sought to examine the effects of labels in circuit diagrams for novice learners. Instruction in electrical circuit analysis relies extensively on a combination of text, diagrams, and mathematical equations [6]–[11]. As briefly reviewed in Section I-D, successful learning from such a combination of text, diagrams, and equations (referred to in cognitive psychology as *multiple external representations*) requires mental integration of these various external representations. Can diagram labels help novice engineering learners achieve the integration of these multiple external representations and improve learning outcomes?

This study examined this research question by comparing the scores on problem-solving post-tests of novice learners who studied elementary circuit analysis using circuit diagrams either without labels, with static provided labels, or with interactive labels that the learners generated themselves. These three labeling conditions were crossed with the abstract and contextualized representation conditions in a 2 (representation types) × 3 (labeling conditions) experimental design.

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C. Study Setting

This experimental design was applied in the context of a computer-based instructional module that teaches novice learners, without a background in engineering, the basic principles of electrical circuits and parallel circuit analysis. In particular, the instructional module was embedded in a technology literacy session for non-engineering majors. Technological literacy education has received significant attention [12]–[16], and some such technology courses include instructional units on basic electrical circuit analysis [17]–[20].

D. Overview of Cognitive Theory of Multimedia Learning

The Cognitive Theory of Multimedia Learning (CTML) [21] is a common theoretical model of the cognitive processes that take place when humans learn from multiple external representations. According to the CTML, learning from multiple external representations involves three primary cognitive processes. During the first stage, *selecting relevant material*, the learner selects the essential text and diagram elements from the presented information. Because working memory (the cognitive component that temporarily holds information for active processing) capacity is limited [22]–[25], learners must distinguish important information from less important information and attend to/mentally process that important information in order to successfully accomplish the subsequent stages of multimedia learning. The second stage, *organizing selected material*, involves processing selected text and images to create structural relationships between verbal elements and also between pictorial elements. These processes are executed within working memory and, at that point, do not involve making connections between verbal and visual information.

The third and final stage, *integrating selected material with existing knowledge*, involves constructing mental connections between the organized verbal model and the organized visual model and making connections between this information and prior knowledge (i.e., long-term memory). The integration stage of multimedia learning is the most cognitively demanding because it requires simultaneous processing of new verbal and visual information and existing knowledge from long-term memory. Thus, instructional techniques that facilitate this process and/or make the need to do so apparent to the learner have the potential to improve learning outcomes considerably.

E. Concrete Versus Abstract Representations

Novice learners may more easily interpret contextualized representations because these relate to their everyday experiences [26]–[29]. Because novices can more readily recognize everyday electrical components, contextualized representations may promote effective organization of visual information by triggering prior knowledge structures, thereby increasing learning. Relatively few prior investigations have demonstrated learning benefits from contextualized representations, namely studies on teaching electrochemical concepts [30], teaching mathematics to kindergarten students [31], and teaching organization (department) structures [32].

Abstract representations may be more effective in encouraging learners to pay attention to elements related to the underlying structure of the problem, rather than perceptually salient information that changes from problem to problem [33]. Because novice learners struggle to identify relevant and conceptually appropriate information among the information presented, the abstract representational format may serve to reduce search processes related to the selection phase of multimedia learning [21]. This consequently frees limited cognitive resources for the active processes related to organizing and integrating information within multiple external representations. Abstract representations have been found to benefit learning in science [34], [35] and mathematics [36], [37].

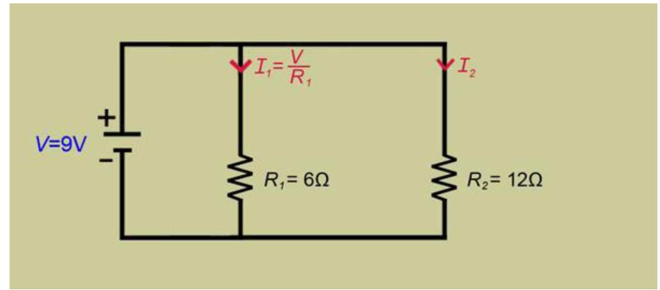
Recent studies conducted by the authors of this paper on teaching elementary electrical circuit analysis [5], [38], [39] have also found learning benefits with abstract representations. These prior studies, however, did not consider instructional support mechanisms that could explicitly aid novice learners in interpreting and comprehending the abstract or contextualized circuit representations. As noted in Section I-A., interpreting circuit representations is a significant challenge for novice learners; thus instructional support mechanisms for interpreting and comprehending circuit representations are an important research topic. The present study advances the research on effective circuit representations for novice learners by examining instructional support that is directly integrated into the circuit diagrams, that is, diagram labels. A complementary approach employing verbal instructional support (guidance) in the narration text accompanying circuit diagrams without labels has recently been examined [40]. The verbal guidance approach did not give an overall main effect on learning; rather, it improved only the learning with contextualized circuit diagrams (by prompting students to examine the circuit structure with the familiar lifelike illustrations more carefully). The present study examines the direct integration of instructional support (diagram labels) into the circuit diagrams and finds a significant overall main effect for the interactive labeling that is directly integrated into the circuit diagram; see Section III-B.

A number of related studies have recently examined the relative benefits of hands-on activities versus virtual computer-based simulations employing a combination of contextualized and abstract representations [41]–[43], while hands-on activities with contextualized and abstract circuit elements have been explored in [44]. As a complement to the existing research literature, the present study examined the effects of diagram labels in abstract versus contextualized representations when teaching introductory circuit analysis.

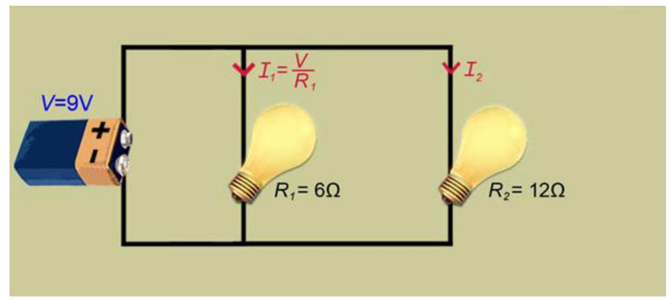
F. Labeling Mechanisms for Supporting Learning From Diagrams

The static integration of textual information (labels) within diagrammatic representations has been examined in a wide range of knowledge domains, in the research literature on the split attention effect [45]–[48] and the spatial contiguity effect [49]. Within the electrical engineering domain, studies on static text labels have primarily considered qualitative troubleshooting, e.g., arranging circuit elements to form a closed circuit while avoiding a short circuit [23], [50]–[52]. For these qualitative circuit learning tasks, static labels that contain text explanations of the functions of the circuit elements and are provided by the learning module have been found to improve learning. Again as a complement to the existing literature, the present study examines the effects of static labels that name the circuit elements for a quantitative learning task that involves the evaluation of circuit quantities.

Novice learners often underestimate the informational content of visual representations and believe a quick glance is an adequate allocation of their attention for comprehension [53]. Instructional techniques that prompt novice students to actively integrate multiple sources of information may elicit generative learning processes related to organization and integration within the CTML [21]. A drag-and-drop format of interactive labeling has been examined in an elementary technology context, namely the operation of a tire pump [54]. The study [54] found a learning advantage for interactive labeling only when the learning task was sufficiently difficult for the learners. A similar investigation [55] showed that learners who were required to actively integrate text and diagram using a drag-and-drop format learned more than those provided with a pre-integrated format. Complementary to these existing studies, the present study examines the effect of an interactive labeling format where learners enter text in entry fields and receive feedback.



(a)



(b)

Fig. 1. Sample circuit diagrams from both the no labels (N) conditions: Only the variables denoting the circuit quantities are included in the diagram. There are no text labels that explain the meanings of the symbols for the circuit components in the abstract representation or the illustrations of the circuit components in the contextualized representation. (a) Abstract representation (A). (b) Contextualized representation (C).

II. Study Methodology

A. Design and Participants

The experiment had a 2×3 between-subjects factorial design. The first factor was the representation type [abstract (A) or contextualized (C)]. The second factor was the labeling of circuit diagram elements [no labels (N), static labels (S), and interactive labels (I)]. A total of 162 undergraduate non-engineering students (122 females and 40 males) of a large public university located in the southwestern US participated in this study. The participants had a mean age of 23.36 years (standard deviation $\mathrm{SD} = 6.17$ years).

B. Computerized Materials

1) Overview: The computerized materials consisted of an interactive instructional module with the following parts: 1) a demographic questionnaire in which students reported age, gender, and ethnicity; 2) a pre-test; 3) an instructional session giving a conceptual overview of electrical circuit analysis; and 4) a problem-solving practice session.

The pre-test assessed the participant's existing circuit analysis knowledge before entering the instructional session. The pre-test consisted of 12 multiple-choice questions on single resistor analysis. Each question was scored as one point when answered correctly, for a maximum pre-test score of 12 points. The test had an internal reliability of Cronbach $\alpha = 0.79$ [56].

The instructional session (Part 3) presented the functions of elementary circuit elements, such as voltage sources and resistors, as well as the meanings and units of elementary electrical quantities, such as electrical current, voltage, and resistance. The instruction demonstrated how to evaluate the total resistance of a parallel circuit with given values for the individual resistors and source voltage from basic principles (the objective was not to either derive or use the formula for the total resistance $1/R_{\text{total}} = 1/R_1 + 1/R_2 + \ldots$ for parallel circuits). Based on Ohm's Law as well as Kirchhoffs Current and Voltage Laws [57], three analysis steps were demonstrated: 1) calculate the value of the current flowing through each individual resistor by observing that the same voltage is applied over each individual resistor using Ohm's Law; 2) sum the currents flowing through the individual resistors to obtain the total current flowing in the parallel circuit; and 3) apply Ohm's Law to the entire parallel circuit to calculate the total resistance of the parallel circuit. Instruction was self-paced. Each screen of the instruction displayed the circuit diagram, as in Fig. 1, at the top of the screen and concurrently played an audio narration of the instructional text. After the narration was complete, the previously narrated instructional text was displayed at the bottom of the screen, and the participant was able to progress to the next screen of instruction by clicking on a "Continue" button.

The practice session (Part 4) presented two practice problems that required students to attempt to calculate the total resistance of a parallel circuit with given source voltage and individual resistance values by following the three solution steps demonstrated in the instructional session. As in the instruction, practice problems displayed a circuit diagram representing the parallel circuit problem in the top half of the screen. The practice session was also self-paced; after the student provided input for each solution step, the computer program provided immediate feedback that included the correct solution and an explanation of the solution step [58]. Students progressed through each subsequent solution step and completed the problem at their own pace after receiving feedback. Answers to the six practice problem steps were logged, resulting in a practice problem score that ranged between 0 and 6 points.

2) Representation Conditions: The representation conditions differed in the instruction and practice session portions of the computer program. In the abstract representation (A) conditions, all diagrams, narrations, and problem texts were

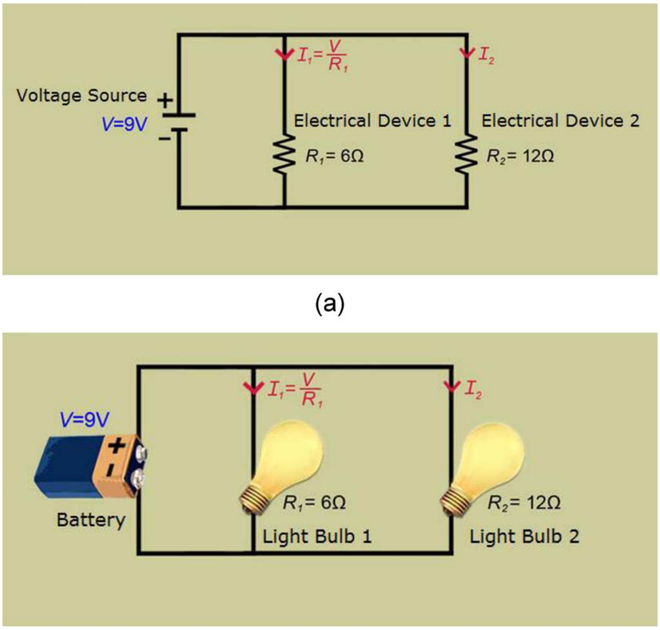


Fig. 2. Sample circuit diagrams from both the static labels (S) conditions: Static text labels explain the meanings of the symbols for the circuit components in the abstract representation or the illustrations of the circuit components in the contextualized representation. (a) Abstract Representation (A). (b) Contextualized representation (C).

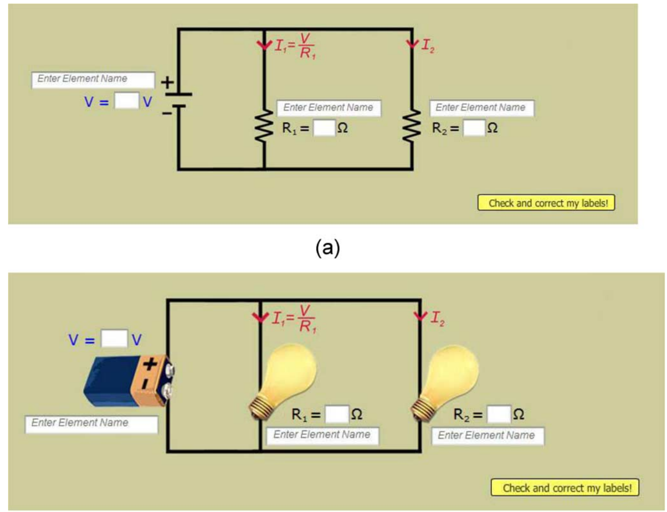


Fig. 3. Sample circuit diagrams from both the interactive labels (I) conditions: The learners were asked to enter the text labels describing the circuit components as well as the numeric values of the associated circuit quantities, which were specified in the instructional text accompanying the circuit diagram. Then, feedback was given in the form of the correct labels and values displayed next to the learner entries. (a) Abstract representation (A) with empty text entry fields. (b) Contextualized representation (C) with empty entry fields.

presented in an abstract format. Specifically, in the circuit diagrams, the electrical circuit elements, such as voltage source and resistors (which modeled electrical devices), were represented using the conventional abstract symbols of electrical engineering, as shown in Fig. 1(a). Also, the narration accompanying the instruction and the practice problems used abstract terms, e.g., "voltage source" and "electrical device."

In contrast, in the contextualized representation (C) conditions, all graphical depictions, narrations, and problem texts were presented in a contextualized format. Specifically, the electrical circuits were graphically represented with real-life illustrations of circuit components from everyday devices, e.g., battery and light bulbs, as shown in Fig. 1(b). The narration and the problems used contextualized terms, e.g., "battery" and "light bulb."

3) Labeling Conditions: Each representation condition had a version without labels (N), a version with static labels (S), and a version with interactive labels (I). Labeling conditions differed in the instructional session portion of the program. For the conditions without labels (N), the elements in circuit diagrams were not accompanied by text labels identifying circuit components, as illustrated in Fig. 1.

In the static labels (S) conditions, the circuit diagrams included text labels for the circuit components, such as "Voltage Source" and "Electrical Device" for the abstract condition [Fig. 2(a)], and "Battery" and "Light Bulb" for the contextualized condition [Fig. 2(b)].

In the interactive labels (I) conditions, the text labels for the circuit components of the static labels (S) conditions were replaced with fields for free text entry that initially stated "Enter Element Name." In addition, the numeric values of the circuit quantities, such as voltage and resistance values, were replaced with initially empty text entry fields, as illustrated for the two representation conditions in Fig. 3(a) and (b). For the instructional session of this interactive labels (I) condition, the self-paced progression of the other conditions, as described above, was modified: At the conclusion of the instructional text narration for a given screen, the following statement was added: "*In the diagram above, type the correct labels for each element. When you are done, click 'Check and correct my labels!'*," and a "Check and correct my labels" button appeared in place of the "Continue" button on the screen. After the student had filled in the text fields and clicked the button, the program checked whether an entry had been made for each field. If a field was still empty, a feedback text message appeared on the screen with an arrow pointing to the empty field, requiring the student to fill in the field. Once all the fields had been completed and the button clicked, the program offered feedback by displaying correct labels next to the entries made by the student.

C. Paper and Pencil Material

The paper and pencil post-test included three near-transfer problems and three far-transfer problems, which were validated in [5]. In the present study, the level of mastery of the elementary parallel circuit analysis principles, as measured by the problem-solving post-test, is considered as a measure of learning. The problems were stated in a contextualized format, as is typical for real-life engineering problems.

The three near-transfer problems (Cronbach $\alpha = 0.89$) assessed students' ability to transfer their problem-solving skills to isomorphic problems. These problems had the same underlying structure as the presented instructional and practice problems, but different surface characteristics, i.e., different electrical devices and different numerical values. A sample problem was: "You wire a subwoofer speaker with resistance $R_s = 16\,\Omega$

and a regular speaker with a resistance of $R_{\rm r} = 8\ \Omega$ in parallel and operate this electrical circuit with a $V = 6$ V battery. What is the total resistance of this electrical circuit?" The three near-transfer test questions were scored by two engineering instructors who were unaware of the experimental conditions (interrater reliability was 98.5%, calculated as percentage agreement between instructors). Three points were awarded for each correctly solved problem, and one point partial credit was given for each correctly solved solution step, resulting in a maximum near-transfer post-test score of nine points.

The three far-transfer problems (Cronbach $\alpha = 0.90$) were designed to measure students' ability to transfer their problem-solving skills to novel problems that differed both in underlying structure and surface characteristics from those in the instruction and practice problems. Specifically, far-transfer problems required students to evaluate the total current in the parallel circuit, given individual resistance values and current through one of the resistors. A sample problem was: "To keep cool in summer you connect two fans in parallel to a battery. The one small fan has resistance $R_{\rm fs} = 12\ \Omega$ and the one large fan has resistance $R_{\rm fl} = 24\ \Omega$. To ensure proper functioning, the current through the small fan must be at least $I_{\rm fs} = 0.4$ A. How much total current is drained from the battery?" To solve far-transfer items, participants needed to employ the same principles (Ohm's Law, Kirchhoffs Voltage and Current Laws) as in the instruction and practice session, however, the sequence of procedures varied from the problems demonstrated and practiced in the instructional module. Similarly to the near-transfer post-test, the far-transfer test questions were scored by two engineering instructors (interrater reliability 99.8%) with three points for each correctly solved problem, giving a maximum far-transfer post-test score of nine points.

D. Apparatus

The instructional module was created with Adobe Flash CS3 software, which is an authoring tool for Web-based and stand-alone multimedia programs. The program was displayed using a desktop personal computer, with a screen size 15.6 in and a resolution of 1680 × 1050 pixels, and headphones.

E. Procedure

After providing informed consent for participation, following randomized controlled trial procedures [59], each participant was randomly assigned to one of the six experimental conditions and seated at the computer. The experimenter commenced the respective version of the instructional module and instructed participants to work independently on all parts of the module. Once participants finished the computerized instructional module, they completed the paper-based post-test.

III. Results

Preliminary analyses were run on instructional time and pre-test scores. A 2 (representation type: C or A) × 3 (labeling: N, S, or I) analysis of variance (ANOVA) [60], with instructional time as a dependent variable did not indicate a main effect of representation type ($F(1,156) < 1$) nor labeling condition ($F(2,156) = 1.95, p = 0.15$) on learning time, which had a mean of $M = 22.4$ min and standard deviation of $SD =$ 3.7 min. Nor was there a main effect of representation type ($F(1,156) < 1$) or labeling condition ($F(2,156) < 1$) on the pre-test scores ($M = 2.65, SD = 2.77$). Also, there were no statistically significant interactions between the two factors for learning time, $F(2,156) = 2.54, p = 0.08$, or pre-test scores, $F(2,156) < 1$. The learner input for the interactive labels was scored according to a rubric that considered both abstract and contextualized terminology for the circuit elements as correct. Students were overall very successful in generating correct labels for diagram elements (only seven participants missed one or two of the labels), and the success rate was not influenced by the representational format.

Table I provides descriptive statistics for the main dependent variables, namely practice problem score as well as near- and far-transfer post-test scores, by representation type and labeling condition. In order to determine potential main effects of representation type and labeling and interactions between these two factors, a series of 2 (representation type) × 3 (labeling) ANOVAs were conducted, with each of the student practice and learning measures as dependent variables and representation type and labeling as between subjects variables.

A. Practice Problems

The analysis of the practice problem scores revealed a significant main effect of labeling, $F(2,156) = 3.88, p = 0.023, \eta_{\rm p}^2 = 0.05$. Follow-up pairwise comparisons indicated that the static labels conditions had significantly lower practice scores than both the no-labels conditions ($p = 0.018$) and the interactive-labels conditions ($p = 0.015$). There was not a significant difference in the performance of students in the interactive- and no-labels conditions ($p = 0.952$). The analysis indicated that practice performance was not significantly impacted by the representation type, $F(1,156) < 1$, and there was not a significant interaction between representation type and labeling, $F(2,156) = 2.44, p = 0.091$.

B. Learning Outcomes

Results for the near-transfer post-test indicated a significant main effect of representation type, $F(1,156) = 10.26, p = 0.002, \eta_{\rm p}^2 = 0.06$. Participants had higher near-transfer scores in the abstract (A) conditions than in the contextualized (C) conditions. There was also a marginally significant main effect of labeling condition, $F(2,156) = 2.87, p = 0.060, \eta_{\rm p}^2 = 0.04$. Follow-up pairwise comparisons indicated that the interactive labeling (I) conditions scored significantly higher on near transfer than the no labels (N) condition ($p = 0.044$) and the static labels (S) condition ($p = 0.037$). There was not a significant difference in near-transfer scores between the no-labels and static-labels conditions ($p = 0.941$). The analysis did not reveal a significant interaction between representation type and labeling condition, $F(2,156) < 1$.

The analysis on far-transfer post-test revealed a significant main effect of representation type, $F(1,156) = 5.60, p = 0.019, \eta_{\rm p}^2 = 0.04$, with participants in the A conditions scoring significantly higher on the far-transfer problems than those in the C conditions. There was not a significant main effect for labeling condition, $F(2,156) = 1.82, p = 0.165$, nor a significant interaction between representation type and labeling, $F(2,156) = 1.44, p = 0.239$.

IV. Discussion

The experiment compared the problem-solving performance of novice learners randomly assigned to study electric circuit analysis with abstract (A) representations or contextualized (C) representations. The two types of representations were presented without diagram labels (N), with static (instructional module-provided) diagram labels (S), or with interactive diagram labels (I) that were generated by the student.

A. Effects of Representation Type

When averaging across the three labeling conditions, abstract representation conditions generally led to better near- and far-transfer scores than contextualized representation conditions. This result mirrors earlier findings supporting better learning effects with abstract representations than with contextualized representations in math and sciences [34]–[37] as well as electrical engineering [5], [38]. Thus, the result of the present study strengthens the general conclusion that abstract representations can better promote learning outcomes than can contextualized representations for novice learners.

An explanation for this general conclusion is that abstract external representations may guide attention to conceptually relevant information and processing of the underlying problem structure. In contrast, contextualized representations may distract learners with perceptually salient, but conceptually irrelevant superficial problem features that change from problem to problem. The abstract representation conditions support the active learning processes related to selection of relevant information from the Cognitive Theory of Multimedia Learning [21] and reduce unnecessary search processes, freeing cognitive resources for active processes related to organization and integration. The abstract representation is also conducive to the formation of robust knowledge structures that are transferable across isomorphic abstract problems.

B. Effects of Labeling

Generally, our results indicated that interactive labeling fostered student problem-solving skills in electric circuit analysis. The interactive labeling condition led to better near-transfer problem solving, compared to both the no labels and static labels conditions. These findings are in line with previous research demonstrating a positive learning effect of active integration with sufficiently complex learning materials [54]. This previous study is similar to the present study in that it used simple textual and algebraic labels for visual representations of a domain that is relatively complex for learners. However, unlike the previous study [54], in which students dragged-and-dropped textual and algebraic components into diagrams, in this study students were required to construct labels from scratch, without access to a "word bank." Nonetheless, the success rate of the labeling indicates that even novice learners are capable of providing accurate labels for the diagrams, when provided the accompanying narratives that provide descriptions of diagram elements.

Unlike interactive labeling, the static labeling (provided diagram labels) did not foster learning compared to the no-labels condition. Requiring learners to actively reflect on the circuit diagram elements and attempt to externally integrate terms introduced in the narration with the corresponding elements in the diagram may have promoted germane processes related to organization and integration [21], which led to more developed internal representations. Simply providing these labels to learners for their inspection may have not fostered additional generative processing of the material. Because integration is the most difficult stage in multimedia learning, students may not spontaneously engage in sufficient processing to fully integrate verbal and pictorial information. Requiring active integration can assist the learner by forcing him/her to explicitly integrate verbal and pictorial information.

Interestingly, analysis of the students' practice problem scores showed that static labels had an inhibitory effect (i.e., led to lower scores than no labels) on practice performance. It is possible that the presence of these verbal labels adjacent to the formulas and numeric values in the circuit diagram detracted learners' attention, diminishing their ability to acquire the procedural knowledge required to answer the practice problems. In any case, the negative impact of the static labels on practice performance within the learning environment appears to fade following the practice activities. That is, near-transfer and far-transfer scores were equivalent for the no labels and static labels conditions at post-test. Some may interpret this finding as contradicting the split-attention effect [45], [49]. However, in this study, the static labels were in very close proximity to the diagram elements to which they referred. Previous studies demonstrating a split-attention effect, e.g., [47], [52], and [61], have typically compared a traditional, split-source format, in which diagrammatic elements are spatially separated from verbal information (usually on separate halves of a page or computer display), to an integrated format, in which verbal information is integrated in diagrams in a similar manner to the static labels condition in the present study. Furthermore, in previous split-attention studies, the verbal information was usually lengthy, in comparison to the labels utilized in this study, where explanatory verbal information was narrated. The static labels condition probably did not present a split-attention dilemma to learners; they were capable of holding visual and verbal information in working memory simultaneously because complex verbal information was processed aurally, rather than visually [21].

Although there was no significant benefit of the interactive labeling for the far-transfer post-test performance ($p = 0.165$), there was a tendency for interactive labeling to result in higher far-transfer scores ($M = 6.24$) compared to the no-labels ($M = 5.61$) and static-labels ($M = 5.06$) conditions. Learning investigations often find smaller effect sizes for far transfer, compared to near transfer [62], [63].

The benefit of interactive labeling over no labels was not attained within the practice session; practice problem scores for interactive labeling students did not differ from the no-labels condition. It is possible that learners require practice with isomorphic problems in order for earlier generative integration processes (i.e., the interactive labeling) to fulfill their potential. Although the practice problems did not require learners to input labels, the students may have covertly enacted similar mental processes related to integrating the text of the problems with the displayed circuit diagrams.

TABLE I
MEANS (M) AND STANDARD DEVIATIONS (SD) FOR SCORE ON PRACTICE PROBLEMS IN INSTRUCTIONAL MODULE AS WELL AS NEAR-TRANSFER AND FAR-TRANSFER POST-TEST SCORES, BY REPRESENTATION TYPE AND LABELING CONDITION. THE ABSTRACT REPRESENTATION (A) RESULTED IN SIGNIFICANTLY HIGHER NEAR- AND FAR-TRANSFER POST-TEST SCORES COMPARED TO THE CONTEXTUALIZED REPRESENTATION (C). INTERACTIVE LABELS GAVE SIGNIFICANTLY HIGHER NEAR-TRANSFER POST-TEST SCORES THAN THE NO-LABELS AND STATIC-LABELS CONDITIONS

Representation Type	Labeling Cond.	Practice score (max = 6) *M* (*SD*)	Near-transfer Posttest (max = 9) *M* (*SD*)	Far-transfer Posttest (max = 9) *M* (*SD*)
Abstract (A)	No labels (*N* = 28)	4.82 (1.39)	7.96 (1.86)	6.79 (2.77)
	Static lab. (*N* = 27)	3.74 (1.79)	7.67 (2.30)	5.33 (3.63)
	Inter. lab. (*N* = 27)	5.00 (1.00)	8.41 (1.85)	6.56 (3.29)
	Total (*N* = 82)	4.52 (1.52)	8.01 (2.01) [a]	6.23 (3.26) [a]
Context. (C)	No labels (*N* = 26)	4.54 (1.27)	6.31 (2.13)	4.35 (2.99)
	Static lab. (*N* = 26)	4.31 (1.64)	6.54 (3.36)	4.77 (3.75)
	Inter. lab. (*N* = 28)	4.39 (1.31)	7.68 (2.18)	5.93 (3.03)
	Total (*N* = 80)	4.41 (1.40)	6.86 (2.65)	5.04 (3.30)
Totals	No labels (*N* = 54)	4.69 (1.33) [c]	7.17 (2.14)	5.61 (3.11)
	Static lab. (*N* = 53)	4.02 (1.73)	7.11 (2.90)	5.06 (3.66)
	Inter. lab. (*N* = 55)	4.69 (1.20) [c]	8.04 (2.04) [b,c]	6.24 (3.14)

Notes: [a] Significantly higher than the C conditions
[b] Significantly higher than the no labels conditions
[c] Significantly higher than the static labels conditions

V. CONCLUSION

A. Theoretical Implications

The results of the experiment provide evidence for the learning benefit of abstract representations in electrical engineering instruction intended for novice learners. An interpretation of this result is that the abstract representation, by excluding perceptually rich superficial elements used in contextualized representations, permits students to direct attention to the conceptually relevant information that is critical for learning the underlying problem and solution structures. By focusing attention on this conceptually relevant information, learners are better able to encode the underlying structure of presented problems and build flexible knowledge of the essential principles to be transferred to novel problems with differing superficial (near-transfer) or structural features (far-transfer). Learners who practiced with abstract representations are better equipped to recognize similar problem configurations in test problems even when questions are stated in a contextualized format.

The results of the experiment suggest that requiring learners to generate their own labels for diagram elements and numeric values is an effective means to promote problem-solving skills, at least for isomorphic (i.e., near-transfer) problems. Some instructional manipulations that require additional student effort represent "desirable difficulties" [64], [65] that enhance retention or comprehension, even though they may lead students to perceive materials as more difficult [66]. The authors' results suggest that requiring active integration through interactive labeling is a desirable difficulty, leading to generative processes related to learning the conceptual and procedural knowledge required for problem solving. The findings also contribute to resolving remaining ambiguities related to the "assistance dilemma" [67]: how to balance *providing* information or assistance in instructional materials with *requesting* interactivity from students. Providing integration support (i.e., static labeling) was not effective, whereas requiring students to generate integrated representations (i.e., interactive labeling) benefited learners.

B. Practical Implications

Instructional materials for elementary electrical engineering for novice learners, such as K–12 students, e.g., [68], and technological literacy learners, e.g., [12]–[20], often include contextualized representations of engineering problems. Recent findings on the representation of electrical circuits for novice K–12 students [5], [38] as well as the findings of the present study for novice technological literacy learners indicate that abstract representations are more conducive to learning elementary electrical circuit analysis than are contextualized representations with real-life electrical components and illustrations. Indeed, K–12 students in the middle and high school grades as well as college-age technological literacy learners have the cognitive capability for abstract thinking [69], [70]. Thus, a practical implication of [5], [38] and the present study is that learning elementary problem-solving skills in electrical circuits is better fostered by abstract representations rather than contextualized representations. However, it is possible that K–12 and technological literacy learners perceive the contextualized representation as more entertaining; this aspect was not examined in the present study and is an interesting direction for future research.

The findings on diagram labeling from the present study suggest that novice learners of electrical circuit analysis benefit from labeling components of circuit diagrams and receiving feedback on their generated labels. This instructional strategy can be readily implemented in computer-based instruction, e.g., in online Web-based learning modules [71], [72].

C. Future Research Directions

One interesting direction for future research is to study whether the effect of interactive labeling of diagrams can be intensified if learners are required to provide more elaborate integration of the textual and diagrammatic information, for example by entering short descriptions of the circuit components alongside the depicted circuit elements. Another interesting direction for future research is to examine fading strategies for diagram labels; that is, the labels could initially be provided, similar to worked example solutions [73], [74], then transition to interactive labels, and later be omitted altogether. Other interesting directions are to examine diagram labeling in conjunction with representation transitioning [75] or in conjunction with the integration of equations into the circuit diagrams [76].

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