Color Coding of Circuit Quantities in Introductory Circuit Analysis Instruction

Jana Reisslein, Amy M. Johnson, and Martin Reisslein, *Fellow, IEEE*

***Abstract*—Learning the analysis of electrical circuits represented by circuit diagrams is often challenging for novice students. An open research question in electrical circuit analysis instruction is whether color coding of the mathematical symbols (variables) that denote electrical quantities can improve circuit analysis learning. The present study compared two groups of high school students undergoing their first introductory learning of electrical circuit analysis. One group learned with circuit variables in black font. The other group learned with colored circuit variables, with blue font indicating variables related to voltage, red font indicating those related to current, and black font indicating those related to resistance. The color group achieved significantly higher post-test scores, gave higher ratings for liking the instruction and finding it helpful, and had lower ratings of cognitive load than the black-font group. These results indicate that color coding of the notations for quantities in electrical circuit diagrams aids the circuit analysis learning of novice students.**

***Index Terms*—Circuit diagram, electrical circuit analysis, font color, multiple representations, novice learners.**

I. Introduction

SUPPORTING novice learners in their initial learning experiences in introductory circuit analysis is often a challenge. Novices typically struggle with their conceptual understanding of electrical circuit quantities and their behaviors in circuits [1]. Also, novices often become overwhelmed by the multiple representations [2] (such as equations, circuit diagrams, and narrated or written explanatory text) employed in circuit analysis instruction.

Generally, successful solving of engineering problems is facilitated by the use of effective representations and being able to transition fluidly between these different representations [3], [4]. Cognitive models of learning from multiple representations [5], [6] suggest that effective learning involves selection, organization, and integration processes of the information provided in the different representations. While a wide range of instructional strategies for aiding learning from multiple representations has been examined in the educational psychology literature, as briefly reviewed in Section II, there is a paucity of research on instructional strategies specifically for electrical circuit instruction.

Elementary electrical circuit analysis mainly revolves around the three quantities related by Ohm's Law, namely voltage, current, and resistance. These three quantities typically appear throughout the multiple representations in electrical circuit instruction. This study investigated whether consistent color coding of the mathematical symbols (variables) denoting the three different circuit quantities can facilitate learning from introductory circuit analysis instruction. Specifically, in this study, the equations were integrated into the circuit diagram. The authors had found in a prior study [7] that, while solving a circuit problem, learning is improved by cumulatively (successively) integrating the equations into the circuit diagram, instead of presenting the equations separate from the circuit diagram. Building on the prior study [7], the present study employs the cumulative equation-integration strategy from [7] in the examination of the effects of color coding. In the present study, the variables for the three quantities were consistently presented either color coded or in black font in the circuit diagrams (in the integrated equations) and in the instructional text prompts.

The study results indicate that the students who learned with color-coded variables achieved significantly higher scores on a problem-solving post-test and rated their cognitive load significantly lower than the students who learned with the black-font circuit variables. An interpretation of these results is that the color coding reduces extraneous cognitive load and facilitates the selection, organization, and integration processes involved in learning introductory circuit analysis.

II. Background

A. Challenges of Learning From Multiple Representations

Generally, novice learners in science, technology, engineering, and mathematics (STEM) domains struggle to identify essential information in learning environments that use multiple external representations, such as diagrams, texts, equations, illustrations, and tables, because their existing understanding of the domains is inadequate [2], [8]–[10]. For effective learning from multiple representations, the novice needs to not only identify the relevant information within each representation, but also understand the sometimes complex relationships between the multiple representations. Understanding these relationships requires that learners pay attention to corresponding elements and form referential connections between representations [11]. Educational psychology research indicates that techniques for

Manuscript received November 07, 2013; revised January 20, 2014 and February 12, 2014; accepted March 10, 2014. Date of publication April 04, 2014; date of current version January 30, 2015. This work was supported by the National Science Foundation under Grant 1025163.

J. Reisslein and M. Reisslein are with the School of Electrical, Computer, and Energy Engineering, Arizona State University, Tempe, AZ 85287-5706 USA (e-mail: jreissl@asu.edu; reisslein@asu.edu).

A. M. Johnson is with the College of Technology and Innovation, Arizona State University, Mesa, AZ 85287-5706 USA (e-mail: amjohn43@asu.edu).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TE.2014.2312674

effectively focusing learner attention on relevant information facilitate the mental integration processes necessary to develop coherent and accurate mental representations of systems from multiple external representations [11]–[13]. Color in instructional materials may serve as an effective means to direct learners' attention to essential information within provided representations.

B. Overview of Cognitive Load Theory Framework

Cognitive load theory [14] is a widely accepted theoretical framework for the cognitive learning processes involved in learning from multiple representations. The theory considers the intrinsic cognitive load due to the inherent difficulty of the subject matter, the germane cognitive load due to construction of mental (internal) representation of the subject matter, and the extraneous cognitive load due to superfluous cognitive processing induced by the presentation (instructional design) of the subject matter. Instructional designs that induce high extraneous cognitive load can overwhelm the learners' cognitive resources, resulting in reduced learning [14].

When learning from instruction with multiple representations, the main cognitive processes giving rise to cognitive load are: selecting relevant material from the presented textual and diagrammatic representations; organizing the selected textual and diagrammatic material; and integrating the materials with long-term memory (prior knowledge) [5].

C. Color Coding in Multiple Representation Instruction

The emergence of color displays spurred research on the effects of colored presentation of instructional materials compared to black-and-white presentation [15], [16]. Generally, the studies found that the random use of color does not benefit learning. However, employing color as a cue or code for relevant information has the potential to facilitate learning [17]–[21].

For instruction with multiple representations, e.g., text and diagrams, recent studies have examined the use of color to direct learners' attention to correspondences between representations. The majority of these multimedia instruction studies have considered domains outside of electrical and computer engineering. For instance, Berthold and Renkl [22] examined color coding the correspondences of outcomes of interest in tree diagrams illustrating elementary conditional probability calculations. Ozcelik *et al.* [23] examined the effects of a form of color coding where labels in diagrams of synapses in the nervous system had the same color as the corresponding terms in instructional text. In a related study, Folker *et al.* [24] examined the effects of color coding of cell components on learning about mitotic cell division. These prior color coding studies generally found that color coding tends to improve learning performance (as measured with post-tests) and reduce learning time compared to control conditions without color coding.

Color cueing (the color highlighting of the diagram component corresponding to a specific passage of instructional text) is an instructional design technique closely related to color coding; it has also been examined in a few studies. Jamet *et al.*, [25] investigated color cueing of cerebral lobes on learning of the cerebral base of language production. Ozcelik *et al.* [26] examined the effects of color cueing of the labels of components of a turbofan jet engine in instruction on the conceptual operation of such an engine. Tabbers *et al.* [27] considered color cueing in a lesson on instruction design principles. These color cueing studies generally found that color cueing improves post-test performance compared to control conditions without cueing.

D. Color Coding in Electrical Engineering Instruction

Few prior studies on color coding in multiple representation instruction considered the electrical engineering domain. In particular, Kalyuga *et al.* [28] examined the effects of using color to indicate correspondences between circuit components (e.g., circuit breaker and light bulb) depicted in diagrams and mentioned in text. The study [28] focused on the qualitative concept of constructing a closed electrical circuit and did not consider quantitative evaluation of circuit quantities. Kalyuga *et al.* found that color coding increases instructional effectiveness, i.e., increases the performance on a qualitative post-test while reducing cognitive load, compared to conventional instruction without color coding. Wiebe *et al.* [29] compared two mental workload measures in the context of electronic circuit instruction. The study [29] considered the impact of color cueing of circuit elements in graphics on mental (cognitive) workload, but did not examine effects of color cueing on learning. Wiebe *et al.* found that color cueing reduces extraneous cognitive load compared to instruction without color cueing.

Color coding is often employed in electrical and computer engineering instruction. For instance, color has been used to code components of circuit boards [30] and telecommunication systems [31]. Color has also been used to represent concept maps [32], singularities in robot movements [33], and terms in digital logic expressions on a K-map [34] as well as frames and phases in communications protocols [35], [36]. However, these prior studies did not specifically examine electrical circuit analysis instruction, nor did they examine the impact of color coding on learning.

Electrical circuit analysis is a core topic in electrical engineering [37], [38], and many aspects of instruction in circuit analysis have been researched. For instance, recent research has focused on project-based learning [39] and strategies for effective practice and study notes [40]–[42]. Popular textbooks on electrical circuit analysis, e.g., [43] and [44], and recent computer-based electric circuit tutorials [45] employ color coding to illustrate node and mesh equations, while other instructional approaches color code the voltage potential [46]–[48]. However, to the best of the authors' knowledge, the effects of color coding have not been previously examined in the research literature on electrical circuit instruction.

In prior studies [49]–[52], the authors examined a different research issue related to the representation of electrical circuits on learning, namely abstract representations using engineering symbols (e.g., the zigzag symbol for a resistor) versus contextualized representations using illustrations of everyday circuit elements (e.g., light bulbs). These prior studies [49]–[52] found that abstract representations improve learning compared to contextualized representations. In the prior study [53], the authors also found that verbal labels for the circuit representations (e.g., labeling the zigzag resistor symbol as representing an "*electrical device*") assist only with learning from contextualized representations, as the labels foster more active cognitive processing of the diagrams with the familiar contextualized representations. Labels did not aid learning from abstract representations; learning performance was equivalent for abstract representations without labels and for contextualized representations with labels. These prior studies on abstract versus contextualized circuit representations did not examine the impact of color coding.

E. Examined Research Question and Study Hypothesis

The present study complements the existing research literature on electrical circuit analysis instructing by focusing on the comparison of colored-coded and black-font presentation of circuit variables. Specifically, the present study examines the research question of whether consistent color coding of the font for the variables denoting electrical circuit quantities improves learning performance and learning perceptions compared to black font variables. Based on the principles of cognitive load theory and the benefits of color coding and cueing found in prior empirical research studies, the authors predicted that color coding of the circuit variables would improve learning performance and perceptions compared to black-font circuit variables.

III. Study Methodology

A. Design and Participants

The study compared two groups, namely the black-font (B) group with the color-coded (C) group. The study participants were a total of 74 students (34 females and 40 males) in a public high school in the Southwestern US. The mean age of the students was 14.6 years with standard deviation 0.9 years. Each student was randomly assigned to one of the two experimental groups following the procedures for a randomized controlled trial.

B. Instructional Material

The instruction was embedded in an engineering outreach session for pre-college students. The instructional module considered in this study was designed to introduce novice learners without prior engineering or physics knowledge to elementary principles of electrical circuits and analysis of parallel electrical circuits. The instruction was presented through a computer-based multimedia module consisting of the sections: 1) a demographic questionnaire requesting age and gender information; 2) a pre-test of relevant prior knowledge; 3) an instructional session that introduced elementary electric circuit analysis; 4) a practice session; and 5) a survey.

The pre-test consisted of six multiple-choice questions on elementary algebra and elementary single-resistor circuits. Elementary algebra was included in the pre-test since pilot tests [49] indicated that some high school students had weak algebra skills that limited their ability to evaluate expressions with two variables. Each correct answer scored one point, giving a maximum pre-test score of six points. The internal reliability of the pre-test was $\alpha = 0.65$ as measured by Cronbach's α.

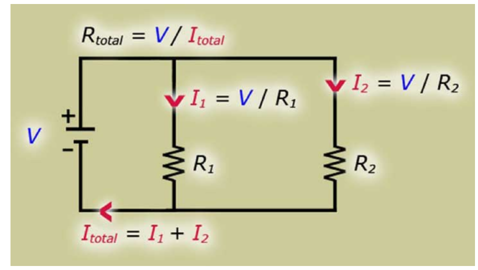

Fig. 1. Sample diagram from the instructional session for the color (C) group. Voltage variables were blue, current variables were red, and resistance variables were black; all variables were black for the black-font (B) group.

The instructional session introduced the basic electrical quantities of electrical voltage, current, and resistance by presenting their physical meanings and units. The students were then shown how to evaluate the total resistance of a parallel circuit with given source voltage and resistance values through direct application of Ohm's Law [54] and Kirchhoff's Current and Voltage Laws [55]. The demonstration consisted of three steps: first, to observe that each parallel resistor experiences the source voltage and find the current through each resistor with Ohm's Law; second, to add the currents through the individual parallel resistors to find the total current flow; and third, to divide the source voltage by the total current to find the total resistance.

For each screen of the instructional session, the computer-based multimedia module displayed a circuit diagram, such as the example in Fig. 1. Building on the authors' prior studies [49]–[52] indicating that abstract representations of the circuit elements better foster learning than contextualized representations, the present study employed abstract representations. Moreover, building on the authors' prior result [53] that verbal labels for the symbols in the circuit diagram do not significantly improve learning from abstract circuit representations, the present study employed abstract representations without verbal diagram labels. Concurrently, audio narration of the accompanying instruction test was played out. The students progressed through the module at their own pace by clicking a "Continue" button that was enabled after the narration for the screen had concluded.

The practice session provided the students with four isomorphic parallel circuit problems. Each problem was represented by a circuit diagram in the top half of the screen, as in Fig. 2. For each solution step, the student was prompted for a solution attempt, with the prompt appearing in the bottom half of the screen, as illustrated. After submitting the solution attempt, the student received immediate corrective and explanatory feedback [56]. The authors' prior study [56] had found that such immediate feedback improves circuit learning for novice learners compared to delayed feedback. Specifically, for a correct solution attempt, the module confirmed the correctness, while for an incorrect attempt, the module showed the correct solution as well as an explanation of the correct solution.

Throughout the instructional and practice sessions, as the demonstration or problem solution progressed, the

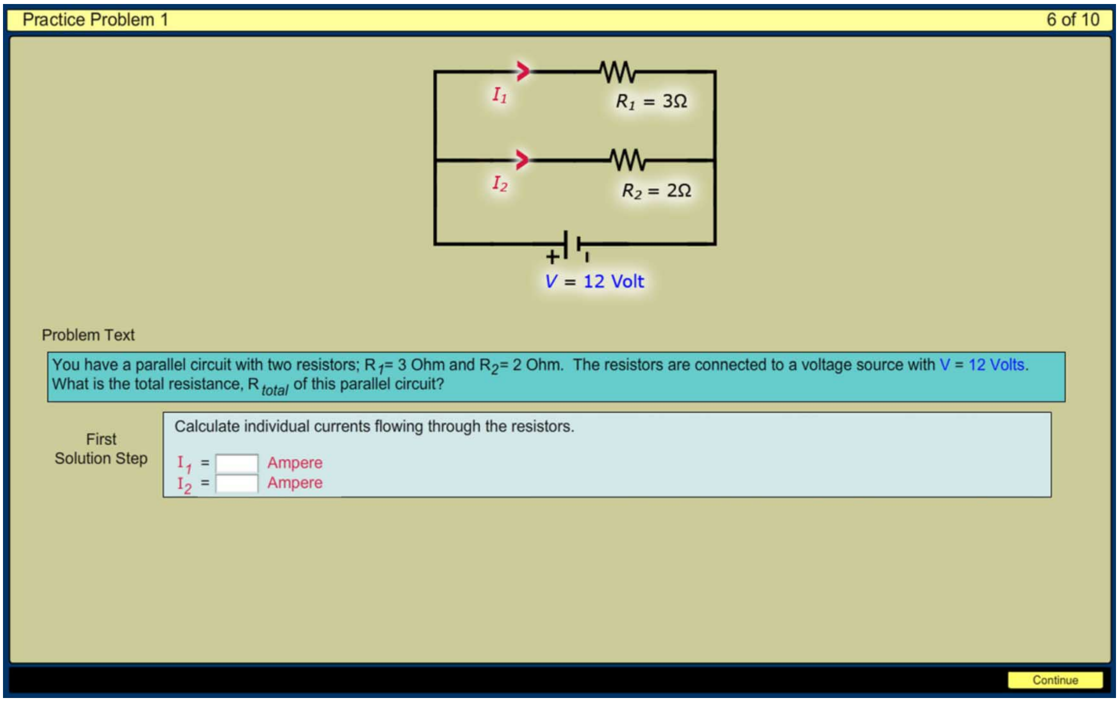

Fig. 2. Sample screenshot from practice session for color (C) group. Circuit variables had consistent color coding in circuit diagram and text prompts. For the black-font (B) group, the variables were black throughout the circuit diagram and text prompts. (In order to avoid distracting the pre-college students with challenging arithmetic or prefixes, e.g., "k" for "kilo," the circuit parameters were chosen to given circuit quantities in integers or simple fractions.)

corresponding equations were cumulatively integrated into the circuit diagram [7]. For instance, at the beginning of the demonstration in the instructional session, only the given source voltage V and resistance values R_1 and R_2 were integrated into the circuit diagram, as illustrated in Fig. 2. As the demonstration progressed through the three solution steps, the corresponding equations for the individual currents I_1 and I_2, then the total current I_{total}, and finally the total resistance R_{total} were successively added into the circuit diagram, arriving at the diagram shown in Fig. 1. Analogously, for the practice problems, the equations corresponding to the completed solution steps were successively integrated into the circuit diagrams.

The entire multimedia instructional module, including the instructional and practice sessions, was identical for the two groups, except for the display of the symbols (variables) in the circuit diagrams as well as the prompts and feedback. For the black-font (B) group, all variables were displayed in black. For the color (C) group, all variables were color-coded. Specifically, all voltage-related variables were in blue, current-related variables in red, and resistance-related variables in black.

The computer-based instructional module concluded with a survey consisting of six items that asked the students to rate their perceptions of the learning experience on a Likert-like scale from 1 (strongly disagree) to 5 (strongly agree). The construct validity of the survey items had been verified with the judgment of subject matter experts [57]. Two of the survey items, "I liked the lesson" and "I enjoyed learning with the lesson," related to overall liking of the instruction and had an internal reliability as measured by Cronbach alpha of $\alpha = 0.89$. Similarly, two items related to the helpfulness of the module had an $\alpha = 0.92$. Perceived cognitive load [58], [59] was assessed with two items adopted from [60], "The lesson was difficult" and "Learning the material in the lesson required a lot of effort", and had an $\alpha = 0.79$.

C. *Post-Test*

The post-test was given in black print font on white paper after completion of the computer-based instructional module. The post-test contained four problems that were isomorphic to the problems in the instructional module. Specifically, the test contained four problems with novel surface features that could be solved with the same solution strategy as demonstrated and practiced in the instructional module. Two engineering instructors without knowledge of the experimental groups scored the post-tests by assigning one point for each correct solution step. The maximum post-test score was 12 points, and the post-test had an internal reliability of Cronbach's $\alpha = 0.77$.

IV. Results

A preliminary analysis confirmed that the two groups did not differ in their pre-test scores, $t(72) = 0.023$, $p = 0.982$.

A. *Learning Time*

An independent sample t-test indicated that the B group took significantly longer ($M = 990.8$ s, $SD = 236.8$ s) to complete the instructional and practice sessions, i.e., had significantly longer learning time, compared to the C group ($M = 831.6$ s, $SD = 159.9$ s), $t(72) = 3.41$, $p = 0.001$, $d = 0.79$. Bivariate correlations were analyzed between learning time and each of the dependent variables (practice problem and post-test scores, as well as program liking, helpfulness, and cognitive

TABLE I
ADJUSTED MEANS (M) AND STANDARD ERRORS (SE) FOR ALL DEPENDENT VARIABLES, BY EXPERIMENTAL CONDITION

Dependent Variable	Experimental Condition	
	Color coding (C) ($n = 38$)	Black font (B) ($n = 36$)
	M (*SE*)	*M* (*SE*)
Practice Score (max = 12)	8.32 (0.39)	6.49 (0.40)
Post-test Score (max = 12)	9.40 (0.39)	8.07 (0.40)
Program Liking Rating (max = 5)	3.63 (0.14)	3.04 (0.15)
Helpfulness Rating (max = 5)	3.61 (0.15)	2.94 (0.15)
Cognitive Load Rating (max = 5)	2.15 (0.13)	3.18 (0.14)

load ratings). The results indicated significant negative relationships between learning time and practice score ($r = -0.203$, $p = 0.042$) and between learning time and post-test score ($r = -0.212, p = 0.035$). Additionally, learning time was positively related to cognitive load ratings ($r = 0.288$, $p = 0.006$). Learning time was not significantly correlated with program liking or helpfulness ratings ($p > 0.05$).

In each of the following analyses on dependent variables, instructional time was used as a covariate. Adjusted means (using the covariate to adjust) and standard errors for each of the dependent variables, by experimental condition, are displayed in Table I.

B. Practice Problems

An analysis of covariance (ANCOVA) was conducted, using the total practice score as the dependent variable, experimental condition as the independent variable, and instructional time as the covariate. The results demonstrated that there was a significant difference between the two experimental conditions on practice problems, $F(1, 71) = 10.24$, $MSE = 5.22$, $p = 0.002$, $\eta_{\mathrm{p}}^2 = 0.13$. The C group outperformed the B group.

C. Post-Test

An ANCOVA was conducted using the total post-test score as dependent variable, experimental condition as independent variable, and instructional time as covariate. The results revealed that the C group significantly outperformed the B group on the post-test measure, $F(1, 71) = 5.25, MSE = 5.32, p = 0.025$, $\eta_{\mathrm{p}}^2 = 0.07$.

D. Learner Perceptions

Three separate ANCOVAs were conducted, using student ratings for: 1) liking the program; 2) helpfulness; and 3) cognitive load, as dependent variables, experimental condition as independent variable, and instructional time as covariate. The results revealed that the C group produced significantly higher ratings for program liking, $F(1, 71) = 7.77, MSE = 0.71, p = 0.007$, $\eta_{\mathrm{p}}^2 = 0.10$, and for helpfulness, $F(1, 71) = 9.50$, $\mathrm{MSE} = 0.77$, $p = 0.003$, $\eta_{\mathrm{p}}^2 = 0.12$. Furthermore, the B group had significantly higher ratings of cognitive load, compared to the C group, $F(1, 71) = 27.95, MSE = 0.61, p < 0.001, \eta_{\mathrm{p}}^2 = 0.28$.

V. DISCUSSION

The study results indicate that the color coding (C) of the electrical circuit variables led to significantly reduced learning time as well as significantly higher scores on the practice problems in the instructional module; it also led to significantly higher scores on the post-test compared to the black-font (B) display for the considered novice learners. These results can be explained through the cognitive processes involved in learning from multiple representations [5] within the theoretical framework of cognitive load theory [14].

First, the color coding aids the novice learners in selection of the information relevant at each stage of the instruction and practice. For instance, when demonstrating the addition of the individual currents I_1 and I_2 to obtain the total current I_{total}, the red-colored circuit variables help in identifying these current related variables in the colored version of the circuit diagram in Fig. 1 compared to the black-font version of the circuit diagram. The B display forces the learners to search for the variables for a particular circuit quantity among the variables for all the other circuit quantities. Such search processes constitute extraneous cognitive load [14] and can be time-consuming [61]. Likely, the extraneous search processes caused the B learners to take significantly longer to complete the instructional and practice sessions in the instructional module.

The color coding may also aid the novice learners in organizing their internal (mental) representation of a given external representation, e.g., the circuit diagram, in that the coloring suggests a strategy for overlaying the circuit variables and the electrical phenomena they characterize, e.g., current flows, on the given circuit (which is drawn in black).

Moreover, the color coding may aid the learners in integrating the different representations by consistently employing the same color for a specific circuit quantity across the different representations. For instance, in the textual prompt given in the practice problem for calculating the individual currents I_1 and I_2, the red color for the current variables immediately nudges learners to link these current quantities to the red-colored I_1 and I_2 in the circuit diagram; see Fig. 2. Thus, the color coding facilitates the selection, organization, and integration processes [5] that are involved in constructing coherent internal (mental) representations of the electrical circuit analysis knowledge.

In contrast, the black-font (B) display affords the novice learners no help in selecting, organizing, and integrating circuit variables within a given representation and across representations. The B group learners had to expend additional cognitive effort, i.e., extraneous cognitive load, to accomplish the cognitive learning processes of selection, organization, and integration compared to the learners in the C group.

These results are similar to prior studies demonstrating positive learning effects of color coding elements among representations [22]–[28]. However, the present study adds to the emerging understanding of positive impact of color coding in the context of electrical circuit analysis. Prior eye-tracking studies demonstrated that the benefit of color coding multiple representations is probably due to its directing visual attention to relevant and corresponding information between representations [23], [26]. Similarly, students in this study who received color-coded materials may have benefitted from the direction of visual attention provided by the color coding.

The B group took significantly longer to learn using the instructional module, compared to the C group. Instructional time was significantly correlated to practice and post-test scores, as well as cognitive load ratings. Across experimental groups, the longer students took to learn, the worse their performance on practice and post-test problems, and the more difficult they perceived the instruction to be. Part of this result may well stem from the differing learning times between the experimental conditions.

The learning perceptions results further underscore the benefits of color coding of circuit variables for novice learners. The learners in the color group perceived the instructional module as being significantly more likable and helpful as well as imposing significantly lower cognitive load than did the learners in the B group. It is possible that the higher liking rating for the color version is due to general tendencies for humans to perceive color displays as more likable and enjoyable [15], [17]. The higher helpfulness and lower cognitive load ratings of the color group complement the higher practice and post-test scores of the color group. The color learners likely felt that the learning was easier and the instructional module more helpful due to the support that color coding provided for their learning processes.

VI. Conclusion

The results of the present study indicate that consistent color coding of variables denoting the main different types of circuit quantities, namely voltage, current, and resistance, significantly improves the elementary circuit analysis learning of novice learners. The study results are consistent with theoretical models [5] of learning from multiple external representations, such as text and circuit diagrams. The color coding of the circuit quantities can assist with the selection, organization, and integration of relevant information about the circuit quantities and their interrelationships. In contrast, the uniform black font color for the circuit variables in the black-font display may force the novice learners to search for the circuit variables that are relevant at each stage of circuit analysis, thus increasing extraneous cognitive load [14]. This study thus provides a research base for extending the use of color coding in electrical circuit instructional materials, e.g., [43]–[45], to the variables denoting circuit quantities.

The present study makes an important original contribution to the scholarship of discovery in the area of effective instructional strategies for teaching elementary electrical circuit analysis to novice learners. The present study has demonstrated that a very simple color manipulation of the variables denoting the circuit quantities brings significant improvements in learning performance and learning perceptions. The authors believe that the simplicity of color coding combined with its high effectiveness makes color coding of circuit variables a very attractive instructional design strategy for teaching circuit analysis.

Color production of paper-based circuit analysis learning materials incurs higher cost than does black-and-white printing. Thus, instructional designers for print circuit instructional materials for novice learners will need to trade off the increased cost with the improved learning and learning perceptions. Instructional materials presented in a computer-based format, e.g., [62]–[64], can readily incorporate color. The consistent use of color for the various circuit quantities is recommended based on the results of this study.

There are several important directions for future research on color coding for electrical circuit analysis instruction. The present study considered novice learners (high school students) without prior exposure to circuit analysis. One future research direction is to examine advanced learners (e.g., electrical engineering college students). It is possible that more advanced learners do not benefit significantly from the support provided by color coding as they have already formed highly efficient internal representations (schemata) [14] for basic circuit analysis that allow them to efficiently select, organize, and integrate multiple representation instruction on advanced circuit analysis. Color coding may be a redundant instructional support strategy for advanced learners that, according to the general expertise reversal effect [65], does not help or may actually impede further learning.

The present study cumulatively integrated circuit analysis equations into the circuit diagram [7], as illustrated in Fig. 1. This integration of equations and circuit diagram mitigates the split-attention effect [66]. One future research direction is to examine color coding of circuit quantities in a split-source format where equations are displayed separately from the circuit diagram, requiring the learner to integrate instructional text, equations, and the circuit diagram. It is possible that in such a split-source format, the effect of the color coding becomes more pronounced as the required integration processes are more demanding.

Another important direction for future research is to examine the impact of color coding in different topic areas within electrical and computer engineering, for example in the areas considered in [30]–[36].

References

[1] L. C. McDermott and P. S. Shaffer, "Research as a guide for curriculum development: An example from introductory electricity. Part I: Investigation of student understanding," *Amer. J. Phys.*, vol. 60, no. 11, pp. 994–1003, Nov. 1992.

[2] S. Ainsworth, "The functions of multiple representations," *Comput. Educ.*, vol. 33, no. 2, pp. 131–152, Sep. 1999.

[3] A. Johri and V. Lohani, "A framework for improving engineering representational literacy through the use of pen-based computing," *Int. J. Eng. Educ.*, vol. 27, no. 5, pp. 958–967, 2011.

[4] T. J. Moore, R. L. Miller, R. A. Lesh, M. S. Stohlmann, and Y. R. Kim, "Modeling in engineering: The role of representational fluency in students' conceptual understanding," *J. Eng. Educ.*, vol. 102, no. 1, pp. 141–178, Jan. 2013.

[5] R. E. Mayer, "Cognitive theory of multimedia learning," in *The Cambridge Handbook of Multimedia Learning*, R. E. Mayer, Ed. New York, NY, USA: Cambridge Univ. Press, 2005, pp. 31–48.

[6] W. Schnotz, "An integrated model of text and picture comprehension," in *The Cambridge Handbook of Multimedia Learning*, R. E. Mayer, Ed. Cambridge, U.K.: Cambridge Univ. Press, 2005, pp. 49–69.

[7] G. Ozogul, A. M. Johnson, R. Moreno, and M. Reisslein, "Technological literacy learning with cumulative and stepwise integration of equations into electrical circuit diagrams," *IEEE Trans. Educ.*, vol. 55, no. 4, pp. 480–487, Nov. 2012.

[8] S. R. Goldman, "Learning in complex domains: When and why do multiple representations help?," *Learning Instruct.*, vol. 13, no. 2, pp. 239–244, Apr. 2003.

[9] R. Kozma, "The material features of multiple representations and their cognitive and social affordances for science understanding," *Learning Instruct.*, vol. 13, no. 2, pp. 205–226, Apr. 2003.

[10] M. D. Patrick, G. G. Carter, and E. N. Wiebe, "Visual representations of DNA replication: Middle grades students' perceptions and interpretations," *J. Sci. Educ. Technol.*, vol. 14, no. 3, pp. 353–365, Sep. 2005.

[11] T. Seufert, "Supporting coherence formation in learning from multiple representations," *Learning Instruct.*, vol. 13, no. 2, pp. 227–237, Apr. 2003.

[12] L. Kester, P. A. Kirschner, and J. J. G. Van Merriënboer, "The management of cognitive load during complex cognitive skill acquisition by means of computer-simulated problem solving," *Brit. J. Educ. Psychol.*, vol. 75, no. 1, pp. 71–85, Mar. 2005.

[13] K. Scheiter, P. Gerjets, and R. Catrambone, "Making the abstract concrete: Visualizing mathematical solution procedures," *Comput. Human Behav.*, vol. 22, no. 1, pp. 9–25, Jan. 2006.

[14] J. Sweller, J. J. G. van Merrienboer, and F. W. C. Paas, "Cognitive architecture and instructional design," *Educ. Psychol. Rev.*, vol. 10, no. 3, pp. 251–296, Sep. 1998.

[15] F. M. Dwyer, "Color as an instructional variable," *AV Commun. Rev.*, vol. 19, no. 4, pp. 399–416, 1971.

[16] N. Katzman and J. Nyenhuis, "Color vs. black-and-white effects on learning, opinion, and attention," *AV Commun. Rev.*, vol. 20, no. 1, pp. 16–28, 1972.

[17] F. M. Dwyer and R. J. Lamberski, "A review of research on the effects of use of color in the teaching-learning process," *Int. J. Instruct. Media*, vol. 10, no. 4, pp. 303–327, 1982–83.

[18] D. Pett and T. Wilson, "Color research and its application to the design of instructional materials," *Educ. Technol. Res. Dev.*, vol. 44, no. 3, pp. 19–35, 1996.

[19] T. Gnambs, M. Appel, and B. Batinic, "Color red in web-based knowledge testing," *Comput. Human Behav.*, vol. 26, no. 6, pp. 1625–1631, Nov. 2010.

[20] P. van Schaik and J. Ling, "The effect of link colour on information retrieval in educational intranet use," *Comput. Human Behav.*, vol. 19, no. 5, pp. 553–564, Sep. 2003.

[21] J. Ling and P. van Schaik, "The effect of text and background colour on visual search of Web pages," *Displays*, vol. 23, no. 5, pp. 223–230, Nov. 2002.

[22] K. Berthold and A. Renkl, "Instructional aids to support a conceptual understanding of multiple representations," *J. Educ. Psychol.*, vol. 101, no. 1, pp. 70–87, Feb. 2009.

[23] E. Ozcelik, T. Karakus, E. Kursun, and K. Cagiltay, "An eye-tracking study of how color coding affects multimedia learning," *Comput. Educ.*, vol. 53, no. 2, pp. 445–453, Sep. 2009.

[24] S. Folker, H. Ritter, and L. Sichelschmidt, "Processing and integrating multimodal material: The influence of color-coding," in *Proc. Annu. Conf. Cogn. Sci. Soc.*, 2005, pp. 690–695.

[25] E. Jamet, M. Gavota, and C. Quaireau, "Attention guiding in multimedia learning," *Learning Instruct.*, vol. 18, no. 2, pp. 135–145, Apr. 2008.

[26] E. Ozcelik, I. Arslan-Ari, and K. Cagiltay, "Why does signaling enhance multimedia learning? Evidence from eye movements," *Comput. Human Behav.*, vol. 26, no. 1, pp. 110–117, Jan. 2010.

[27] H. K. Tabbers, R. L. Martens, and J. J. Merriënboer, "Multimedia instructions and cognitive load theory: Effects of modality and cueing," *Brit. J. Educ. Psychol.*, vol. 7, no. 1, pp. 71–81, Mar. 2004.

[28] S. Kalyuga, P. Chandler, and J. Sweller, "Managing split-attention and redundancy in multimedia instruction," *Appl. Cogn. Psychol.*, vol. 13, no. 4, pp. 351–371, Aug. 1999.

[29] E. N. Wiebe, E. Roberts, and T. S. Behrend, "An examination of two mental workload measurement approaches to understanding multimedia learning," *Comput. Human Behav.*, vol. 26, no. 3, pp. 474–481, May 2010.

[30] D. Dankovic, L. Vracar, A. Prijic, and Z. Prijic, "An electromechanical approach to a printed circuit board design course," *IEEE Trans. Educ.*, vol. 56, no. 4, pp. 470–477, Nov. 2013.

[31] H. Aliakbarian, P. J. Soh, S. Farsi, H. Xu, V. E. Van Lil, B. Nauwelaers, G. Vandenbosch, and D. Schreurs, "Implementation of a project-based telecommunications engineering design course," *IEEE Trans Educ.*, vol. 57, no. 1, pp. 25–33, Feb. 2014.

[32] H.-H. Chen, Y.-J. Chen, and K.-J. Chen, "The design and effect of a scaffolded concept mapping strategy on learning performance in an undergraduate database course," *IEEE Trans. Educ.*, vol. 56, no. 3, pp. 300–307, Aug. 2013.

[33] A. Gil, A. Peidro, O. Reinoso, and J. M. Marin, "Implementation and assessment of a virtual laboratory of parallel robots developed for engineering students," *IEEE Trans. Educ.*, 2014, to be published.

[34] Z. Stanisavljevic, V. Pavlovic, B. Nikolic, and J. Djordjevic, "SDLDS—System for digital logic design and simulation," *IEEE Trans Educ.*, vol. 56, no. 2, pp. 235–245, May 2013.

[35] T. J. Mateo Sanguino, C. Serrano Lopez, and F. A. Marquez Hernandez, "WiFiSiM: An educational tool for the study and design of wireless networks," *IEEE Trans. Educ.*, vol. 56, no. 2, pp. 149–155, May 2013.

[36] W. Zhan, J. R. Porter, and J. A. Morgan, "Experiential learning of digital communication using LabVIEW," *IEEE Trans. Educ.*, vol. 57, no. 1, pp. 34–41, Feb. 2014.

[37] T. Ogunfunmi and M. Rahman, "A concept inventory for an electric circuits course: Rationale and fundamental topics," in *Proc. IEEE Int. Symp. Circuits Syst.*, 2010, pp. 2804–2807.

[38] L. Trajovic, "Teaching circuits to new generations of engineers," in *Proc. IEEE Int. Symp. Circuits Syst.*, 2011, pp. 1187–1190.

[39] J. P. Becker, C. Plumb, and R. A. Revia, "Project circuits in a basic electric circuits course," *IEEE Trans. Educ.*, 2014, to be published.

[40] A.-K. Carstensen and J. Bernhard, "Student learning in an electric circuit theory course: Critical aspects and task design," *Eur. J. Eng. Educ.*, vol. 34, no. 4, pp. 393–408, Aug. 2009.

[41] A. L. Holmes, "The effect of reworking exam problems on problem-solving performance in a circuit analysis course: An exploratory study," *IEEE Trans. Educ.*, 2014, to be published.

[42] O. Lawanto, "The use of enhanced guided notes in an electric circuits class: An exploratory study," *IEEE Trans. Educ.*, vol. 55, no. 1, pp. 16–21, Feb. 2012.

[43] D. Irwin and M. R. Nelms, *Basic Engineering Circuit Analysis*, 8th ed. Hoboken, NJ, USA: Wiley, 2008.

[44] C. K. Alexander and M. Sadiku, *Fundamentals of Electric Circuits*. New York, NY, USA: McGraw-Hill, 2004.

[45] B. J. Skromme, Q. Wang, P. Reyes, J. M. Quick, R. K. Atkinson, and T. Frank, "Teaching linear circuit analysis techniques with computers," in *Proc. ASEE*, 2013.

[46] J. J. Clement and M. S. Steinberg, "Step-wise evolution of mental models of electric circuits: A "learning-aloud" case study," *J. Learning Sci.*, vol. 11, no. 4, pp. 389–452, 2002.

[47] E. R. Doering, "CircuitViz: A new method for visualizing the dynamic behavior of electric circuits," *IEEE Trans Educ.*, vol. 39, no. 3, pp. 297–303, Aug. 1996.

[48] C. R. Sullivan, "Three dimensional circuit animation visualizes voltage," in *Proc. ASEE*, 2002.

[49] R. Moreno, G. Ozogul, and M. Reisslein, "Teaching with concrete and abstract visual representations: Effects on students' problem solving, problem representations, and learning perceptions," *J. Educ. Psychol.*, vol. 103, no. 1, pp. 32–47, Feb. 2011.

[50] M. Reisslein, R. Moreno, and G. Ozogul, "Pre-college electrical engineering instruction: The impact of abstract vs. contextualized representation and practice on learning," *J. Eng. Educ.*, vol. 99, no. 3, pp. 225–235, Jul. 2010.

[51] J. Reisslein, G. Ozogul, A. M. Johnson, K. L. Bishop, J. Harvey, and M. Reisslein, "Circuits kit K–12 outreach: Impact of circuit element representation and student gender," *IEEE Trans. Educ.*, vol. 56, no. 3, pp. 316–321, Aug. 2013.

[52] A. M. Johnson, J. Reisslein, and M. Reisslein, "Representation sequencing in computer-based engineering education," *Comput. Educ.*, vol. 72, pp. 249–261, Mar. 2014.

[53] A. M. Johnson, K. R. Butcher, G. Ozogul, and M. Reisslein, "Introductory circuit analysis learning from abstract and contextualized circuit representations: Effects of diagram labels," *IEEE Trans. Educ.*, 2014, to be published.

[54] M. S. Gupta, "Georg Simon Ohm and Ohm's Law," *IEEE Trans. Educ.*, vol. E-23, no. 3, pp. 156–162, Aug. 1980.

[55] F. R. Quintela, R. C. Redondo, N. R. Melchor, and M. Redondo, "A general approach to Kirchhoff's Laws," *IEEE Trans. Educ.*, vol. 52, no. 2, pp. 273–278, May 2009.

[56] R. Moreno, M. Reisslein, and G. Ozogul, "Optimizing worked-example instruction in electrical engineering: The role of fading and feedback during problem-solving practice," *J. Eng. Educ.*, vol. 98, no. 1, pp. 83–92, Jan. 2009.

[57] L. R. Aiken, *Psychological Testing and Assessment*, 9th ed. Boston, MA, USA: Allyn & Bacon, 1997.

[58] A. L. Holmes, "Work in progress—Quantifying intrinsic cognitive load in DC circuit problems," in *Proc. IEEE FIE*, 2009, pp. 693–694.

[59] M. Mina and A. W. Moore, "Work in progress—Using cognitive development approaches in teaching electrical engineering concepts," in *Proc. IEEE FIE*, 2010, pp. F3G-1–2.

[60] F. G. W. Paas and J. J. G. Van Merrienboer, "Variability of worked examples and transfer of geometrical problem-solving skills: A cognitive load approach," *J. Educ. Psychol.*, vol. 86, no. 1, pp. 122–133, Mar. 1994.

[61] R. E. Christ, "Review and analysis of color coding research for visual displays," *Human Factors*, vol. 17, no. 6, pp. 542–570, Dec. 1975.

[62] L. Palma, R. F. Morisson, P. N. Enjeti, and J. W. Howze, "Use of web-based materials to teach electric circuit theory," *IEEE Trans. Educ.*, vol. 48, no. 4, pp. 729–734, Nov. 2005.

[63] L. Weyten, P. Rombouts, and J. De Maeyer, "Web-based trainer for electrical circuit analysis," *IEEE Trans Educ.*, vol. 52, no. 1, pp. 185–189, Feb. 2009.

[64] L. Weyton, P. Rombouts, B. Catteau, and M. DeBock, "Validation of symbolic expressions in circuit analysis e-learning," *IEEE Trans. Educ.*, vol. 54, no. 4, pp. 564–568, Nov. 2011.

[65] S. Kalyuga, P. Ayres, P. Chandler, and J. Sweller, "The expertise reversal effect," *Educ. Psychol.*, vol. 38, no. 1, pp. 23–31, 2003.

[66] P. Ginns, "Integrating information: A meta-analysis of the spatial contiguity and temporal contiguity effects," *Learning Instruct.*, vol. 16, no. 6, pp. 511–525, Dec. 2006.

Jana Reisslein received the Ph.D. degree in educational technology from Arizona State University, Tempe, AZ, USA, in 2005.

Amy M. Johnson received the Ph.D. degree in experimental psychology (cognitive track) from the University of Memphis, Memphis, TN, USA, in 2011.

She is a Postdoctoral Research Associate with Arizona State University, Polytechnic, Mesa, AZ, USA.

Martin Reisslein (A'96–S'97–M'98–SM'03–F'14) received the Ph.D. degree in systems engineering from the University of Pennsylvania, Philadelphia, PA, USA, in 1998.

He is a Professor with the School of Electrical, Computer, and Energy Engineering, Arizona State University, Tempe, AZ, USA.