Technological Literacy Learning With Cumulative and Stepwise Integration of Equations Into Electrical Circuit Diagrams

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***Abstract*—Technological literacy education involves the teaching of basic engineering principles and problem solving, including elementary electrical circuit analysis, to non-engineering students. Learning materials on circuit analysis typically rely on equations and schematic diagrams, which are often unfamiliar to non-engineering students. The goal of this experimental study was to investigate the effects of the integration of equations into circuit diagrams on the learning of non-engineering undergraduate students. This experimental study compared three integration designs. In the cumulative integrated design, as each practice problem solution progressed, the equations were cumulatively integrated into the circuit diagram. In the stepwise integrated design, only those equations relevant to the present step of the problem were integrated into the circuit diagram; previously displayed equations were moved to an adjacent frame and recorded there. The nonintegrated design recorded all equations in the adjacent frame throughout each of the problems. Student learning was measured with a problem-solving near-transfer and far-transfer post-test. Students rated the helpfulness of the diagrams and difficulty of the instructional program. Results indicated that participants in the cumulative integrated condition scored significantly higher on the near-transfer post-test and marginally significantly higher on the far-transfer post-test compared to the stepwise and nonintegrated conditions. Findings indicate that circuit analysis instruction for non-engineering students should integrate equations into circuit diagrams in a cumulative fashion so as to avoid the split-attention effect for both the previously displayed equations as well as the equations for the present problem step.**

***Index Terms*—Diagram-equation integration, electrical circuit analysis, spatial contiguity, technological literacy education.**

I. Introduction

A. Teaching Electrical Circuit Analysis to Non-Engineers

INCULCATING technological literacy, that is, a basic understanding of engineering and technological principles, in the general populace has been widely recognized as an important education goal [1]–[3]. The curricula for undergraduate university courses that introduce non-engineering majors to the basics of engineering and technology have received significant attention among engineering educators [4] and typically include instructional modules on elementary electrical circuit analysis. However, the instructional design of learning materials for effective teaching of electrical circuit analysis to non-majors is largely an open research problem.

This study examined the pedagogical effects of integrating equations characterizing electrical quantities into electrical circuit diagrams on the circuit analysis learning of non-engineering students. This study was conducted with a computer-based instructional module that introduces students without any prior knowledge in engineering or physics to the basic principles of electrical circuits and parallel circuit analysis. The module is well suited for integration into technological literacy courses.

The learning materials of many popular nontechnical undergraduate programs, such as communication, journalism, and psychology, consist primarily of text. In contrast, circuit analysis learning materials rely extensively on schematic diagrams and mathematical equations characterizing electrical quantities for representing circuit analysis concepts and problem scenarios [5]–[7]. For instance, both introductory engineering texts [8]–[10], which are employed in some technological literacy courses [4], and common elementary circuit analysis instruction materials [11], [12] consist of text explanations, mathematical equations embedded in the text explanations, and schematic circuit diagrams. Since majors from nontechnical undergraduate programs are often unaccustomed to learning materials containing equations and diagrams, the instructional design relating to equations and diagrams for these learners has potentially profound effects on their learning of electrical circuit analysis.

In general, the field of multimedia learning [13], [14] examines the educational and cognitive psychology aspects of learning from combinations of multiple representations[1] of information. Engineering materials consisting of text, equations, and diagrams are one specific instance of such a combination of multiple representations. The cognitive processes involved in learning from multiple representations are commonly modeled and interpreted based on the theories of working memory [15] and cognitive load theory [16].

B. Overview of Working Memory and Cognitive Load Theories

The bases of cognitive load theory derive from Baddeley's theory of working memory [15]. Baddeley presents working memory as: 1) limited in capacity; and 2) subdivided into the visual–spatial sketch pad and the phonological loop. The

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[1]In subsequent references to "representation," unless explicitly noted, "representation" refers to external, i.e., provided, representations.

visual–spatial sketchpad is responsible for processing visually presented information, and the phonological loop processes auditory information. Building on the central assumption of limited working memory capacity, according to cognitive load theory, every instructional condition places a particular burden (load) on the working memory.

The total cognitive load experienced at any given time is comprised of three distinct types: 1) intrinsic cognitive load; 2) extraneous cognitive load; and 3) germane cognitive load [17]. Intrinsic cognitive load can be thought of as the natural demand imposed by the learning material for a particular domain (e.g., electrical engineering), *per se* [18], [19]. According to Sweller *et al.* [17], this type of cognitive load stems from the amount of "element interactivity" encompassed in a particular learning task. Extraneous cognitive load encompasses the unnecessary processing demands placed on the cognitive system as a result of the format of instruction, rather than the learning task itself. Extraneous load does not contribute to learning and can detract from learning if the constraints of working memory [15] are exceeded. For example, a learning environment that includes a considerable amount of unimportant information will increase extraneous load because learners are required to search through the irrelevant material to find the relevant information they should be learning. Germane cognitive load refers to the conscious effort made by the learner to use appropriate cognitive processes to construct internal (mental) representations of the material. A learning environment with high extraneous cognitive load can overburden a learner's working memory capacity, reducing cognitive resources for germane (productive) cognitive processing, thus hindering productive learning [17].

C. Overview of Split Attention Effect

While combinations of multiple representations have been demonstrated to support cognitive processes for deep conceptual learning [20], they impose the cognitive burden of comprehending and integrating separate external representations [21]. The split-attention effect [22] is the effect of visually switching between two spatially separate sources of information. The inverse of the split-attention effect, i.e., the effect of physical integration of the multiple sources of information, is commonly referred to as the spatial-contiguity effect [23]. The split-attention effect is widely viewed as the primary challenge when learning from multiple representations [24]. The conventional explanation for the split-attention effect is that the split-source format leads to interfering representations in working memory. Specifically, the learner needs to retain information from one representation in working memory while searching the accompanying representation for relevant information. This information retention increases the extraneous cognitive load [25], [26], reducing available cognitive resources for germane processing, and ultimately diminishing productive learning.

The research on mitigating the split-attention effect can be categorized into instructional designs that integrate multiple representations so as to avoid splitting information into separate sources [16], [24], [25], and designs that facilitate the processing of multiple representation, e.g., through color-coding corresponding elements [26], [27], attention guidance [28], or connecting lines or hyperlinks [29]. This study focuses on integrated instructional designs—specifically, the integration of equations into electrical circuit diagrams.

D. Integrated Instructional Designs

Integrated instructional designs physically integrate multiple representations of information into one integrated presentation. The integrated presentation achieves spatial contiguity, e.g., through the physical integration of text or equations into diagrams [16]. Most existing studies of integrated instructional designs have focused on the integration of textual comments into diagrams [30]–[34].

Only two prior studies have examined the integration of equations into diagrams, namely the studies by Sweller *et al.* [35] and by Tarmizi and Sweller [36]. In particular, Sweller *et al.* [35] studied the integration of equations for the evaluation of slopes and intersection points of straight lines into a diagrammatic representation of the lines in a coordinate system with ninth grade students. Tarmizi and Sweller [36, Experiments 4 and 5] investigated the effects of integrating given and calculated angle values in a worked example on cyclic quadrilaterals on the geometry learning of eighth and ninth grade students.

No prior studies have examined the integration of equations in diagrams in the electrical engineering domain. There have only been efforts to represent mathematical equations characterizing electrical circuits [37] and multimedia communication systems [38] in graphical form.

E. Present Study: Cumulative or Stepwise Integration of Equations in Circuit Diagrams

The goal of the present study was to examine the relative benefits of two distinct instructional designs of the integration of equations into circuit diagrams for the circuit analysis learning of students from non-engineering majors. In particular, this study strives to answer the open research question whether integrated information in diagrams should accumulate and remain visible within the diagram following its introduction (cumulative integration), or whether each piece of information should only remain integrated in the diagram during discussion of a specific problem step (stepwise integration). More specifically, should circuit analysis instruction employ a cumulative integrated design where the equations for a particular problem step are accumulated in the diagram as the problem solution progresses? Or should circuit analysis instruction employ a stepwise integrated design where the relevant equations only remain integrated in the circuit diagram during the particular problem step?

II. Study Methodology

A. Participants and Design

The study participants were a total of 165 undergraduate psychology students (73% female) at a large public university in the southwestern US. The mean age of the participants was 25.62 years with standard deviation $SD = 8.49$ years.

B. Materials

1) Computerized Materials: Each participant received computerized materials consisting of an interactive program with five sections: 1) a demographic information questionnaire in which students were asked to report their gender, age, and ethnicity; 2) a pretest; 3) an instructional session providing a conceptual overview of electrical circuit analysis; 4) a problem-solving practice session; and 5) a program rating questionnaire.

The pretest consisted of three multiple-choice questions and three open-ended single-resistor problems, e.g., "You connect a lamp with a resistance of $R = 3\ \Omega$ to a 6 Volt battery. How large is the current flow?" The pretest was designed to measure the participant's domain-specific prior knowledge before entering the instructional session and had an internal reliability as measured by Cronbach's α of .68 [39].

The instructional session first presented the students with the physical meanings and units of electrical current, voltage, and resistance. Next, the session presented how to calculate the total resistance of a parallel circuit with given source voltage and individual resistance values, using the fundamental properties of voltages and currents in parallel circuits as described by Ohm's Law and Kirchhoff's Current and Voltage Laws. This was broken into three steps: 1) note that the voltage is the same over each individual resistor and calculate the value of the current flowing through each individual resistor using Ohm's Law; 2) calculate the total current flowing in the circuit by summing the currents flowing through the individual resistors; and 3) calculate the total resistance of the parallel circuit by applying Ohm's Law to the entire circuit. The instructional objective was neither to derive nor apply the total resistance formula $1/R_{\text{total}} = 1/R_1 + 1/R_2 + \cdots$ for parallel circuits. Instead, the objective was to teach how to analyze an elementary parallel circuit from basic principles.

The practice session presented two electrical circuit problems that asked students to compute the total resistance of a parallel circuit with given source voltage and individual resistance values by applying the three solution steps taught in the instructional portion of the program. The practice part of the module was self-paced. After completing each solution step, participants received feedback. Specifically, if the solution was correct, the program confirmed the correctness of the solution. If the solution was incorrect, the program presented an explanation about how to solve the step correctly as well as the correct solution. After studying the explanatory feedback, students could click on the "Continue" button to proceed to the next solution step while the correct solution for the preceding step remained on the screen. After all three steps in a problem had been completed, students could click on the "Next Problem" button to move to the next practice problem. Once the participants had submitted their answers, they were not allowed to return to previous steps or problems.

The instructional session and practice session portion of the program had three different versions, one for each of the three integration designs examined in this study, which are illustrated in Fig. 1. In the integrated condition, all equations—that is, both those specifying the given parameter values (battery voltage and resistance values) and those evaluating the intermediate and final results (individual currents, total current, and total resistance)—were integrated into the circuit diagram, as illustrated in Fig. 1(a). This integration was cumulative; as the instructional session on a given circuit or a given practice problem solution progressed, the equations were cumulatively added to the circuit diagram. For example, the initial statement of a practice problem had only the equations specifying (characterizing) the given parameter values in the circuit diagram. In the first solution step, the evaluation of the individual currents, the equations characterizing the individual currents were added to the circuit diagram. In the second solution step, the evaluation of the total current, the equation for the total current was added to the circuit diagram, as depicted in Fig. 1(a).

In contrast, in the stepwise condition, only equations relevant for the present step of the instruction or problem solution were integrated into the circuit diagram; previously displayed equations were moved to a box to the right of the circuit diagram and recorded there, as illustrated in Fig. 1(b). For instance, an initial problem statement in the problem-solving practice session included the equations specifying the given parameter values in the circuit diagram. In the first solution step, only the equations for the individual currents were integrated in the circuit diagram; the equations for the given parameter values were removed from the diagram and moved to the box while the corresponding engineering notations (symbols), V, R_1, and R_2, remained in the circuit diagram. In the second solution step, which is illustrated in Fig. 1(b), only the equation characterizing the total current was included in the circuit diagram; the equations for the given parameter values and the individual currents were moved to the box, while the symbols for the given parameters and individual currents remained in the circuit diagram.

In the nonintegrated condition, only the symbols for the electrical quantities were included in the circuit diagram, while the equations were cumulatively added only into the box to the right of the circuit diagram, as illustrated for the second step of a practice problem in Fig. 1(c).

The module included a program rating questionnaire, which was a four-item Likert instrument asking participants to rate their learning perceptions on a five-point scale that ranged from 0–strongly disagree to 4–strongly agree. The reliability of the survey instrument was examined with a factor analysis using principal axis estimation, which showed that two factors accounted for 87.1% of the variance of subject ratings. One factor related to learner perceptions of the diagram helpfulness (assessed by two survey statements, e.g., "The pictures in the program helped me solve the problems"; with factor coefficients 0.85 and 0.86), while another factor related to perceived cognitive load (two survey statements adapted from [40], e.g., "Learning the material in the lesson required a lot of effort"; with coefficients 0.85 and 0.86). High internal reliabilities of the subscales were demonstrated for both the diagram helpfulness subscale (Cronbach's $\alpha = 0.85$) and cognitive load subscale (Cronbach's $\alpha = 0.85$).

2) Paper and Pencil Materials: The paper and pencil materials consisted of three near-transfer questions and three far-transfer questions. The problem statements on the tests were in contextualized form, as is common for real-life engineering problem settings. The near-transfer test was designed to assess students' ability to transfer their problem-solving skills to solve an isomorphic set of problems. In particular, the near-transfer portion consisted of three problems (Cronbach's $\alpha = 0.94$) that had the same underlying structure but different surface characteristics than the problems presented during the computer-based program. An example of a near-transfer posttest problem

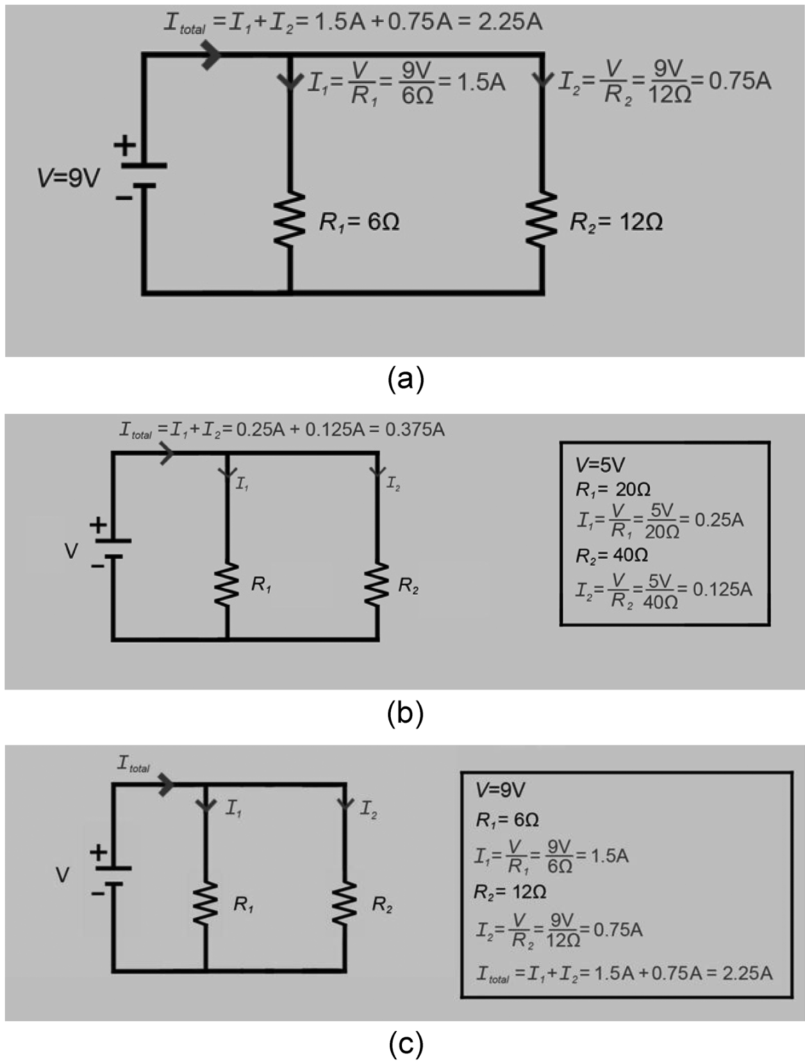

Fig. 1. Sample images from the three integration conditions. (a) Cumulative integrated condition. (b) Stepwise integrated condition. (c) Nonintegrated condition.

was "The electrical system of a remote-controlled toy helicopter consists of a motor with resistance $R_{\mathrm{m}} = 4.5\ \Omega$, a siren with resistance $R_{\mathrm{s}} = 18\ \Omega$, and a control unit with resistance $R_{\mathrm{c}} = 72\ \Omega$. All these components are wired in parallel and are connected to a $V = 9$ V battery. What is the total resistance of this parallel electrical circuit?" Two engineering instructors scored the near-transfer test questions (interrater reliability 98.5%).

The three far-transfer questions ($\alpha = 0.95$) were designed to assess students' ability to transfer their problem-solving skills to solve a novel set of problems. These questions had different underlying structure and different surface features than the problems within the computer-based learning environment. Specifically, given the individual resistance values and the current through one of the resistors, the students were asked to calculate the total current in the parallel circuit. A sample problem was "To keep you cool in summer you connect two fans in parallel to a battery. The one small fan has resistance of $R_{\mathrm{fs}} = 12\ \Omega$ and the one large fan has resistance of $R_{\mathrm{fl}} = 24\ \Omega$. To ensure proper functioning, the current flowing through the small fan must be at least $I_{\mathrm{fs}} = 0.4$ A. How much total current flow is drained from the battery?" In order to solve the far transfer problems the participants had to apply the same basic principles (Ohm's Law, basic properties of voltages and currents in parallel circuits) as in the practice problems, but the sequence in which these principles were employed and the circuit element to which Ohm's Law was applied varied from the problems and solution steps presented in the computer-based program. Two engineering instructors who were blind to the experimental condition (interrater reliability 99.8%) scored the far-transfer test questions.

Each of the six post-test problems had a three-step solution. Each step solved correctly received one point, resulting in a maximum score of three points for each post-test question, and a maximum overall post-test score of 18 points (9 for near-transfer, 9 for far-transfer).

3) Apparatus: The computer-based instructional module used in the study was developed using Adobe Flash CS3 software, an authoring tool for creating Web-based and standalone multimedia programs. The apparatus consisted of a desktop computer system, with a screen resolution of 1680×1050 pixels, and headphones.

C. Procedure

Before participants entered the lab, each computer was set up with a randomly assigned treatment (cumulative integrated, stepwise integrated, or nonintegrated) within individual cubicles. After signing consent forms, participants were randomly

TABLE I
DESCRIPTIVE STATISTICS MEAN M AND STANDARD DEVIATION *SD* FOR PRETEST SCORE, PRACTICE SCORE, DIAGRAM RATING, AND COGNITIVE LOAD RATING, AS WELL AS ADJUSTED MEAN M (adj.) AND STANDARD ERROR *SE* FOR NEAR- AND FAR-TRANSFER POST-TEST SCORES, BY INTEGRATION CONDITION WITH N DENOTING STUDENT NUMBERS IN THE CONDITIONS

		Pretest (Max: 6)		Practice (Max: 6)		Diagram Rating (Max: 4)		Cog. Load Rating (Max: 4)		Near Transfer (Max: 9)		Far Transfer (Max: 9)	
Group	*N*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M* (adj.)	*SE*	*M* (adj.)	*SE*
Cumulative Integrated	54	0.65	1.18	3.35	1.59	3.27	0.71	1.73	1.07	6.87[a]	0.50	4.48[b]	0.49
Stepwise Integrated	56	0.96	1.43	3.18	1.40	3.07	0.78	1.79	1.12	5.14	0.49	2.91	0.48
Nonintegrated	55	0.98	1.28	3.65	1.58	2.85	1.00	1.44	1.01	5.20	0.49	3.26	0.49

Notes: [a] The cumulative integrated condition significantly outperformed both stepwise and nonintegrated conditions.
[b]The cumulative integrated condition significantly outperformed the stepwise condition.

assigned to a cubicle and were given a calculator. Participants were tested in groups of between one to seven students per session. Once seated, participants worked through the five sections of the computer module. Subsequently, participants were given the paper-based post-test and a pencil without an eraser.

III. RESULTS

A preliminary analysis of variance (ANOVA) of the pretest scores indicated no difference among the groups in prior domain-specific knowledge, F-ratio $F(2,162) = 1.13$, mean square error $\mathrm{MSE} = 1.70$, significance level $p = 0.33$. Also, an ANOVA showed that there was no significant difference in the time taken to complete the instructional and practice sessions, $F(2,162) = 0.02$, $\mathrm{MSE} = 1.18 \times 10^{-8}$, $p = 0.98$. Differences in post-test learning outcomes were tested with the analysis of covariance (ANCOVA). The ANCOVA uses a covariate (e.g., pretest scores representing prior domain-specific knowledge) to reduce variability among experimental conditions that exists before any experimental manipulation is implemented [41]. Throughout, least significant difference (LSD) *post hoc* tests were used to establish significant differences among pairs of conditions.

An ANCOVA was conducted, using experimental condition as independent variable, total near-transfer score as dependent variable, and total pretest score as covariate. No interaction existed between pretest and experimental condition, $F(2,159) = 0.003$, $p = 0.99$, assuring that the assumption of homogeneity of regression slopes was met. The analysis revealed a significant main effect of experimental condition on post-test near-transfer performance, $F(2,161) = 3.84$, $\mathrm{MSE} = 13.43$, $p = 0.02$, $\eta^2 = 0.05$. LSD pairwise comparisons among the groups indicated that the cumulative integrated condition had significantly higher near-transfer scores, compared to both the nonintegrated condition ($p = 0.02$) and the stepwise integrated condition ($p = 0.02$). There was no significant difference between the nonintegrated condition and the stepwise integrated condition ($p = 0.93$). Estimated marginal means M *(adj.)* and standard errors *SE* are displayed in Table I.

An ANCOVA conducted on the far-transfer score, using pretest score as covariate, indicated a marginally significant effect of experimental condition on total far-transfer score, $F(2,161) = 2.81$, $\mathrm{MSE} = 12.99$, $p = 0.06$, $\eta^2 = 0.03$. No interaction existed between pretest and experimental condition, $F(2,159) = 0.695$, $p = 0.50$, assuring that the assumption of homogeneity of regression slopes was met. LSD pairwise comparisons among the groups demonstrated that the cumulative integrated condition had significantly higher far-transfer scores than the stepwise condition ($p = 0.03$), and marginally significantly higher far-transfer scores than the nonintegrated condition ($p = 0.08$). No other comparisons were significant.

An ANOVA was conducted on the practice problems, using experimental condition as the between-subjects factor. The analysis indicated no significant effect of experimental condition on participants' performance on the practice problems, $F(2,162) = 1.38$, $\mathrm{MSE} = 2.33$, $p = 0.25$.

An ANOVA indicated a significant effect of experimental condition on participants' ratings of the diagram helpfulness, $F(2,162) = 3.34$, $\mathrm{MSE} = 0.70$ p $= 0.034$, $\eta^2 = 0.04$. LSD pairwise comparisons among the groups revealed that the cumulative integrated condition had significantly higher ratings of the diagram helpfulness than the nonintegrated condition ($p = 0.01$). No other comparisons were significant. No significant differences were revealed in participants' perceived cognitive load, $F(2,162) = 1.77$, $\mathrm{MSE} = 1.14$, $p = 0.17$.

IV. DISCUSSION

A. Cumulative Integrated Equations Versus Nonintegrated Equations

Compared to the nonintegrated condition, learners in the cumulative integrated condition had significantly higher near-transfer post-test scores. Furthermore, learners in the cumulative integrated condition had marginally significantly higher far-transfer post-test scores than learners in the nonintegrated condition. The higher efficacy of the cumulative integrated design compared to the nonintegrated design suggests that integrating equations within the circuit diagrams in a cumulative fashion reduces demands placed on the limited capacity of working memory (i.e., extraneous load [17]). Learners in the cumulative integrated condition were not required to switch back and forth visually between the two separate representations. Thus, they did not have to hold one representation in working memory while viewing and processing the other representation. The working memory occupied for holding one representation reduces the working memory available for processing the other representation. Therefore, the switching between separate representations tends to increase the likelihood of overload of the limited working memory capacity. Effectively, the visual switching between separate representations increases the extraneous cognitive load and reduces the cognitive resources available for productive learning (germane cognitive load). Also, visual switching can consume precious learning time during the intervals between fixations (gaze maintenance).

The integrated format made clear the correspondences between the multiple representations, inherently linking circuit quantities in the diagram to their corresponding engineering notations (symbols) and characterizing equations. Learners often experience difficulty selecting the relevant portions of diagrammatic representations that correspond to segments of symbolic representations (e.g., text, equations) and manipulations that provide assistance in locating corresponding elements can lead to more effective use of attention and increased learning outcomes [27]. With the integrated format, learners did not need to map the engineering symbols (e.g., V or I_1) and their characterizing equations with the corresponding diagram elements; the close proximity of equations to the diagram elements provided this mapping.

The practice scores, being the number of correctly solved practice problem steps, did not differ among conditions. Throughout, the practice session presented the practice problems as well as the correct solution after each attempted problem step in the respective compared instructional designs. Thus, the learning processes with the compared integration conditions were still ongoing in the practice session. Taken together, the results for practice and post-test scores indicate that while employing the different integration designs in the instructional session (conceptual overview) did not result in differences in practice scores, employing the different integration designs in both instructional and practice sessions resulted in significantly different post-test scores. Thus, employing the cumulative integrated design throughout the presentation of the engineering concepts as well as their application in practice problems appears to be important.

The diagram helpfulness ratings in the cumulative integrated condition were significantly higher than in the nonintegrated condition. The nonintegrated design forces learners to split attention between diagrams and equations, which may have been a frustrating experience. In contrast, in the cumulative integrated design, learners are no longer required to switch back and forth between spatially separated representations and do not need to search diagrams for elements that correspond to the equations. The higher learner-perceived diagram helpfulness thus provides additional indication of the benefits of the cumulative integrated design.

The learners' self-reported ratings for the cognitive load scale adopted from [40], which commonly measures total cognitive load [42], [43], did not differ among conditions. However, cumulative integration led to significantly improved learning. It is therefore likely that similarly to the recent study [25], the integrated design reduced extraneous load while increasing germane load such that the total cognitive load remained unchanged. Developing and validating measures that distinguish the different types of cognitive load and employing such detailed cognitive load measures for the integration of equations and diagrams is an important direction for future research.

In summary, the cumulative integrated design has the potential to reduce unnecessary (extraneous) load on learners' working memory and increase learning outcomes and perceptions of the learning experience. According to the spatial contiguity principle [13], [23], [24] and cognitive load theory [35], the reduction of extraneous load through integration frees up cognitive resources for germane processes (processes which lead to learning) and improves the mental integration of the two sources of information [25]. Better mental integration of the two external representations leads to more coherent and stable mental representations of the information, ultimately resulting in better learning.

B. Stepwise Integrated Equations Versus Cumulative Integrated and Nonintegrated Equations

Near-transfer scores for the stepwise integrated condition were significantly lower than for the cumulative integrated condition. Also, the stepwise integrated condition had significantly lower far-transfer scores than the cumulative integrated condition. The stepwise integrated condition did not differ from the nonintegrated condition for near-transfer scores, nor for far-transfer scores. These results indicate that an integrated format that integrates equations into the circuit diagram, but removes each successive formulaic step from the diagram when introducing the next step, is not effective in promoting learners' mental integration of the two representations. The significant difference between stepwise integration and cumulative integration suggests that maintaining every equation within the diagram promotes learning more than removing each equation upon introduction of the subsequent problem-solving step.

The stepwise integrated condition effectively corresponds to: 1) the integrated design for the equation relevant for the present step of the problem-solving process; and 2) the nonintegrated design for the earlier equations, i.e., the equations that were relevant for earlier steps of the problem-solving process. The nonintegrated design has the split-attention drawback of leading to higher consumption of working memory and higher extraneous cognitive load, as elaborated in the preceding section, for the processing of the equations of earlier problem steps. An advantage of the stepwise integration is that it provides more explicit signaling of the equation and corresponding element of the diagram relevant for the present problem-solving step. In particular, with stepwise integration, only the equation for the present problem-solving step is integrated into the circuit diagram, whereas with cumulative integration, the equations for the present step as well as the preceding steps are integrated into the diagram (and the learner has to inspect all integrated equations visually to identify which equation is currently relevant). The identification of the equation for the present step is therefore likely to pose lower demands on working memory and lower extraneous cognitive load in the stepwise integrated condition than in the cumulative integrated design.

The results indicate that the split-attention drawback of the stepwise integrated design outweighs the advantage of signaling the currently relevant equation. That is, the learners appear to be referring back extensively to earlier steps, which can be reviewed in the cumulative integrated condition without incurring a split-attention effect. Although the present problem step may not directly refer to these other areas of the circuit diagrams and earlier presented equations, learners may be mentally simulating successive steps of the problem, through reinspecting the earlier equations and corresponding diagram components [44]. The improved performance of cumulative integration over stepwise integration suggests that learners need to retain the ability to refer to earlier steps of the problem.

C. Practical Implications

The results of this study indicate that the cumulative integration of equations into circuit diagrams is a successful instructional design strategy to facilitate the learning of electrical circuit analysis by non-engineering majors. Integrated formats are effective in maximizing the processing capabilities of working memory and capitalizing on the potential of multimedia instruction. The results further indicate that integration of equations in circuit diagrams is not successful if equations are removed from the diagram upon the introduction of each subsequent problem-solving step. Computer-based multimedia environments afford instructional designers the ability to create dynamic presentations [45], [46]. For teaching basic circuit analysis to non-engineering majors, these dynamic capabilities may best be used to develop multimedia that displays problem steps in a just-in-time fashion, keeping the equations for each successive problem step embedded within the circuit diagram following their initial presentation.

The implications of this experiment apply also to traditional classroom instruction. The findings from this study suggest that the instructor should directly integrate equations into the circuit diagrams in cumulative fashion as the solution progresses on the presentation medium employed, such as writing in chalk on a blackboard. Specifically, the equations should be written out right next to the corresponding variable denoting the circuit quantity of interest, as illustrated in Fig. 1(a). Defining only the variables for the circuit quantities in the diagram and writing out the corresponding equations next to the diagram, as illustrated in Fig. 1(c), forces the learners to split attention and map between the diagram and equation listing, which impairs productive learning. In contrast, the integrated presentation, following the illustration in Fig. 1(a), reduces split-attention and assists learners in locating corresponding information within equations and diagrams, thus fostering learning.

Textbooks used for technological literacy courses [8]–[10], which include chapters on electrical circuits, predominantly display the equations isolated from diagrams. The findings from this study suggest that the equations should rather be directly integrated into the circuit diagrams to improve learning by exploiting the spatial contiguity effect [23]. The specific cumulative integration design of this study could be implemented in a textbook through a sequence of diagrams, whereby each diagram in the sequence adds the equations for one problem-solving step. An alternative implementation strategy is to include all equations in the diagram and indicate their sequence through sequential equation numbering. The examination of these specific implementation strategies for textbooks is an important direction for future research.

D. Future Directions

There are several important directions for future research for teaching electrical circuit analysis. One interesting direction in the context of technical literacy education is to examine the integration of equations and circuit diagrams in the context of instructional strategies based on worked examples, which have received growing interest [47]–[49]. Another direction is to examine the integration of equations into circuit diagrams in the context of more complex circuit analysis taught to engineering majors. Yet another direction is analyze the underlying cognitive processes involved in circuit analysis learning, perhaps through concurrent eye tracking.

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