Investigating the Learning Impact of Coordinating STEM Representations in Digital Electronics

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Abstract

In engineering classrooms, students often fail to perceive the cohesion of central concepts as they are instantiated in a variety of different representations across multiple settings and social structures. We hypothesized that teachers' making explicit connections across different representations (*coordination*) can enhance learning in an engineering lesson. Student participants observed a digital electronics lesson that either did or did not coordinate truth tables with algebraic expressions. Participants in the experimental condition completed the post-lesson assessment more quickly and performed better on questions coordinating words and variables. Students with less rigorous previous mathematics coursework performed more slowly when they did not observe coordination, but more quickly when they observed coordination, compared to students who took AP-level mathematics. This study provides early support for our hypothesis that explicitly making connections for novice learners across representations and contexts is important in improving student learning outcomes in STEM areas. It also suggests that such connections may be especially important for students with lower previous mathematics achievement. This has significant implications for teacher education, in that it provides early evidence that implementing a singular pedagogical technique can have empirically validated learning benefits for students.

Keywords: engineering education, experimental design, science education, multiple representations, Next Generation Science Standards, STEM education

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As the Next Generation Science Standards[1] continue to undergo revision and preparation for the state-by-state review process, a significant shift in the national priorities for science education is evident. Engineering is increasingly playing a central and vital role in the national science curriculum, and with this growing emphasis, new and unique challenges arise in establishing effective pedagogical practices for engineering teachers. In order to successfully implement the future science standards, science and engineering teachers will need to integrate within and across the STEM (science, technology, engineering, and mathematics) content, practices, and crosscutting concepts that comprise the standards.

Such integration can be challenging for teachers, given that engineering courses are often collaborative, project-based experiences for students, who encounter a broad range of representations of quantitative and qualitative relationships that take many different surface forms. These rich, dynamic contexts can increase engagement and interest in science (e.g., Renninger & Nam, 2012). However, these complex learning contexts also potentially introduce considerable obstacles for learners, since students often fail to perceive the cohesion of central concepts as they are instantiated in a variety of different representations (equations, graphs, diagrams, words, gestures, models, simulations), across a range of settings (wet labs, lectures, machine shops), and social structures (lectures, collaborative teams, seatwork) (Kozma, 2003; Nathan, Srisurichan, Walkington, Wolfgram, Williams, & Alibali, in press). Given the dynamic nature of the engineering classroom itself, the need to integrate the content, practices, and crosscutting concepts of the standards compounds the difficulties of teaching engineering to secondary students, yet such integration remains critical to ensuring successful student learning (Pellegrino, Chudowsky, & Glaser, 2001).

The following study investigated the hypothesis that student learning of the relevant STEM concepts of an engineering lesson will be enhanced when the teacher makes explicit connections across the relevant representations. We focus on students' abilities to translate between a source representation (e.g., words, tables, symbols) and a target representation (words, tables, symbols), which we refer to as *coordination*. This study offers early insights into successful implementation of STEM integration—a complex and urgent area of science and engineering education research that has implications for both teacher education and student learning.

Theoretical Framework

Project-based learning (PBL) is a promising educational approach (e.g., Burghart et al., 2010; Kolodner et al., 2003; Lachapelle et al., 2009) that naturally aligns with many of the aims of current engineering education reform (ABET, 2008; Brophy et al., 2008). Yet, evidence of the benefits of K-12 engineering curricula like Project Lead the Way (PLTW) on high-stakes student achievement in other STEM fields is mixed. Independent published studies of the effects of enrollment in K-12 engineering courses on high stakes tests, controlling for demographics, scholastic background, and selection bias, generally show small to negligible academic gains in science and mathematics for high-performing STEM students (Tran & Nathan 2010b; Schenk et al., 2011), and flat or negative impact for low-performing students (Tran & Nathan 2010a). Given that approximately an additional hour a day of STEM education yields little benefit on STEM assessments, and that low-performing students benefit the least from such curricula, further research investigating the relationship between student learning and forms of STEM instruction appears to be critical for science education reform.

One explanation of these mixed results may be a failure to address a central challenge for science and engineering students: maintaining an understanding of key concepts that constitute the deep conceptual structure of the activities, such as universal physical laws and mathematical theorems. These concepts often become unrecognizable to students when they appear in dramatically different surface representations and in varied contexts, providing a natural way to study knowledge transfer. Cognitive and learning science research predicts that learners will face challenges integrating concepts across representations that are encountered in different times, surface forms, and contexts (e.g., Greeno et al., 1993; Mayer, 2002), and these challenges may prove even more daunting for at-risk students.

In contrast, to be successful in project-based STEM classrooms, students need to develop high levels of representational fluency (Nathan et al., 2002; Lesh & Lehrer, 2003) and meta-representational competence (diSessa, 2004; diSessa & Sherin, 2000). Students must be able to look for and subsequently build connections across the disparate representations endemic to these contexts, such as sketches, equations and simulations (Kozma, 2003). A central part of meaning-making when using different representations involves building a network of *relational semantics* (Kaput, 1989), defined as the ability to translate within and among various representational systems.

Recent research on STEM education suggests that making the deep conceptual connections explicit for students may support the kind of integrative thinking that leads to representational fluency. Specifically, building and maintaining the *cohesion* of the central concepts in these activities appears to be key to fostering integrated STEM understanding (e.g., Nathan et al., in press; Nathan, Alibali, Wolfgram, Srisurichan, & Felton, 2011; Walkington, Nathan, Wolfgram, Alibali, & Srisurichan, in press). By *cohesion*, we mean (1) understanding how the same concepts arise in different forms, and (2) "seeing" the underlying mathematical and scientific ideas in each activity.

If benefits arise from learning experiences that provide explicit integration of STEM concepts, why is it rare to see students exhibit these benefits? Classroom observations and curriculum analyses suggest that curriculum developers and teachers often take cohesion of deep conceptual ideas across representations and activities for granted in engineering classrooms (Prevost et al., 2009; Welty et al., 2008). However, classroom observations show that teachers cannot assume that cohesion is being established in the classroom. Indeed, cohesion must be actively produced and maintained for students to attend to and build the necessary connections to support meaning making (Nathan, Wolfgram, Srisurichan & Alibali, 2011; Walkington et al., in press). Using coordination (Hutchins, 2005; Stevens & Hall, 1998), both teachers and learners explicitly connect different representations of the same concept on the basis of their shared underlying deep conceptual structure.

Of particular interest is the area of digital electronics, since this domain requires students to coordinate multiple representations (e.g., truth tables, Karnaugh maps, breadboards, etc.) that integrate rich mathematical concepts, such as Boolean algebra, throughout the engineering design process.

The investigation focused on two hypotheses.

1. H1. Explicit coordination across digital electronics representations leads to improved student performance.
2. H2. Specific improvements in representational fluency, as measured by translation from words to numbers, numbers to variables, and words to variables, contribute to the positive influence of coordination.

Methods

Participants

Participants were 37 undergraduate students (68% male) enrolled in an introductory psychology course at a large Midwestern university and recruited through the Psychology Department subject pool. Participants volunteered in exchange for one extra credit point for every 30 minutes of participation, for a total of three credits for the 90-minute experiment. Table 1 summarizes all demographic information collected. Cohorts of four to six participants were randomly assigned to the experimental ($N = 19$) or control condition ($N = 18$).

Procedure

Participants completed a questionnaire asking them to rate their level of familiarity on a scale of 1 (Very Unfamiliar) to 5 (Very Familiar) for the following concepts: algebra, probability theory, formal logic, digital circuits, analog circuits, breadboarding, truth tables, logic gates, binary numbers, DeMorgan's theorem, and Karnaugh maps (K-maps).

Figure 1 depicts the different components of each lesson sequence used in the study. Participants observed a live lesson on digital circuits, which involved designing a voting machine that collected votes from a president, vice president, and secretary in order to determine if a given bill would pass the executive committee. Both experimental conditions observed the following lesson segments: a broad, but brief introduction to digital circuits, constructing truth tables, representing logical statements using Boolean algebraic expressions, and use and meaning of the "AND" and "OR" operators. The control group then reviewed truth tables and algebraic expressions a second time (controlling for time-on-task with the treatment condition), while the experimental group received instruction *explicitly coordinating* the truth tables with the Boolean algebraic expressions. This coordination involved translating a truth table into Boolean algebraic expressions, and then translating the Boolean algebraic expressions back into a truth table, along with explanations that made explicit element-by-element connections between the two representations. Finally, both groups received a summary of the lesson.

After the lesson, participants in both conditions completed a 23-item paper-and-pencil assessment measuring: recall of basic information (five questions), creating a truth table from a word problem (seven questions), generating a logical rule from a truth table (five questions), understanding the binary nature of truth tables (three questions), and using algebra to simplify logic statements (two questions). Of the 23 questions, seven involved coordinating words (descriptive statements) and numbers (truth table entries), eight involved coordinating numbers and variables (algebraic expressions), two involved coordinating words and variables, and six involved no coordination. Table 2 provides examples of each type of question and each type of coordination. Finally, participants completed a paper-and-pencil demographic questionnaire.

Data Sources

The rankings on a scale of 1 (Very Unfamiliar) to 5 (Very Familiar) from the pre-lesson familiarity questionnaires were averaged together for a composite familiarity score. The individual and composite familiarity scores were then used to assess whether there were any systematic pre-lesson differences in the background of the two groups. Previous math experience was determined based on the highest self-reported level of math completed in high school (High = completed any AP-level calculus vs. Low = did not complete any AP-level calculus). This variable was used to assess whether there were differences between the two groups in terms of mathematics background.

The response to each item on the post-lesson assessment was scored as either correct or incorrect. In order to be scored as correct, answers were expected to be complete (for fill-in truth table questions), match the answer key exactly (for multiple choice, algebraic simplification, and fill-in-the-blank questions), or incorporate pre-determined key words (for open-ended items). Each student was also timed during the post-assessment in order to examine if there were differences in their efficiency when taking the assessment.

Independent sample t-tests were used to compare familiarity for individual items, composite familiarity scores, sum scores on the assessment, scores on individual assessment items, and sum scores on assessment items grouped by type of coordination (i.e., words and numbers, words and variables, numbers and variables, or none) between the two groups. A 2x2 ANOVA was used to compare the completion time of the two groups and the mathematics background of participants in each group. Variances were assumed to be equal when Leverene's Test for Equality of Variances was not significant; when the test statistic was significant, variances were not assumed to be equal.

Results

The pre-lesson familiarity questionnaire indicated that participants were unfamiliar with most concepts ($M = 2.30$, $SD = 1.04$). The two groups did not significantly differ in their overall level of familiarity with the concepts ($t(34) = -1.126$, $p = .268$), or on any individual concept. Table 3 summarizes the scores for each experimental group on each familiarity item. No significant group differences were found on any of the items from the demographic questionnaire (See Table 1). The two groups also did not differ significantly in their previous math background ($t(35) = 1.551$, $p = .130$).

The overall average time to complete the post-lesson assessment was 27.84 minutes. The experimental group took less time to complete the post-lesson assessment than the control group ($M = 23.26$ minutes, $SD = 6.73$ vs. $M = 32.67$ minutes, $SD = 9.96$). In addition to the practically large reduction in time of about one-third, a 2x2 ANOVA (condition, math level) found that there was a significant main effect for condition ($F(1, 32) = 9.551$, $p = .004$)179. There was no main effect for math level ($F(2, 32) = 0.253$, $p = .778$); however, there was a marginally significant interaction between condition and math level ($F(1,32) = 3.2$, $p = .083$), in that the participants with a low-math background took longer than those with a high-math background in the control condition, but took less time in the experimental condition. This provides partial support for Hypothesis 1, which posited that coordination across representations would lead to superior overall post-test performance. It also introduces a potentially important unpredicted finding—that students of a lower math background might benefit disproportionately from the process of explicit coordination in terms of increasing their efficiency in accessing multiple representations of a mathematical construct.

The overall average score on the post-lesson assessment was 54.76%, with scores ranging from 13.04% to 86.96% ($SD = 4.59$). Descriptively, the experimental group performed better overall on the post-lesson assessment than the control group ($M = 58.35\%$ vs. $M = 50.97\%$). However, this difference did not reach statistical significance ($t(35) = 1.099$, $p = .279$). Table 4 provides the means and standard deviations for the accuracy of the two experimental groups, for each sub-group of the post-lesson assessment.

The experimental group showed statistically significant advantages on specific measures of representational fluency, as posited by Hypothesis 2. The experimental group performed better ($M = 100.00\%$, $SD = .00$) compared to the control group ($M = 75.00\%$, $SD = .429$) on the questions that coordinated words and variables, $t(17) = –2.474$, $p < .05$, which provides partial support for Hypothesis 2. Experimental performance on the items coordinating words and variables was at ceiling for every participant, suggesting that we might see an even greater effect favoring the use of coordination, if the items had provided a wider range of performance at the high end. Although the experimental group exhibited superior performance on each of the groups of items (see the last column of Table 4), there was no statistical difference between the groups for subsets of questions that involved coordinating words and numbers, numbers and variables, or that involved no coordination. There were also no statistical differences between the groups for subsets of questions of different types (i.e., Recall, Truth Tables, Logical Rule, Binary, or Algebra Simplification). However, looking across the range of measures, the experimental group exhibited superior performance compared to the control group in every sub-group of the assessment, grouped by question type and grouped by coordination (See Table 4).

Discussion

Interpretations of Findings

The control and experimental groups showed some differences that support the proposed hypotheses. The experimental group took significantly less time to complete the post-lesson assessment, indicating one type of performance advantage for the intervention (Hypothesis 1). Greater speed with one's knowledge is a valuable indicator of the level of understanding and certainty of one's knowledge. It can also have practical benefits such as leading to higher levels of productivity. One potential explanation for this finding is that coordination led to stronger connections between the STEM representations in long-term memory. Furthermore, the interaction between condition and mathematics background approached significance (p = .083), in that students with a lower-level mathematics background took more time than those with a higher-level background on the post-lesson assessment in the control condition, but took less time in the experimental condition. This implies that students with less advanced mathematics coursework especially benefit from explicit coordination of multiple representations. A potential explanation for this marginally significant interaction is that providing multiple paths to understanding a mathematical concept strengthens the connections for students with less previous mathematics experience, whereas it may possibly seem redundant to those with stronger mathematics background, which could perhaps result in decreased engagement in the lesson for these students. Further investigation into this potential interaction will be necessary to explore this and alternative hypotheses.

The higher accuracy on questions coordinating words and variables suggests that coordination enhanced participants' ability to assign meaning to symbolic representations. This finding provides some support for Hypothesis 2. Taken together, the results paint a useful picture about coordination. Instruction that uses coordination between particular forms representations (truth tables and Boolean algebraic expressions) can lead to reliable benefits for fostering representational fluency between some representational forms (words and variables). However, the effect is fairly localized, and does not radiate to those processes that affect fluency among all of the relevant representations. Finding the effect has limited scope is not surprising in light of the rather limited nature of transfer in many areas of study (Greeno & Moore, 1993; Singley & Anderson, 1989). In addition, it is important to note that all of the results were in the predicted direction, but did not reach statistical significance. This suggests that a new study with greater power and more sensitive measures could reveal additional effects due to coordination.

Implications for Instruction

Often, instructors and curriculum designers assume that learners will make conceptual connections across representations and context. This seems to follow from their view that students will think like them and see the connections that they, as content area experts, readily see. But instructors and curriculum designers need to be wary that they may operate with an expert blind spot that prevents them from accurately seeing the world as it appears to their novice students (Nathan & Petrosino, 2003). The use of explicit coordination during STEM instruction can help teachers to avoid this often-faulty assumption and provide learners with the detailed conceptual connections they need to access and apply their science, mathematics, and engineering knowledge in an integrative manner, and thereby exhibit the deep thinking that is the long-term goal of STEM education. This may prove to be particularly essential for students with less robust mathematics backgrounds.

Limitations and Future Work

This study as currently implemented had several limitations. First, the analysis techniques used here are relatively simple (*t*-tests and ANOVA), and the sample size was also relatively small. A larger study is underway with an increased sample size to allow for greater statistical power to detect the differences between the groups that we observed were in the predicted direction in this study. For the larger study that is underway, we plan to use confirmatory factor analysis and regression models. Because the post-lesson assessment that participants complete is content-specific, and therefore not previously validated, confirmatory factor analysis will serve as a measure of construct validity. This statistical method allows us to test the hypothesis that the questions in the post-lesson assessment coordinating different representations (i.e. words, variables, and numbers) are based upon common latent factors and therefore can be grouped together for analysis. Regression models will be used to test the hypothesis that the participant group who viewed explicit coordination will score significantly higher on the post-lesson assessment, controlling for key demographic variables such as prior mathematics achievement.

Second, the lesson instruction naturally showed some systematic variability because the instructor who carried out the live lesson was not blinded to experimental condition. In the next iteration of this research, we have eliminated potential confounds across the experimental and control conditions by developing a set of video-based lessons that vary the exposure to coordination but are identical in every other respect to provide more consistency across the lessons. Finally, in the next iteration, we intend to assess both immediate and delayed learning, as well as the potential for future learning of a related but distinct engineering concept. The intention is that a learning measure may be more sensitive to revealing treatment differences than standard performance measures. Delayed re-testing may also reveal more subtle processes at play.

Conclusion

As the Next Generation science standards begin to take shape, engineering courses will increasingly require teachers to integrate content, practices, and crosscutting concepts that span a variety of different representations across a wide range of settings and social structures. Given that engineering courses are collaborative and project-based, engineering teachers have opportunities for authentic PBL that integrates STEM skills and concepts. However, PBL can create additional barriers to learning as students strive for cohesion in such dynamic learning environments. This study underscores the importance of making such cohesion explicit for students via teacher-produced coordination of multiple representations of locally invariant mathematical relationships. In the context of the three dimensions of the Next Generation science standards, this cohesion is simultaneously more challenging and more critical for engineering teachers to integrate in their pedagogy.

From an education perspective, this research underscores the importance of explicitly making connections for novice learners across representations and contexts, even though these connections may be evident to expert teachers and curriculum developers. This may prove to be even more critical for students with less extensive and rigorous previous mathematics coursework. From a scientific standpoint, understanding the processes that contribute to the production of cohesion will advance our understanding of complex cognition, which will lead to more sophisticated theories of STEM learning and practice. We anticipate that our current revised experimental approach will enable us to move towards a deeper understanding of the mechanism of coordination and the improved learning outcomes that coordination can promote.

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Figures

Figure 1. Experimental procedure for control and experimental conditions. Half (*N* = 18) of participants observed a live lesson consisting of the sections in the first row. Half (*N* = 19) observed a live lesson consisting of the sections in the second row. The control group observed the “Truth Tables” and “Algebraic Expressions” sections a second time, whereas the experimental group observed *coordination* of truth tables and algebraic expressions instead.

Table 1

Summary of Demographic Information Responses From Participants

Demographic Variable	Overall	Control	Experimental
Age	*M* = 19.4 years	*M* = 19.3 years	*M* = 19.6 years
Gender			
Male	*N* = 25 (67.6%)	*N* = 12 (66.7%)	*N* = 13 (68.4%)
Female	*N* = 12 (32.4%)	*N* = 6 (33.3%)	*N* = 6 (31.6%)
Year in School			
Freshman	*N* = 27 (72.9%)	*N* = 15 (83.3%)	*N* = 12 (63.2%)
Sophomore	*N* = 5 (13.5%)	*N* = 2 (11.1%)	*N* = 3 (15.8%)
Junior	*N* = 2 (5.4%)	*N* = 0 (0.0%)	*N* = 2 (10.5%)
Senior	*N* = 3 (8.1%)	*N* = 1 (5.6%)	*N* = 2 (10.5%)
GPA	*M* = 3.174	*M* = 3.202	*M* = 3.119
ACT Score			
Overall	*M* = 29	*M* = 29.1	*M* = 28.9
English	*M* = 30.4	*M* = 32.0	*M* = 29.1
Math	*M* = 29.9	*M* = 31.9	*M* = 28.4
Reading	*M* = 29.5	*M* = 29.0	*M* = 29.9
Science	*M* = 28.8	*M* = 28.2	*M* = 29.1
English as Secondary Language			
Yes	*N* = 4 (10.8%)	*N* = 2 (11.1%)	*N* = 2 (10.5%)
No	*N* = 33 (89.2%)	*N* = 16 (88.9%)	*N* = 17 (89.5%)
Highest HS Math			
Below Pre-Calc	*N* = 3 (8.1%)	*N* = 2 (11.1%)	*N* = 1 (5.3%)
Pre-Calculus	*N* = 16 (43.2%)	*N* = 5 (27.8%)	*N* = 11 (57.9%)
AP Calculus	*N* = 18 (48.6%)	*N* = 11 (61.1%)	*N* = 7 (36.8%)
Highest College Math			
None	*N* = 10 (27.0%)	*N* = 5 (27.8%)	*N* = 5 (26.3%)
Pre-Calculus	*N* = 6 (16.2%)	*N* = 5 (27.8%)	*N* = 1 (5.3%)
Calculus 1	*N* = 15 (40.5%)	*N* = 5 (27.8%)	*N* = 10 (52.6%)
Calculus 2	*N* = 3 (8.1%)	*N* = 2 (11.1%)	*N* = 1 (5.3%)
Calculus 3	*N* = 3 (8.1%)	*N* = 1 (5.6%)	*N* = 2 (10.5%)
HS Comp. Sci. or Engineering			
Yes	*N* = 3 (8.1%)	*N* = 0 (0.0%)	*N* = 3 (15.8%)
No	*N* = 34 (91.9%)	*N* = 18 (100.0%)	*N* = 16 (84.2%)
College Comp. Sci. or Engineering			
Yes	*N* = 2 (7.4%)	*N* = 1 (5.6%)	*N* = 1 (5.3%)
No	*N* = 35 (94.6%)	*N* = 17 (94.4%)	*N* = 18 (94.7%)
Prior Math Background			
High	*N* = 17 (48.6%)	*N* = 11 (61.1%)	*N* = 6 (31.6%)
Low	*N* = 19 (51.4%)	*N* = 7 (38.9%)	*N* = 12 (63.2%)

Table 2

Example Questions From the Post-Lesson Assessment

Question Type	Example
Recall of Basic Information ($N = 5$)	For the voting machine you learned about today, what **value** would you put into a truth table when a person votes FOR the bill?
Creating a Truth Table from a Word Problem ($N = 7$)	You are designing a digital circuit for a new pedestrian stoplight that will be installed along a busy street. The light flashes the WALK sign (i.e. the output is TRUE) **only** when traffic from both the right and the left is stopped (i.e. when the input is FALSE). Create a truth table for this circuit.
Generating a Logical Rule from a Truth Table ($N = 5$)	What is the *rule* that the logic in the truth table is following? Explain in your own words.
Understanding the Binary Nature of Truth Tables ($N = 3$)	If we had **four** variables, how many total combinations would there be?
Using Algebra to Simplify Logic Statements ($N = 2$)	Given the list of identities [not shown here], simplify the following algebraic expressions: $(X \bullet \overline{Y}) + (X \bullet Y)$
Question Coordination	**Example**
Words and Numbers ($N = 7$)	There is an operator called the NAND operator. The NAND operator produces the *exact opposite* output as the AND operator. Create the truth table for the NAND operator.
Numbers and Variables ($N = 8$)	Given the following ***simplified*** algebraic expression, create the truth table: $(A \bullet B) + (B \bullet C) + (A \bullet C)$
Words and Variables ($N = 2$)	For the voting machine you learned about today, how would you write the **variable** for a person X when he or she votes AGAINST the bill?
No Coordination ($N = 6$)	If we had **four** variables, how many total combinations would there be?

Table 3

Differences in Familiarity Levels Between Conditions

Pre-lesson familiarity questionnaire	Control *Mean (SD)*	Experimental *Mean (SD)*
Algebra	4.53 (0.62)	4.26 (0.56)
Probability Theory	3.35 (1.17)	3.32 (0.82)
Formal Logic	3.23 (1.09)	3.42 (1.02)
Digital Circuits	1.59 (0.87)	1.79 (0.63)
Analog Circuits	1.47 (0.62)	1.74 (0.65)
Breadboarding	1.41 (0.62)	1.37 (0.50)
Truth Tables	2.18 (1.07)	2.20 (1.30)
Logic Gates	1.71 (0.85)	1.74 (0.81)
Binary Numbers	2.47 (1.07)	3.05 (1.13)
DeMorgan's theorem	1.29 (0.59)	1.69 (1.29)
Karnaugh Maps (K-Maps)	1.35 (0.61)	1.32 (0.58)

Table 4

Differences in Post-Lesson Assessment Sub-Scores and Completion Time Between Conditions

Post-lesson assessment	Control *Mean (SD)*	Experimental *Mean (SD)*	Superior Group
Question Type			
Recall ($N = 5$)	83.16% (0.28)	94.74% (0.09)	Experimental
Truth Tables ($N = 7$)	36.84% (0.34)	45.11% (0.29)	Experimental
Logical Rule ($N = 5$)	61.05% (0.26)	64.21% (0.29)	Experimental
Binary ($N = 3$)	38.60% (0.49)	49.12% (0.46)	Experimental
Algebra Simplification ($N = 2$)	23.68% (0.39)	31.58% (0.38)	Experimental
Question Coordination			
Words and Numbers ($N = 7$)	59.03% (0.26)	63.16% (0.21)	Experimental
Numbers and Variables ($N = 8$)	46.11% (0.24)	53.16% (0.22)	Experimental
Words and Variables ($N = 2$)	75.00% (0.43)*	100.00% (0.00)*	Experimental
No Coordination ($N = 6$)	29.63% (0.36)	35.09% (0.38)	Experimental
Overall Accuracy ($N = 23$)	50.97% (0.22)	58.35% (0.18)	Experimental
Completion Time	32.67 (9.96)**	23.26 (6.732)**	Experimental (shorter time)

Note: *$p < .05$. **$p < .005$.

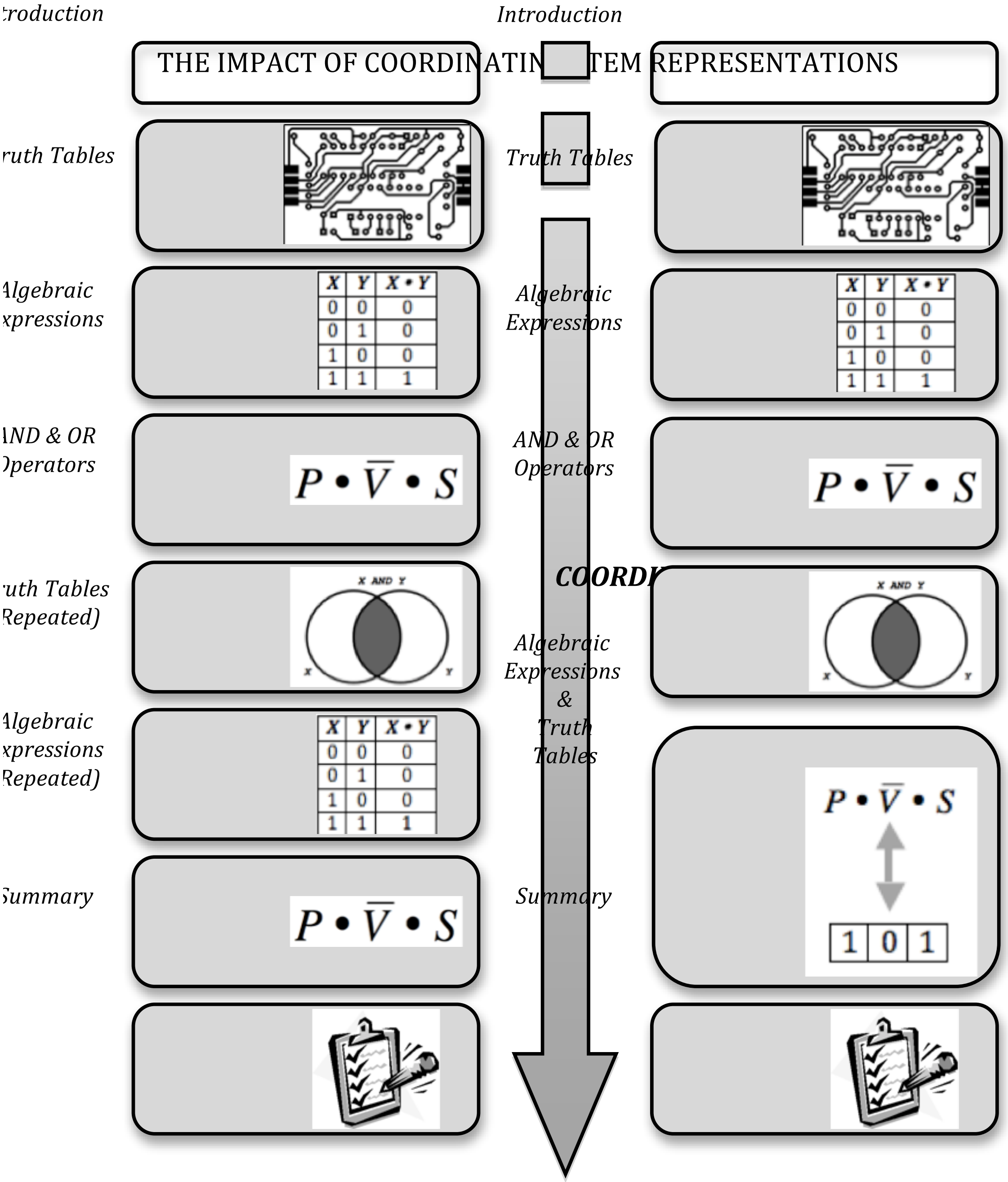

Figure 1. Experimental procedure for control and experimental conditions. Half ($N = 18$) of participants observed a live lesson consisting of the sections in the first row. Half ($N = 19$) observed a live lesson consisting of the sections in the second row. The control group observed the "Truth Tables" and "Algebraic Expressions" sections a second time, whereas the experimental group observed *coordination* of truth tables and algebraic expressions instead.

Endnotes

[1] The Next Generation Science Standards is a joint effort between the National Research Council, the National Science Teachers Association, the American Association for the Advancement of Science, and Achieve, Inc. See http://www.achieve.org/next-generation-science-standards