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Using Students' Representations Constructed during Problem Solving To Infer Conceptual Understanding

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ABSTRACT: The differences in the types of representations constructed during successful and unsuccessful problem-solving episodes were investigated within the context of graduate students working on problems that involve concepts from 2D-NMR. Success at problem solving was established by having the participants solve five problems relating to material just encountered within a computer-based tutorial. The results indicate that representations constructed during successful problem-solving episodes tend to be more accurate and more complete, but not as abstract as those constructed during unsuccessful problem-solving episodes. When more than a single representation was constructed, however, the additional representations associated with successful problem solving tended to be more abstract than those constructed during unsuccessful problem solving. The authors contend that the constructs of accuracy, abstractness, and completeness are useful for characterizing the differences in the representations constructed during successful and unsuccessful problem-solving episodes, and may serve as useful indicators of the degree of conceptual understanding the individual brings to the problem-solving event.

KEYWORDS: *Graduate Education/Research, Chemical Education Research, Problem Solving/Decision Making, NMR Spectroscopy, Qualitative Analysis*

FEATURE: Chemical Education Research

The problem-solving behavior of chemistry students has long been an area of keen interest in chemistry education.[1−13] Traditionally, a bipolar perspective has been used—students are classified as using either an algebraic−algorithmic approach to problem solving or one that is conceptual.[8] Pickering,[14] for example, argued that there are two kinds of students, those who possess the ability to do conceptual problems and those who can do mathematical problems without a molecular understanding. This approach to understanding students' problem-solving behavior may incorrectly lead some to presume that the students who are algebraic−algorithmic problem solvers all have the same level of conceptual understanding, namely, none. Inability to solve a conceptual problem, however, is not indicative of complete lack of conceptualization of the necessary ideas. It only suggests that the level of conceptual understanding is not sufficient. Or, as Nakhleh and Mitchell[3] have noted, the student might have both high algorithmic and high conceptual ability, but chooses to use an algebraic−algorithmic approach when solving a particular problem.

The algorithmic−conceptual dichotomy is too simple a model to allow for substantive advancement in investigating conceptualization during problem solving. Niaz[15] has proposed a model in which the relationship between algorithm- and concept-evoking problems is not dichotomous. Rather, this relationship is best viewed as a continuum along which ever-increasing levels of conceptual understanding exist. In this framework, conceptual development can be construed as a progression from mental models that, at best, operate algorithmically to more sophisticated models possessing ever greater explanatory heuristic power. Niaz has suggested that reconstructing the various strategies used by students to solve problems can provide the necessary information to predict how student understanding progresses from being primarily algorithmic toward being primarily conceptual. In accord with Niaz's suggestion, we believe that systematic investigations of the nature of the representations students construct during problem solving can provide a clearer, more useful understanding of the conceptual development of students.

■ PHILOSOPHICAL FRAMEWORK

The philosophical framework for this study considers cognition and learning, including problem solving, to be based on the manipulation of internal symbolic representations that are based on what individuals perceive.[16,17] Educators attempt to manipulate students' perceptions by presenting intentionally coded messages (e.g., texts, visuals, charts, tables, etc.) to the learner with the expectation that the symbol systems within the coded messages will be adapted for internal use. This idea was captured by Salomon[18] who noted that "any object, movement, gesture, marker, or event can potentially serve in a symbolic capacity, provided it is taken to represent, denote, or express something beyond itself" (18, p 29). Salomon has also suggested that there exists a "certain structural isomorphism and developmental interdependency between our cognitive symbolic forms of representation and the symbol systems of our culture as manifested in the arts, sciences, and media" (18, p xix). From a chemistry education perspective, this can be paraphrased as follows: There is a relationship between the symbolic systems we present to students when teaching chemistry and the representations they construct when solving chemistry problems. Thus, we should expect some degree of

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Table 1. Descriptions of the Three Parameters Used To Relate Students' Constructed Representation to Presented Instructional Material and Additional Cognitive Contributions

Construct	Description
Accuracy	A measure of the degree to which the constructed representation resembles the symbol systems presented during the instructional episode.
Completeness	A measure of the degree to which symbol systems originally a part of the presented representations are missing from the constructed representations.
Abstractness	A measure of the degree to which the constructed representation incorporates additional symbol systems that were not part of the original presented instructional episode. The presumption is that these elements are prior knowledge contributions from the student's cognitive schema.

correspondence between the symbol systems presented during instruction and the symbols associated with the mental representations constructed during instructional practice (i.e., problem solving). Furthermore, differences in degrees of conceptualization among students should be discernible through qualitative investigation of the differences between the symbol systems that students use during the problem-solving process and the corresponding symbol or symbol system presented during instruction.

■ QUALIFYING THE NATURE OF STUDENTS' REPRESENTATIONS

This paper is based on the assumption that it would be useful to construct a better understanding of the relationship between the symbol systems associated with pertinent concepts when they are presented as part of an instructional activity, and the students' representations of these concepts subsequently manifested while solving problems that involve these concepts. We believe this will be useful even for students who would often be classified as being engaged in algebraic−algorithmic problem solving. This is achievable by comparing elements within constructed representations to corresponding symbols within instructional presentations. The comparisons are based on the following three constructs: accuracy, completeness, and abstraction (Table 1). Van der Veer and Melguizo[19] include accuracy and completeness as key descriptors of mental representations, and Barsalou[20] identifies abstraction as a necessary part of mental representation construction. In addition, these constructs have been used in problem-solving research involving mental representation construction in both chemistry and mathematics education.[21,22]

Accuracy is a measure of how closely the student-constructed representation used during problem solving resembles the way the concept was presented during instruction.[22] For example, if water is presented as "H_2O" during instruction, and the individual represents it as "H_2O" while problem solving, then there is a high degree of resemblance between the two. The representation is, quite literally, a re-presentation of what was perceived during instruction. If, on the other hand, water is represented as "water", then this constructed representation has a low level of resemblance (accuracy). An intermediate degree of accuracy might be assigned to the representation "HOH".

Abstractness reflects the degree to which the constructed representation is associated with the prior knowledge or conceptual knowledge the individual brings to the instructional experience.[20] Incorporation of prior knowledge from within the individual's conceptual repertoire results in a representation that is more detached from the experience to which the individual was exposed to during instruction. As individuals contribute more of their prior knowledge to the constructed representations, these become more abstract. Koedinger, Alibali, and Nathan[23] described individuals' constructed representations as being either grounded or abstract. Grounded representations are more specific to the perceived experiences of the individual, whereas abstract representations are less likely to refer directly to a specific experience.

Consider $H_2\ddot{O}$: as another example of a representation of water. This bears a strong resemblance to the presentation used during instruction, but additional conceptually relevant information is also being represented: the two pairs of dots around the "O" that stand for pairs of nonbonding electrons. This information was not part of the instructional presentation and must, therefore, be a contribution abstracted from the individual's cognitive structure. This representation suggests that the individual who constructed it possesses prior knowledge about the Lewis structure of water, as well as the proper formalism for representing nonbonding electrons.

The condition also exists when less information appears to be present in the external representation than was presented during instruction.[22] In such instances, the representation is incomplete. Understanding that the external representations individuals display during the problem-solving process do not possess complete correspondence to their internal mental representations, two conditions become possible when the external representation appears incomplete. It is possible that the problem solver did not consider the information that was omitted from the external representation, in which case the incompleteness of the representation is *explicit*. In other words, the missing information was neither a part of the external or internal representations constructed during the problem-solving process.

It is also possible that the problem solver considered the missing symbol or information, but then consciously excluded it from the external representation that was written. In this case, the incompleteness of the representation is *implicit*. The information is missing from the external representation, but not from the internally constructed mental representation.

If the problem solver is aware that the chemical formula for water is H_2O, for example, but chose not to include the "2" in the external representation because the number of hydrogen atoms has no bearing on the solution to the problem, then the external representation would be labeled as incomplete-implicit. If the individual, however, devotes no conscious thought to the number of hydrogen atoms in a water molecule, then the external representation would be labeled as incomplete-explicit and assumed to be neither a part of the external nor the internal representation. Denoting the incompleteness of the representation as explicit or implicit cannot be achieved solely through examination of the externally constructed representation. This level of categorization is achieved by probing the content and structure of the internal representation using qualitative research techniques such as think-aloud protocols.[24,25]

1. ^{11}B has a spin-quantum number of 3/2. What are the possible spin orientations? Based on the selection rule, list the allowable transitions for ^{11}B.
   [−3/2, −1/2, +1/2, +3/2]; [−3/2 ⇆ −1/2, −1/2 ⇆ +1/2, +1/2 ⇆ +3/2]
2. Predict which case will have the greatest population difference between the least and most stable energy states:
   (a) A sample of protons (^1H) with a total population of 1×10^6 at 500 K experiencing an applied magnetic field of 20 T.
   (b) A sample of nitrogen (^{15}N) with a total population of 1×10^8 at 900 K experiencing an applied magnetic field of 10 T.
   (c) A sample of fluorine (^{19}F) with a total population of 1×10^7 at 1200 K experiencing an applied magnetic field of 30 T.
   [c]
3. In a coupled spin system between two nuclei, ^{13}C and ^1H, predict the order of coherence for the following transition: <+1/2, +1/2> to <−1/2, −1/2>
   [2]
4. Starting from thermal equilibrium (with M° aligned along the *Z* axis) and assuming no delays between pulses, predict on which axis the magnetization vector, M, will lay after experiencing the following pulse sequence (assume the rf transmitter is aligned along the +*X* axis): $90°_x$, $90°_x$, $180°_x$, $90°_x$, $270°_x$, $90°_x$.
   [−*Z* axis]
5. How would you explain the concept of thermal equilibrium to a peer?
   [A dynamic situation where there is a constant flux between two energy states, but the total population difference remains constant. The population difference is dependent on the ambient temperature, the strength of the applied magnetic field, and the magnetogyric ratio of the specific isotope.]

Figure 1. The instrument containing five problems on 2D-NMR used in this study, with answers provided in brackets.

■ METHODOLOGY

This study followed a mixed-methods research design.[26] Both quantitative and qualitative analytical tools were selectively employed to address specific aspects of the analysis.

The pertinent concepts used in the problem-solving tasks for this study are the fundamental concepts of two-dimensional nuclear magnetic resonance (2D-NMR) spectroscopy.[27] The instructional material for this study was based on the 2D-NMR experiment for three reasons:

1. Many of the pertinent concepts can be expressed with a variety of representations.
2. The participants in the study had not received prior instruction on 2D-NMR; thus, the 2D-NMR representations constructed by the participants during problem solving most likely would not be tainted by previous instruction.
3. The concepts of 2D-NMR are built from concepts stemming from 1D-NMR, an aspect of chemistry with which all of the participants were adequately familiar. They should therefore have possessed the requisite prior knowledge needed to learn the material presented in the instruction.

The instructional material was presented as a computer-based tutorial that allowed for nonlinear navigation. The tutorial design followed the prescriptions of modular instruction[28] and contained six independent instructional packages, each covering a single conceptual unit of the 2D-NMR experiment. The order in which these packages were studied was determined by each participant as he or she went through the tutorial. Once a module was chosen, however, the participant had to complete the module and pass an embedded quiz—successfully answering three questions relating to the topic—before proceeding to another module. Each module began by presenting the participants with a set of three learning objectives. The concepts were presented in a variety of formats, using text, graphics, and animation sequences.

The instrument used to evoke the construction of representations by the participants was a set of five problems shown in Figure 1, each of which required application of a particular 2D-NMR concept that was presented within the tutorial. It was presumed that arriving at a solution to the tasks would require the participants to use their existing mental models; thus, the tasks embedded in the instrument can be construed as problems as described by Hafner and Stewart.[29] Each problem was designed to have a specific solution, be solved within about 15 min, and be represented with more than one type of representation. Content validity of the instrument was established by having three experts in the field of 2D-NMR spectroscopy evaluate the problems based upon the above criteria.

The concepts required to solve 2D-NMR problems are quite sophisticated. Participants for the study were therefore solicited from among a population of first- and second-year chemistry graduate students. This sample population was chosen because they were likely to possess the requisite prior knowledge for learning 2D-NMR concepts and this prior knowledge should be well developed within their cognitive framework. Unlike older graduate students, however, they had not yet had the opportunity to receive training in 2D-NMR spectroscopy or use this technique in their own research. Graduate students in the chemistry department at a large, state-supported, research-oriented university were recruited as participants. To minimize the effects of contextual knowledge on problem-solving performance, only first- and second-year graduate students who would eventually use 2D-NMR in their research were recruited. Rittle-Johnson and Koedinger[30] describe contextual knowledge as one of the three types of knowledge—along with procedural (recipe knowledge) and conceptual knowledge—that may affect problem-solving performance. They assert that problem solvers tend to be less successful if the context of the problem situation is not deemed meaningful. For the participants in this study, the topic and subsequent problems were expected to be highly meaningful because the 2D-NMR experiment would eventually figure prominently in their research.

A total of 15 graduate students (6 females and 9 males) volunteered to participate; their average age was 26 years (SD = 3.7). None of the participants indicated having received prior instruction on 2D-NMR, although all indicated prior exposure to the fundamental concepts of 1D-NMR experiments, either during a spectroscopy course or as part of a physical organic

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1. No attempt was made to solve the problem.
2. The participant attempted to solve the problem, but demonstrates no understanding of the pertinent concepts.

   $\Delta m = 2I + 1$

   (Participant used the wrong equation for calculating order of coherence.)
3. The participant displayed knowledge of the appropriate concepts, but could not integrate them together to solve the problem.

   $+1/2, +1/2$

   $+1/2, -1/2\ -1/2, +1/2$

   $-1/2, -1/2$

   $\Delta m = m_I\,(\text{upper}) - m_I\,(\text{lower}) =$

   (Participant knows the pertinent concepts, but cannot combine them to arrive at a solution.)
4. The participant incorrectly solved the problem, but demonstrated an understanding of the necessary concepts. Failure to arrive at a correct solution can be attributed to some type of encoding or computational error.

   $\Delta m = m_I\,(\text{upper}) - m_I\,(\text{lower}) = 1 - -1 = 0$

   (Participant used the correct equation, but makes a computational error.)
5. The participant was able to correctly solve the problem.

   $\Delta m = m_I\,(\text{upper}) - m_I\,(\text{lower}) = 1 - -1 = 2$

Figure 2. Rubric for scoring problem-solving success. Solution paths for Problem 3 are used as examples.

chemistry course. All of them indicated that they expected to use 2D-NMR in their research.

Problem-solving sessions were conducted with the participants on an individual basis. These sessions began with a pretest containing 10 questions that assessed the participants' content knowledge of the material they were about to experience in the tutorial. After receiving instruction on navigating through the tutorial, the participants were given access to the tutorial and allowed to proceed at their own pace. Immediately after completing the tutorial, the participants were given a posttest that was exactly the same as the pretest. A statistically significant positive change in performance on the posttest relative to the pretest would be attributed to the instructional activities in the tutorial. After the posttest, videotaped one-on-one clinical interviews were conducted with the participants. During these interviews, the participants were asked to solve the five problems in Figure 1 while using a think-aloud protocol.[24,25] As part of the protocol, participants were asked explicitly to elaborate on representations that appeared to the researcher as incomplete.

Problem-solving success was established by rating the participants' solutions to each problem on a scale from 1 to 5. Evaluation of problem-solving performance included analysis of the participants' problem worksheets, the videotapes of the clinical interviews, and the associated transcripts. The rating criteria are given in Figure 2. Categorizing the participants' performances as either "successful" or "unsuccessful" on a particular problem followed an excluded-middle design. For each of the five problems, performances rated either 4 or 5 were categorized as "successful" and those that were rated as either 1 or 2 were categorized as "unsuccessful". Because the process by which the performances were rated on a given problem possesses an uncertainty of ± 1, situations in which the performance received a rating of 3 were excluded from this portion of the study. It should be noted, however, ratings of 3 were relatively rare, except for Problem 2. Each problem-solving episode was treated as an individual case. Thus, a participant may have been rated as a 3 for one problem and excluded from that case, but then rated as a 5 for another problem and categorized as "successful" for that problem.

In-depth qualitative analysis of the representations constructed by the participants was conducted by analyzing the representations in terms of accuracy, level of abstractness, and completeness. The accuracy was rated as low, medium, or high. A low rating indicated little or no resemblance between the representation and the presented material. A high rating was assigned if the problem solver's constructed representation was the same as the presented concept. Those representations that resembled the instructional presentation of the concept to some extent were rated as medium.

Representations constructed by the participant that were considered to contain the same amount of information as the instructional presentation were rated as having a low level of abstractness. If the constructed representation contained a limited number (≤ 3) of symbols or notations that were not part of the concept as it was presented during the instruction, the representation was said to have a medium level of abstractness. Representations constructed by the problem solver that contained more than three symbols or notations not originally present in the instructional presentation were deemed to have a high level of abstractness.

A representation was designated as *incomplete-explicit* if information originally part of the instructional presentation was not shown in the constructed representation. If, however, the participant indicated during the think-aloud protocol that he or she knew the missing information was part of the pertinent concept, but simply chose not to include it in the external representation, the representation was categorized as *incomplete-implicit*.

■ RESULTS AND DISCUSSION

The mean score on the pretest of 3.3 (SD = 2.3) indicated that the participants did not demonstrate significant prior knowledge of the material presented in the tutorial. The difference in the mean scores between the posttest (8.0, SD = 2.5) and the pretest is statistically significant ($t = 5.11$, $p < 0.0005$). Therefore, we regarded the interaction between the participants and the tutorial as leading to the construction of relevant knowledge that could be used during the problem-solving sessions.

Confidence in the ratings of the participants' solutions was established by calculating an inter-judge reliability coefficient.[31] Four judges (one of the authors and three chemistry education graduate students who were not participants in the study) independently scored the problems of five randomly chosen participants. Prior to scoring, each graduate student met individually with the first author who provided him or her with the problem-scoring rubric. During these sessions, the author

Table 2. Distribution of Accuracy, Abstractness, and Completeness Ratings of Representations for Successful and Unsuccessful Problem Solving

	Problem-Solving Result[a]	Low, %	Medium, %	High, %
Accuracy	Successful	43	20	37
	Unsuccessful	56	25	19
Abstractness	Successful	42	15	44
	Unsuccessful	33	14	53
Completeness		Complete	Incomplete, Implicit	Incomplete, Explicit
	Successful	85	13	1
	Unsuccessful	61	36	3

[a]For successful problem-solving results, n = 89; for unsuccessful problem-solving results, n = 36.

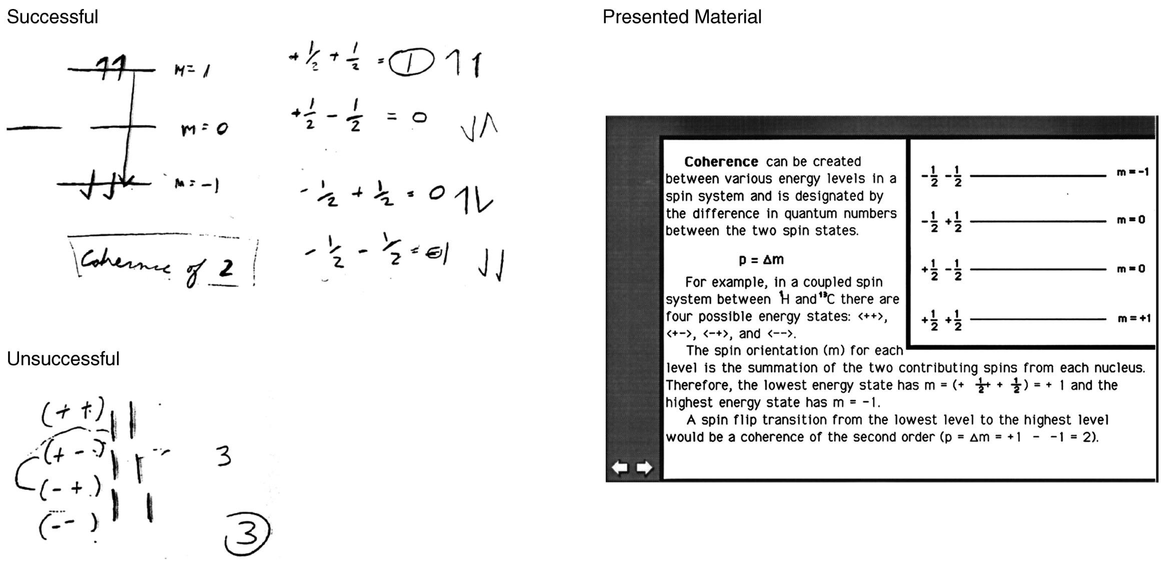

Figure 3. Representations constructed during a successful (top left) and an unsuccessful problem-solving episode (bottom left) and the corresponding presented information (right).

and graduate student analyzed the solutions of one participant, discussed how the solution met the criteria of the scoring rubric, and assigned a specific number to the solution from the scoring rubric. Inter-judge reliability correlations for the four judges' scores ranged from 0.73 to 0.99.

Table 2 summarizes the distributions of the constructed representations relative to the presented material in terms of accuracy, abstractness, and completeness. Although there were 15 participants in the study and five problems on which they could construct representations, a total of 125 representations were classified because the participants often constructed more than one representation per problem.

Overall, the representations constructed during successful problem-solving episodes tended to resemble the way the concept was presented during the instruction to a much greater extent than those constructed during unsuccessful problem-solving episodes. We found that 37% of the representations constructed during successful episodes were rated as highly accurate compared to only 19% for the unsuccessful episodes. The representations constructed during successful problem solving tended to be classified as complete to a greater extent than those constructed during unsuccessful problem solving (85% vs 61%). Interestingly, unsuccessful problem solvers constructed nearly three times more representations that were deemed incomplete-implicit than successful problem solvers (36% vs 13%). This means that during these unsuccessful problem-solving situations, the participant considered the missing information, but then chose not to include it in the external representation constructed for solving the problem. Figure 3 illustrates differences in accuracy and completeness of the representations constructed during both a successful and an unsuccessful problem-solving episode relative to the presented material. During the successful episode, two representations were constructed. The first one (from right to left) shown on the top left side of Figure 3 bears a much greater resemblance to the presented material than the single representation below it constructed during the unsuccessful episode. It also contains more information that was originally part of the material presented in the tutorial.

Although the representations constructed during successful problem solving were deemed to be more accurate and complete, they were judged to be less abstract than those constructed during the unsuccessful problem-solving episodes. Overall, only 44% of the external representations constructed during successful problem solving were regarded as highly abstract, as compared to 53% for unsuccessful problem solving.

An unsuccessful problem-solving episode was more likely to show evidence of the incorporation of prior knowledge. This additional information, however, was not useful in solving the problem. Evidence for this is found when examining the transcripts of the think-aloud problem-solving sessions. In 31% of the problems that were unsuccessfully solved, the problem solver related the problem statement to his or her prior knowledge. This is illustrated by the following dialogue between one of the researchers (R) and the participant (P) while solving problem five regarding thermal equilibrium:

P: Ok, thermal equilibrium is a state in which there is no net change between two states, but it is a dynamic process and things are going on all the time. I mean, well, if you focus on the overall result, there is no net change of everything, I mean anything, but if you look at one particular molecule, or subject, or it might switch from one state to another and at the same time another molecule will do the same thing to compensate.
R: Ok, And where did you learn this?
P: Thermodynamics and freshman chemistry.

The participant related the concept in the problem statement to previous courses, but made no mention of the section of the tutorial he had just completed in which thermal equilibrium was explained and illustrated. There was no evidence of this occurring for the problems that were successfully solved.

We examined in more detail episodes in which multiple representations were constructed to get a better understanding of the differences between the individual representations. Earlier, we stated that representations constructed during successful problem solving tended to be more grounded than those constructed during unsuccessful problem solving. This seemed counterintuitive; we expected the successful problem solvers to construct more powerful generic conceptual representations by incorporating additional conceptual information into the problem-solving situation than what could be gleaned from the instructional activity. When our results showed otherwise, we decided to examine how the level of abstraction varied when multiple representations were constructed. This analysis focused on how the level of abstraction of the last representation constructed differed from the level of abstractness of the first representation for each problem-solving episode when two or more representations were created for a given problem.

In this analysis, only data sets (n = 35) involving the construction of two or more representations were considered. Our analysis showed that there is a difference between successful and unsuccessful problem solving with regards to the level of abstractness of the last constructed representation relative to the first (Table 3). In 48% of these successful problem-solving episodes, the last representation possessed a higher degree of abstractness relative to the material presented in the tutorial than the first representation. Consider the example shown in Figure 3. In this case, the successful problem solver constructed two representations (top left). The first one (the right-most of the two) is more grounded to the material presented in the tutorial than the second representation to the left of it. The second representation shows a greater contribution from the problem solver's cognitive schema. Spin states that were depicted as different levels within the tutorial have become degenerate within the problem solvers' second representation, whereas they were shown as two distinct levels within her first representation. This relationship was found in only 13% of the multirepresentational systems constructed during unsuccessful problem-solving episodes.

Table 3. Level of Abstractness of the Last Representation Relative to the First Representation

Rating	More Abstract, %	As Abstract, %	Less Abstract, %
Successful (n = 27)	48	37	15
Unsuccessful (n = 8)	13	63	25

We also compared the level of abstractness of the first representation constructed in multirepresentational systems between successful and unsuccessful problem-solving episodes. Our analysis showed that the first representations constructed during successful problem solving were not as abstract as the first representations constructed during unsuccessful problem solving, as shown in Table 4. Collectively, the results depicted in Tables 3 and 4 suggest that *successful* problem solving involves grounding the first representation to the relevant instructional material and then incorporating more information from the problem solver's cognitive schema in subsequent representations constructed for the same problem.

Table 4. Abstractness Ratings of the First Representation Constructed in Multirepresentational Systems Relative to the Material Presented

Rating	Low, %	Medium, %	High, %
Successful (n = 27)	52	19	30
Unsuccessful (n = 8)	50	0	50

■ CONCLUSION

Representations constructed during successful problem solving tended to be more accurate and complete than those constructed during unsuccessful problem solving. However, the representations constructed during successful problem solving were also somewhat less abstract. When the order in which representations are constructed is considered for multirepresentational systems, an interesting pattern emerges: For successful problem-solving episodes, the first representation constructed tends to be more grounded in the instructional material. That is, it appears to possess less of a contribution from the cognitive schema of the problem solver. The second representation, however, is more abstract and the information it represents is more likely to include information that was not presented in the instruction, suggesting a greater contribution from the individual's cognitive schema. These results suggest that an important aspect of improving problem-solving performance is to help students ground their initial representation of a problem to specific instructional situations. Once this is done, students should then construct subsequent representations based on additional contributions from their cognitive schema. This is illustrated in Figure 3. The successful problem solver (Figure 3, top left) grounded her initial representation (right-most depiction). This is inferred from the high degree of resemblance between the representation and the presented material. The next constructed representation (left-most depiction), however, is more abstract, showing evidence of contribution from the problem solver's cognitive schema. In particular, the two spin states where m = 0 are represented as degenerate states.

Finally, our results are consistent with Niaz's[15] view of progressive transitions from algebraic−algorithmic to conceptual understanding and extend his work by suggesting that the qualitative properties of the representation constructed during the problem-solving process might serve as useful measures of the degree of conceptual understanding the individual brings to the problem. In particular, an analysis of the level of abstractness of the second constructed representation for a particular problem might be a useful gauge of the degree to which the problem solver incorporates his or her conceptual understanding. Future research is needed to further clarify how these constructs correspond to students' conceptual understanding of a problem situation. This study suggests that the constructs accuracy, abstractness, and completeness can be effectively used to further discriminate between successful and unsuccessful problem solving and are also useful for gauging degrees of conceptual understanding.

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REFERENCES

(1) Bodner, G. M. *J. Chem. Educ.* **1987**, *64*, 513−514.
(2) Cracolice, M. S.; Deming, J. C.; Ehlert, B. *J. Chem. Educ.* **2008**, *85*, 873−878.
(3) Nakhleh, M. B.; Mitchell, R. C. *J. Chem. Educ.* **1993**, *70*, 190−192.
(4) Nurrenbern, S. C.; Pickering, M. *J. Chem. Educ.* **1987**, *64*, 508−510.
(5) Pickering, M. *J. Chem. Educ.* **1990**, *67*, 254−255.
(6) Sanger, M. J.; Campbell, E.; Felker, J.; Spencer, C. *J. Chem. Educ.* **2007**, *84*, 875−879.
(7) Sawrey, B. *J. Chem. Educ.* **1990**, *67*, 253−254.
(8) Stamovlasis, D.; Tsaparlis, G.; Kamilatos, C.; Papoikonomou, D.; Zarotiadou, E. *Chem. Educ. Res. Pract.* **2005**, *6*, 104−118.
(9) Robinson, W. R. *J. Chem. Educ.* **2003**, *80*, 978−982.
(10) Bennett, S. W. *Chem. Educ. Res. Pract.* **2008**, *9*, 60−64.
(11) Cook, E.; Cook, R. L. *J. Chem. Educ.* **2005**, *82*, 1187−1189.
(12) Cooper, M. M.; Cox, C. T.; Nammouz, M.; Case, E. *J. Chem. Educ.* **2008**, *85*, 866−872.
(13) Overton, T.; Potter, N. *Chem. Educ. Res. Pract.* **2008**, *9*, 65−69.
(14) Pickering, M. *J. Chem. Educ.* **1990**, *67*, 254−255.
(15) Niaz, M. *Sci. Educ.* **1995**, *79*, 19−36.
(16) Goldstone, R. L .; Barsalou, L. W. *Cognition* **1998**, *65*, 231−262.
(17) Prinz, J. *Furnishing the Mind: Concepts and Their Perceptual Basis*; MIT Press: Cambridge, MA, 2004.
(18) Salomon, G. *Interaction of Media, Cognition, and Learning*; Lawrence Erlbaum Associates: Hillsdale, NJ, 1994.
(19) Van der Veer, G.; Melguizo, M. Mental Models. In *The Human−Computer Interaction Handbook*; Jacko, J. Sears, A., Eds.; Erlbaum: Mahwah, NJ, 2003; pp 52−80.
(20) Barsalou, L. W. Abstractness as Dynamic Interpretation in Perceptual Symbol Systems. In *Building Object Categories*; Gershkoff-Stowe, L., Rakison, D., Eds.; Carnegie Symposium Series, Erlbaum: Mahwah, NJ, 2005; pp 389−431.
(21) Frank, D. V. Implementing Instruction To Improve the Problem-Solving Abilities of General Chemistry Students. Doctoral Dissertation, Purdue University, West Lafayette, IN, 1986; DAI 47, pp 141.
(22) Yackel, E. Characteristics of Problem Representation Indicative of Understanding in Mathematical Problem Solving. Doctoral Dissertation, Purdue University, West Lafayette, IN, 1984; DAI 45, pp 2021.
(23) Koedinger, K. R.; Alibali, M. W.; Nathan, M. J. *Cog. Sci.* **2008**, *32*, 366−397.
(24) Bowen, C. W.; Bodner, G. M. *Int. J. Sci. Educ.* **1991**, *13*, 143−158.
(25) Kvale, S. *Interviews: An introduction to Qualitative Research Interviewing;* Sage: Thousand Oaks, CA, 1996.
(26) Johnson, R. B.; Onwuegbuzie, A. J. *Educ. Res.* **2004**, *33* (7), 14−26.
(27) Derome, A. E. *Modern NMR Techniques for Chemistry Research*; Pergamon Press: Oxford, 1987.
(28) Russell, J. D. *Modular Instruction*; Burgess: Minneapolis, MN, 1974.
(29) Hafner, R.; Stewart, J. *Sci. Educ.* **1995**, *79*, 111−146.
(30) Rittle-Johnson, B.; Koedinger, K. R. *Cog. Instr.* **2005**, *23*, 313−349.
(31) Winer, B. J. *Statistical Principles in Experimental Design*, 2nd ed.; McGraw-Hill: New York, 1971.