Development of Conceptual Understanding and Problem Solving Expertise in Chemistry

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Abstract

How does the development of expertise influence problem solving performance? Specifically, do characteristics of expert behavior such as attention to deep features while problem solving and planning solution strategies emerge simultaneously or sequentially? Further, is there evidence that conceptual understanding of the meaning behind calculations can be attributed to differences in problem solving? An analysis of expert/novice problem solving revealed three stages of expertise. Novices failed to attend to deep features while problem solving (e.g., choosing which values to use in a formula) and failed to demonstrate planning of solution strategies. Advanced novices attended to deep features while carrying out specific problem steps, but did not use conceptual information to plan an effective strategy. Finally, experts attended to deep features and used conceptual information to plan effective solution strategies. An analysis of protocol data suggests that problem solving performance relates to a conceptual understanding of the quantities involved in calculations.

Keywords: expertise; science learning; problem-solving; conceptual understanding.

Introduction

Experts and novices solve problems very differently from one another. Many studies of expertise have been conducted in the domain of physics. In these studies experts are typically advanced gradate students or instructors and novices are typically students with recent instruction in the domain. The findings show that experts attend to deep features while problem solving, categorize problems based on core principles, use domain knowledge in the form of principle-based schemas to guide problem solving, and plan solution strategies at an appropriate level of detail. Novices, on the other hand, categorize problems based on surface features, use calculation-based schemas to guide problem solving and plan solution strategies in overly vague or specific terms (e.g., Chi, Feltovich & Glaser, 1981; Larkin, 1981; Larkin, 1983; Priest & Lindsay, 1992; for a review see VanLehn & van de Sande in press).

Although expertise is evident in categorization and planning, it may be difficult to examine in problem solving performance. On the surface, the quantitative solutions by experts and novices may appear very similar. However, careful investigations reveal that the thinking behind the expert and novice solutions is quite different. Experts evoke core principles and domain concepts as they manipulate symbols, whereas novices perform mathematical operations and fail to consider the meaning of the quantities they are manipulating. This behavior results in seemingly inconsistent performance on qualitative and quantitative problem solving activities. For instance, research in both physics and chemistry suggest that students that appear similar to experts in quantitative problem solving often perform very poorly on conceptually similar qualitative problems (e.g., Hake, 1998; Halloun & Hestenes, 1985; Nakhleh & Mitchell, 1993). These studies suggest that students fail to coordinate core concepts with problem solving and are not able to transfer solution strategies to novel situations or generalize from specific problems to global principles.

What changes occur as novices become experts? Although most studies have looked at experts and novices as distinct groups, there is general consensus that the development of expertise is gradual and involves not only the accumulation of new knowledge but also structuring of that knowledge (e.g., Chi et al., 1981; Feltovich, Prietula, & Ericsson, 2006). Based on this prior work, we hypothesize that problem solving performance will undergo qualitative shifts as domain knowledge increases and solvers develop deeper conceptual understanding of the quantities involved in calculations. The current study investigates what aspects of problem solving performance change in the development of expertise. Do particular aspects of expertise (e.g., attending to deep rather than shallow features and planning solution strategies) emerge sequentially or simultaneously as demonstrated by performance on a problem solving task? Further, is conceptual understanding of the quantities involved in calculations reflected in the language used to describe steps of problem solving?

In this study, we investigate problem solving in the domain of chemical equilibrium. Equilibrium, which involves reversible chemical reactions, is a difficult topic for students to master, and the complex nature of problem solving allows for the investigation of varying levels of expertise. As an example of an equilibrium system, consider the reversible reaction 3A + 4B ←→ 2C. In this system, three A molecules combine with four B molecules to produce two C molecules. At the same time, two C molecules combine to re-form three A and four B molecules. Although these reactions continuously occur, the system will eventually reach a steady state, equilibrium, in which the rates of the forward and reverse reactions are equal and the concentrations of A, B and C molecules become stable. When the system is at equilibrium the law of mass action determines that the ratio of concentrations (for this reaction: [C]2/[A]3[B]4) will be equal to an equilibrium constant, K.

A typical equilibrium problem statement contains the chemical reaction (e.g., 3A + 4B ←→ 2C), starting concentrations of the molecules in the reaction (e.g.,1.2M A and 1.8M B) and the equilibrium constant (e.g., K = 1.2x106) and asks students to determine concentrations of each type of molecule (e.g., A, B, and C) when the system reaches equilibrium. This particular problem allows us to investigate the development of two aspects of expertise; attention to deep vs. shallow features and planning solution strategies. Successful performance on the above problem requires the solver to consider the deep features of the law of mass action, that the expression (K = [C]2/[A]3[B]4) is only true when the concentrations are at equilibrium. Solvers that attend to surface features of the problem (e.g., that the law of mass action requires "concentrations" rather than "concentrations at equilibrium") will fail to differentiate between the concentrations of A, B, and C in the initial state (in the problem statement) from concentrations at equilibrium, and will put incorrect values into the mass action formula. More experienced solvers that attend to the deep features of the problem will notice that the values in the problem statement only apply to the initial state and will perform additional calculations to determine equilibrium concentrations before applying the law of mass action.

The equilibrium problem also allows us to examine how solvers plan solution strategies. This type of problem can be approached in two different ways; an algebraic strategy and an approximation strategy. Both strategies are taught in introductory chemistry classes. The algebraic strategy involves a series of mathematical calculations to account for the change in concentrations from the initial to equilibrium state. While this approach is technically correct, it is inefficient for this particular problem and requires difficult mathematical calculations. The approximation strategy requires greater planning and a deeper conceptual understanding of the information in the problem statement. To use this strategy, the solver must approximate equilibrium concentrations using information about the magnitude of K and the chemical reaction and subsequently carry out calculations based on the approximation.

In the current study, we investigated participants' problem solving steps, strategies, and verbal protocols to resolve two questions. First, do two aspects of expertise (attention to deep features and planning solution strategies) emerge simultaneously or sequentially? Our hypothesis was that the application of correct values in the mass action formula would reveal attention to deep features, and the use of the more appropriate approximation strategy would reveal expert-like planning. If these expert behaviors emerge simultaneously, we would expect experts to exhibit both expert behaviors and novices not to exhibit either behavior. However, if expert behaviors emerge sequentially we would expect some solvers to exhibit neither of the expert behaviors, some to exhibit one of the expert behaviors, and some to exhibit both of the expert behaviors. Second, do statements made in the think aloud protocols reveal a developing conceptual understanding of concentration quantities that increases with problem solving expertise? We predict that as conceptual understanding develops, solvers will make more statements that refer to the underlying chemical principles (as revealed by the verbal protocols analysis. In this particular type of problem, we expect experts to refer to two key attributes of the chemical system: 1) that the chemical reaction describes a range of possible states of a system (from all reactants to all products) and that only one state is at equilibrium and 2) that the chemical reaction determines the rules by which molecules break apart and combine and that overall the reaction will progress towards the equilibrium state. Thus, as expertise develops, we expect solvers to make more state-based and reaction-based remarks in the course of problem solving.

Method

Participants

Five experts and 10 novices participated in this study. Experts were 3 chemistry faculty members from Carnegie Mellon University who had recently taught basic chemistry and 2 chemistry graduate students that served as teaching assistants for this course. Ten novices were undergraduate students from Carnegie Mellon University that had completed two semesters of basic chemistry within the past year. Experts were paid for their participation, and novices chose payment or course credit for participation.

Materials

The problem investigated in the current study was the second question in a packet of 5 questions related to chemical equilibrium. The problem was: Consider the following reaction: $3A + 4B \leftrightarrow 2C$, $K = 1.2\times10^6$. 100 ml of 1.2M A is mixed with 50 ml of 1.8M B. What are the concentrations of A, B and C when the system reaches equilibrium?

Design and Procedure

Participants were given instructions on verbal protocols using the script in Ericsson and Simon (1993) and were asked to think aloud as they worked through the problems. Participants were videotaped as they solved problems. They received one problem at a time and worked at their own pace.

Analyses

Analyses of Problems. Both written problem solutions and verbal protocols were coded for analysis. As the problem requires a series of calculations, each problem step was coded for accuracy and for error type. For the current analysis, solutions were coded for 1) problem step – whether solvers used deep features, e.g., equilibrium concentrations (rather than initial concentrations) in the mass action formula and 2) strategy – whether solvers used the algebraic strategy to determining equilibrium concentrations or the more appropriate approximation strategy that requires greater planning.

Analyses of Protocols. Videotapes were transcribed and coded blind to condition by a research assistant (JO) who was unaware of the participants' levels of expertise. Utterances were coded for state-based or reaction-based language that revealed that solvers considered the representation behind the quantities being manipulated. Utterances were coded as state-based if they contained reference to possible state differences in concentration values. Words referring to state changes included "starting concentrations, initial concentrations, initial concentrations, etc." For example, "Initial concentrations are going to be reduced. So, your initial concentration is going to be 100mls times 1.2 for A divided by total volume 150."

Utterances were coded as reaction-based if they used words such as "reacts" or "progresses." A richer representation of the quantities of concentration is the additional constraint that the possible states of concentrations exist along a continuum that is limited by the coefficients of the given chemical reaction. For example, "A, B, and C react in a 3 4 2 ratio" or "Equilibrium constant is very large, so what I'll do when I set this up is have the thing go completely in the forward direction and then algebraically work backwards and see what changes there are."

Most statements in the verbal protocols were related to mathematical problem solving and did not refer to the representation of the quantities being discussed. For example, "1.2 to the third times 1.8 to the 4th. C squared solving by multiplying 1.2 times 1.2 times 10 to the 6th" or "Okay, moles of A divided by 3, 0.12 divided by 3, 0.04. Moles of B is 0.09 over 4."

Results

An analysis of problem solutions revealed that experts were more likely than novices to attend to deep features as demonstrated by the correct application of equilibrium values in the problem step using the mass action formula. An independent samples t-test revealed that this difference was significant, $t(13) = 2.55$, $p < .05$. Further, significantly more experts than novices demonstrated planning as demonstrated by their use of the approximation strategy during problem solving, $t(13) = 3.61$, $p < .01$. See Table 1.

Overall, experts were more successful problem solvers than novices, however the difference between the two groups was not categorical, suggesting that attention to deep features of problem steps and planning strategies do not necessarily emerge together. An inspection of the pattern of these data reveals three categories of problem solvers with overlapping performance for some experts and novices. While no novices demonstrated planning through use of the approximation strategy, 4 of the 10 attended to deep features of the problem step and correctly applied equilibrium values when using the mass action formula. Further, while no experts attended to shallow features and mistakenly applied initial values to the mass action formula, only 3 of the 5 experts demonstrated planning and used the approximation strategy. The results suggest that attention to deep features may develop before effective planning of problem solving, at least in this particular task. The gradual emergence of expert behaviors is supported by the fact that the 2 experts who failed to plan and use the approximation strategy were the chemistry graduate students whereas the 3 experts who successfully planned and used the more appropriate approximation strategy were chemistry faculty.

Table 1. Number of Experts and Novices that used equilibrium values in the mass action (K) formula and used the Approximation strategy.

Equilibrium values in K	Approximation strategy: No	Approximation strategy: Yes
Novice		
No	5	0
Yes	4	0
Expert		
No	0	0
Yes	2	3

In order to determine whether deeper conceptual understanding was reflected in the language used by experts during problem solving, we coded protocols for state-based

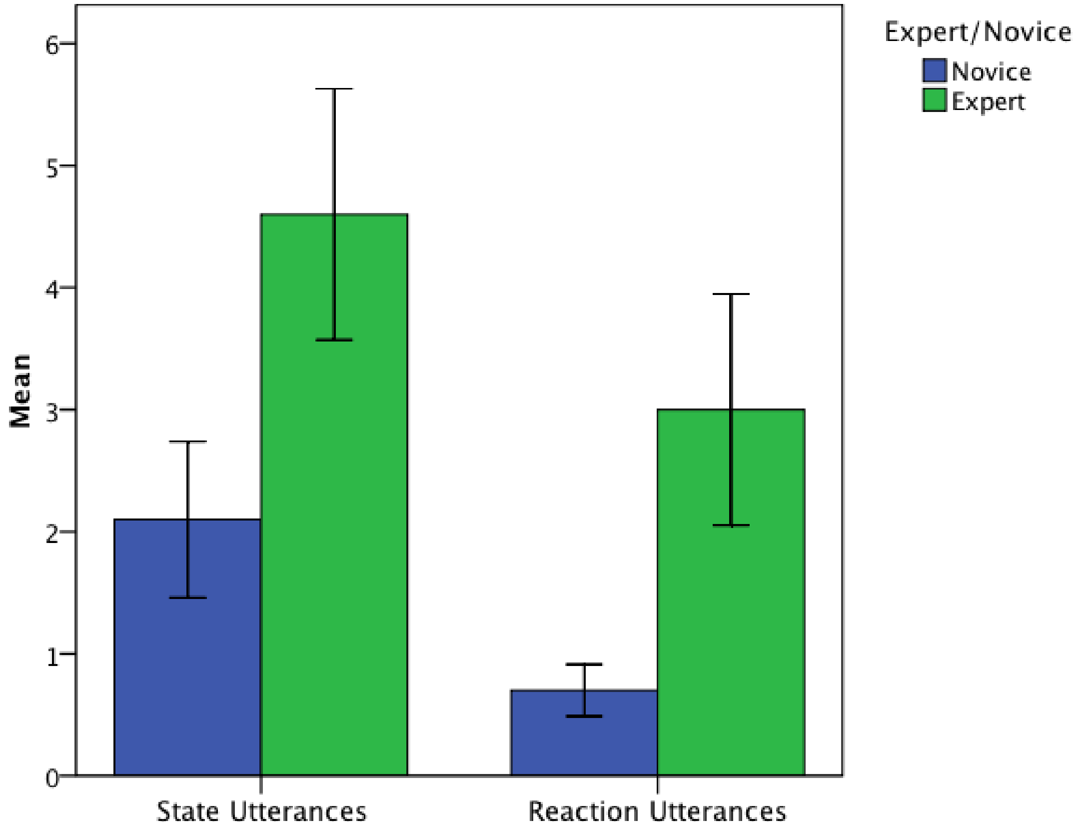

Figure 1: Mean state and reaction-based utterances by expertise as recruited (Novice vs. Expert).

and reaction-based comments. Our hypothesis was that deeper conceptual understanding would be reflected in the words that participants used to refer to the quantities while problem solving. We expected that experts would make a greater number of comments relating to the key features of equilibrium systems than novices. ANOVAs carried out with level of expertise (Novice vs. Expert) as a between-subjects variable revealed that experts made more state-based comments ($M = 4.6$) than novices ($M = 2.1$), $F(1,13) = 4.7$, $p < .05$, and experts made more reaction-based comments ($M = 3.0$) than novices ($M = .7$), $F(1,13) = 10.4$, $p < .01$. See Figure 1.

In a secondary analysis, we investigated whether problem solving performance was related to conceptual understanding as reflected by the number of state and reaction based comments. In order to determine whether increases in problem solving performance co-occurred with increases in the use of relevant chemistry terminology, we grouped participants based on their use of deep features in applying problem steps and planning. Five participants that failed to use deep features and applied incorrect values in the mass action formula and one participant that did not invoke the mass action formula were placed in the Novice category. Six participants that used deep features and applied correct values in the mass action formula but failed to plan and use the approximation strategy were placed in the Novice+ category. The final 3 participants that demonstrated both the use of deep features and planning were placed in the Expert category. An ANOVA was carried out with level of expertise (Novice, Novice+, Expert) as a between-subjects variable and the total number of conceptual utterances (State and Reaction combined) as the dependent variable. See Figure 2. A significant main effect of expertise was found, $F(2, 12) = 6.32$, $p < .05$. A Tukey HSD post-hoc analysis revealed that Experts made significantly more conceptual utterances ($M = 8.33$) than Novices ($M = 2.17$), $p < .05$, but that the difference between Novice+ participants ($M = 4.67$) and Experts and Novices did not reach significance, $p = .13$ and $p = .23$ respectively.

Discussion

The current study investigates what aspects of problem solving performance change in the development of expertise. The data provide evidence for a gradual development of expertise that is related to increasing conceptual understanding of the quantities involved in problem solving. Our study revealed three levels of developing expertise that we dubbed Novice, Novice+, and Expert. Novice participants failed to use deep features when using the mass action formula and did not demonstrate planning when selecting a problem solving approach. Novice+ participants demonstrated attention to deep features as they chose appropriate (e.g., equilibrium)

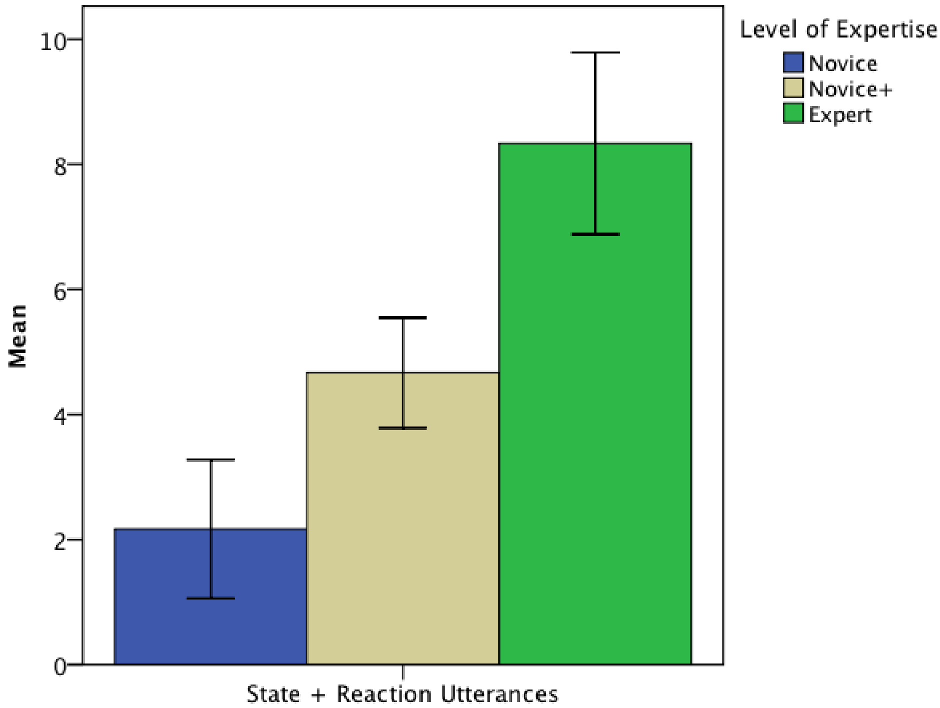

Figure 2: Mean conceptual utterances by expertise as demonstrated by problem solving performance (Novice, Novice+, Expert).

concentrations when applying the mass action formula, but did not demonstrate planning when choosing a solution strategy. Finally, Experts demonstrated both attention to deep features and planning as they selected the more appropriate approximation strategy.

An analysis of the verbal protocols suggests that the development of problem solving expertise is related to conceptual understanding of the quantities involved in the calculations. Novices made very few statements that revealed any conceptual understanding of the concentration quantities and instead referred nearly exclusively to mathematical calculations. Novice+ participants were increasingly likely to demonstrate conceptual understanding by referring to the possible states and chemical reactions behind the calculations. Finally, Experts made the greatest number of utterances related to reactions (suggesting that concentrations change along a continuum) and were most likely to use an approximation strategy that reflected this type of thinking.

While prior work proposed that expertise develops along a continuum, most studies focus on experts and novices as distinct groups. These studies revealed a variety of features of expert problem solving (e.g., planning, attention to deep features, application of problem schemas), but have not specifically looked at the developmental trajectory of these features as they relate to problem solving performance (e.g. Chi et al., 1981; Larkin et al, 1980). The domain of chemical equilibrium enables us to differentiate between solvers that use shallow versus deep features while problem solving as well as solvers that use simple versus sophisticated planning in their choice of a problem solving approach. This allows us to reconcile the seeming paradox of students that perform as well as experts on quantitative but not qualitative problems (e.g., Hake, 1998; Halloun & Hestenes, 1985). Many quantitative problems can be solved without a conceptual understanding of the quantities involved in the calculations. For instance, given the problem "a car has a mass of 1000 Kg and is accelerating at a rate of 1m/s2, what is the net force accelerating the car?" a student that knows F=ma, can "plug in" 1000 times 1, and get the answer 1000. Because the formula applies directly to the given values, students can successfully solve the problem without having a conceptual understanding of forces, mass or acceleration. For the equilibrium problem, the mass action formula only applies to concentrations in the equilibrium state, thus students must have a deeper conceptual understanding of the quantities of concentrations in order to successfully solve the problem.

How do conceptual understanding and problem solving expertise develop? The current study suggests that different features of expertise may develop sequentially. In particular, solvers demonstrated the ability to attend to deep features before demonstrating the use of sophisticated planning of problem solving strategies. Must students first learn to apply deep features before learning to plan effective problem solving strategies? Or would explicit instruction that coordinates conceptual and procedural information and ties together planning strategies with attention to deep features allow students to skip the intermediate, Novice+, stage of problem solving? Little research has investigated the on-line development of conceptual expertise and problem solving ability. VanLehn & van de Sande (in press), propose that conceptual expertise develops only after students develop quantitative problem solving skills. In this account, students must first master the mathematical relationships of formulas and principles and then gradually develop richer representations of the symbols and numbers used in calculations.

An alternative possibility is that the current stages of problem solving ability are the outcome of instruction that emphasizes quantitative problem solving, and that more conceptual instruction may allow students to bypass the intermediate, Novice+, stage of problem solving. Preliminary results from a classroom study conducted by Davenport, Yaron, Klahr and Koedinger suggest that conceptual instruction may greatly increase problem solving ability. New instruction was created that taught equilibrium problem solving using a conceptual framework of the progression of a chemical reaction. This framework made explicit that concentrations can exist on a continuum of possible states and the states are constrained by the coefficients specified in the chemical reaction. Although the new instruction taught identical problem solving steps as instruction in prior years, 50% of the students given the new instruction were successful in problem solving compared with only 17% of the students given the traditional instruction, more than a 2.5 times increase in performance.

The current study provides evidence for the linkage of conceptual understanding and problem solving expertise in the domain of chemistry. As much is known about differences between experts and novices, the larger challenge for future work is to identify how novices transition to experts and to determine what types of practice and instruction are most effective for developing conceptual and procedural expertise.

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