ITS support for conceptual and perceptual connection making between multiple graphical representations

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Abstract. Connection making between representations is crucial to learning in STEM domains, but it is a difficult task for students. Prior research shows that supporting connection making enhances students' learning of domain knowledge. Most prior research has focused on supporting one type of connection-making process: *conceptual* reasoning about connections between representations. Yet, recent research suggests that a second type of connection-making process plays a role in students' learning: *perceptual* translation between representations. We hypothesized that combining support for both conceptual and perceptual connection-making processes leads to higher learning gains on a domain-knowledge test. We tested this hypothesis in a lab experiment with 117 undergraduate students using an intelligent tutoring system for chemistry. Results show that the combination of conceptual and perceptual connection-making supports leads to higher learning outcomes. This finding suggests that the effectiveness of educational technologies can be enhanced if they combine support for conceptual and perceptual connection-making processes.

Keywords: Multiple representations, connection making, conceptual and perceptual processes, intelligent tutoring systems, chemistry.

1 Introduction

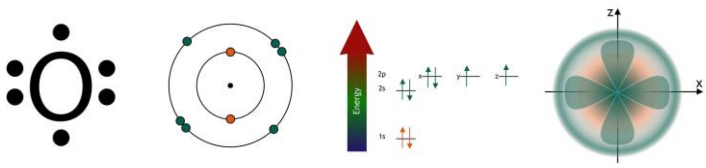

Fig. 1**.** Graphical representations of oxygen: Lewis, Bohr, energy diagram, orbital diagram.

Instructional materials in STEM domains typically use multiple graphical representations to make abstract concepts accessible to students [1, 2]. For example, when learning about atomic structure, students typically encounter the representations shown in Fig. 1: Lewis structures show only valence electrons, Bohr models show all electrons in atomic shells, energy diagrams depict electrons in orbitals by energy level, and orbital diagrams show the spatial arrangement of non-empty orbitals. Each of these representations emphasizes different aspects of domain-relevant concepts. Through connection making, students integrate the information each representation depicts about domain-relevant concepts into a coherent mental model [3]. However, making connections between representations is difficult. Students often do not make connections spontaneously [3], including chemistry students at the graduate level [4]. Difficulties in making connections are a major obstacle to students' success in STEM [5].

Prior research shows that educational technologies can considerably enhance students' learning of domain knowledge if they support students in making connections between representations [6-8]. Most prior research on connection making has focused on supporting only one type of connection-making learning process; namely, *conceptual connection-making processes* [6, 7]. Conceptual support targets explicit connection-making processes by helping students reason about how different representations show the same concepts and how the information shown about the given concept differs between representations [3]. Recent research draws attention to a second type of connection-making process; namely, *perceptual connection-making processes* [8]. Research on perceptual connection-making support builds on research on expertise, which shows that experts can quickly and effortlessly make connections by "just seeing" connections between representations, without cognitive effort [8]. This highly practiced fluency in connection making comes from exposure to large numbers of examples and does not require explicit instruction. Such perceptual fluency frees cognitive headroom that experts can invest in higher-order thinking. Building on this research on expertise, research on perceptual connection-making support proposes that training students to numerous translation tasks while providing feedback on their performance might enhance their learning of domain knowledge. Thus, perceptual support targets implicit connection-making processes. It helps students become acute in paying attention to relevant perceptual features and use them to efficiently translate between representations. Perceptual support has been shown to enhance students' learning of domain knowledge [8]. Cognitive theories of learning propose that both conceptual and perceptual connection making plays a role in robust learning [9].

However, little research has investigated whether instruction is most effective if it provides support for both conceptual connection-making processes and perceptual connection-making processes, or whether support for only one type of connection-making processes is sufficient. To the best of our knowledge, an experiment on elementary-school fractions learning was the first to show that both conceptual and perceptual processes play a role in connection making [10]: An intelligent tutoring system (ITS) that combined conceptual and perceptual support led to higher learning gains than versions of the ITS with either type of connection-making support alone. Yet, it remains an open question whether this finding holds as a general principle. Do conceptual and perceptual connection-making processes play a role in other domains, student populations, and educational settings other than elementary-school fractions?

This question is of particular relevance to ITSs. If both conceptual and perceptual processes play a role in student learning, ITSs that combine both types of support will be most effective. Moreover, knowing which connection-making processes we need to support is a prerequisite to developing adaptive connection-making support. Case studies show that adapting instruction to students' skills in using representations enhances their learning outcomes [11]. Thus, ITSs may be most effective if they adapt connection-making support to a student's ongoing acquisition of conceptual and perceptual connection-making skills. Since connection making is key to success in many STEM domains, this research may yield more effective ITSs at a broad scale.

We conducted a lab experiment to investigate the effects of conceptual and perceptual connection-making support on undergraduate chemistry learning. We hypothesized that combining conceptual and perceptual support is most effective. Further, we explored whether the effectiveness of conceptual and perceptual support interacts with mental rotation ability, because spatial skills are a significant predictor of learning outcomes in STEM fields that rely on the use of graphical representations [12].

2 Methods

2.1 Chem Tutor: An ITS for Undergraduate Chemistry

We conducted the experiment in the context of an ITS for undergraduate chemistry: Chem Tutor [13]. Chem Tutor is a type of ITS called example-tracing tutors [14]. Example-tracing tutors do not use a cognitive model that is based on production rules but rely on generalized examples of correct and incorrect solutions. The design of Chem Tutor is based on user-centered studies [13]. Chem Tutor supports chemistry learning by helping students make connections between graphical representations.

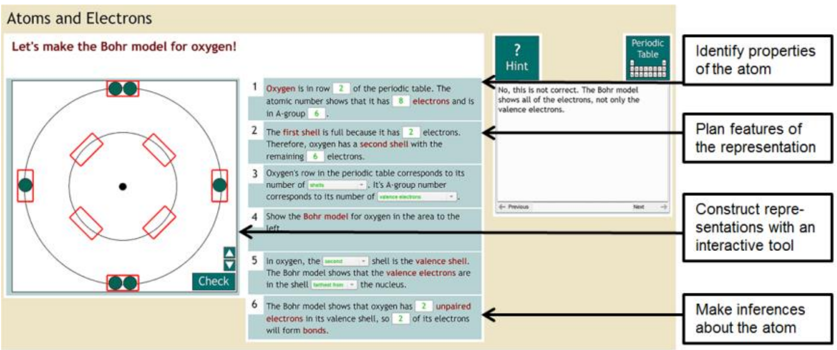

Fig. 2. Example of an individual-representation problem.

Individual-representation problems. Before students can make connections between representations, they have to understand each individual representation [3]. To this end, Chem Tutor provides problems in which students reason about one representation at a time (Fig. 2). First, they reflect on properties of the atom. Second, they plan how to construct the given representation. Third, they use an interactive tool to construct the representation. They receive error-specific feedback on their interactions, and they have to construct a correct representation before they can continue. Fourth, students are prompted to use the representation to make inferences about the atom.

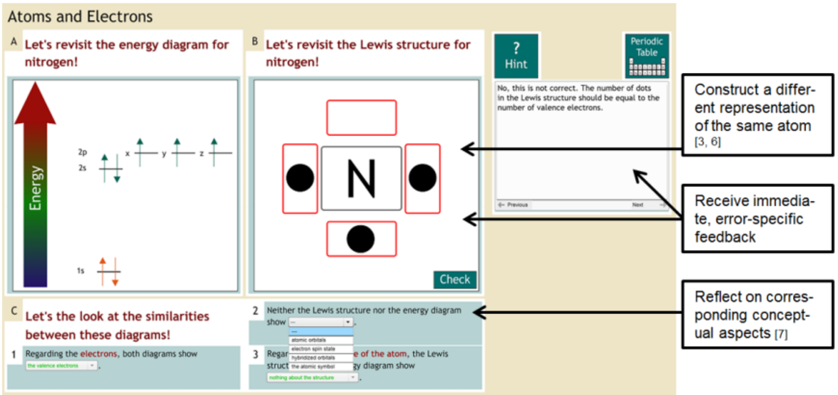

Fig. 3. Example of a conceptual connection-making problem.

Conceptual connection-making problems. In addition, Chem Tutor provides problems designed to help students conceptually make sense of how different representations provide corresponding and complementary information about chemistry concepts (see Fig. 3). First, students receive a representation of an atom and are asked to use an interactive tool to construct a different representation of the same atom. Second, students are prompted to reflect on which concepts are depicted in both representations (e.g., both show the valence electrons) or on what information is shown in one representation but not in the other (e.g., the energy diagram shows orbitals, but the Lewis structure does not). The design of the conceptual problems is based on prior research on conceptual connection-making support [6, 7].

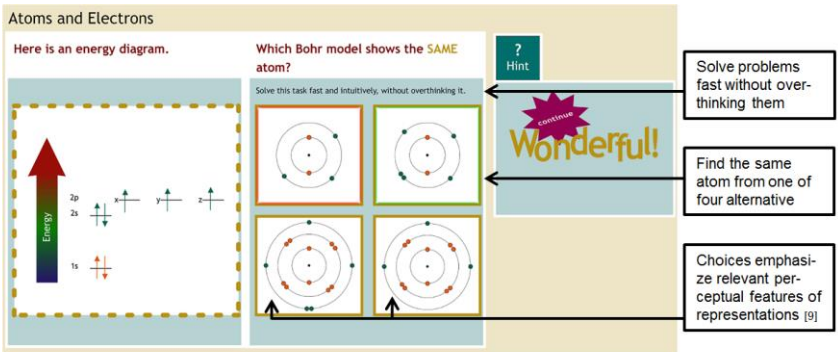

Fig. 4. Example of a perceptual connection-making problem.

Perceptual connection-making problems. Finally, Chem Tutor provides problems designed to help students become perceptually fluent in translating between representations (see Fig. 4). In these problems, students are presented with one representation and have to select one out of four representations that shows the same atom. The four alternative representations are chosen so that they emphasize features that students should learn to pay attention to (e.g., an incorrect representation might show the same number of shells as the correct representation but a different number of valence electrons). The different choice options provide variations of irrelevant features of the representations and contrast perceptual features that provide relevant information (e.g., geometry, location of the local charges). Chem Tutor prompts students to solve these problems fast, without overthinking them, in order to encourage perceptual rather than conceptual strategies. Each problem is short (i.e., it involves only one step). Students receive a dozen of these problems in a row, and they receive only correctness feedback. Thus, the perceptual problems are designed to help students become faster and more efficient at extracting relevant information from graphical representations based on repeated experience with a large variety of problems. The design of the perceptual problems is based on prior research on perceptual connection making [8].

2.2 Test Instruments

We assessed students' chemistry knowledge three times: before they started working with Chem Tutor, after they completed half of the tutor problems, and after they completed all tutor problems. We used three isomorphic test forms that asked structurally identical questions but used different problems (e.g., with different atoms). The order in which students received the test forms was counterbalanced. The tests assessed reproduction and transfer of the chemistry content covered in Chem Tutor. Reproduction items used a format similar to the Chem Tutor problems. Transfer items asked students to apply the knowledge Chem Tutor covered in ways they had not been asked to do in the Chem Tutor problems. The tests included items with and without representations. Further, we used the Vandenberg & Kuse test to assess mental rotation ability [15]. Students completed this test prior to the chemistry pretest.

2.3 Participants

117 undergraduate students participated in the experiment. Students were recruited with posters and by advertising in introductory chemistry courses. 79% of the students were currently enrolled in general chemistry for non-science majors, 13.4% were enrolled in general chemistry for science majors, 2.5% were enrolled in advanced general chemistry, and 5% were not currently enrolled in a chemistry course.

2.4 Experimental Design

Students worked with versions of Chem Tutor designed specifically for this experiment. We used a 2 (conceptual support) x 2 (perceptual support) design to investigate the effects of connection-making support on students' learning of chemistry. The conceptual-support factor had two levels: students either received conceptual connection-making problems or not. The perceptual-support factor also had two levels: students received perceptual connection-making problems or not. Thus, students were randomly assigned to one of four conditions: Students in the no-conceptual / no-perceptual condition worked only on individual-representation problems. Students in the conceptual / no-perceptual condition worked on individual-representation problems and on conceptual connection-making problems. Students in the no-conceptual / perceptual condition worked on individual-representation problems and on perceptual connection-making problems. Students in the conceptual / perceptual condition worked on individual-representation problems, conceptual connection-making problems, and perceptual connection-making problems.

We adjusted the number of problems in each condition so that the number of steps was equal across conditions. For example, students in the control condition worked on more individual-representation problems than students in the other conditions, and students in the conceptual / no-perceptual condition worked on more conceptual problems than students in the conceptual / perceptual condition. Equating the number of steps (rather than the number of problems) was necessary because the problems had different number of steps (e.g., each perceptual problem has only one step). This adjustment yielded interventions that took about the same time for all conditions.

The sequence of individual-representation problems, conceptual and perceptual connection-making problems was organized as follows. For each pair of representations, students first received individual-representation problems (e.g., one Lewis structure problem, and one Bohr model problem). Next, if they were in one of the conceptual conditions, they received conceptual connection-making problems for this pair of representations. Then, if they were in one of the perceptual conditions, they received perceptual connection-making problems for this pair of representations. This sequence proved to be more effective than other sequences in prior research [16].

2.5 Procedure

The experiment took place in the laboratory and involved two sessions of 90 minutes each, no more than three days apart. In session 1, students completed the mental rotation test and the chemistry pretest. They then received an introduction into using Chem Tutor. Next, they worked on half of the tutor problems, using the version of Chem Tutor that corresponded to their condition. At the end of session 1, students took the intermediate chemistry posttest. In session 2, students worked through the remainder of the tutor problems and then took the final chemistry posttest.

3 Results

Table 1 shows means and standard deviations of students' performance on the tests. To report effect sizes, we use p. η^2. An effect size p. η^2 of .01 corresponds to a small, .06 to a medium, and .14 to a large effect. Differences between conditions at pretest were not significant ($F = 1.01$; $p = .39$).

3.1 Learning Gains

First, we investigated whether working with Chem Tutor led to learning gains. We used a repeated measures ANOVA with test-time (pretest, intermediate test, final posttest) as the repeated, within-subjects factor and scores on the chemistry tests as the dependent measure. The main effect of test-time was significant, $F(2,232) = 37.31$, $p < .01$, p. $\eta^2 = .24$. The interaction of test-time with mental rotation ability was not significant; thus students improved regardless of their mental rotation ability.

Table 1. Means and standard deviations (in parentheses) for tests by condition and test time.

	Mental rotation ability	**Chemistry knowledge**		
Condition		***Pretest***	***Intermediate test***	***Final posttest***
No-conceptual / no-perceptual	.58 (.24)	.49 (.20)	.60 (.23)	.62 (.19)
Conceptual / no-perceptual	.63 (.18)	.47 (.21)	.55 (.23)	.6 (.18)
No-conceptual / perceptual	.53 (.23)	.38 (.22)	.52 (.19)	.55 (.17)
Conceptual / perceptual	.55 (.20)	.42 (.20)	.58 (.19)	.61 (.20)

3.2 Effects of Conceptual and Perceptual Connection-Making Support

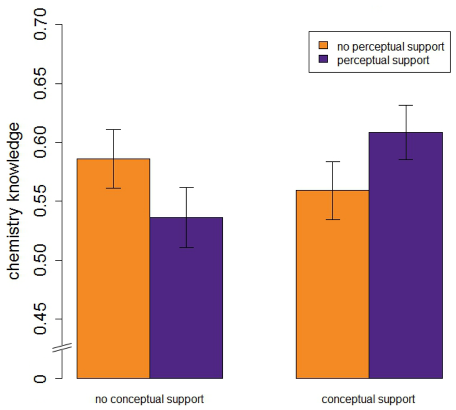

Fig. 5. Effects of conceptual and perceptual support on the chemistry knowledge posttest.

Next, we investigated the hypothesis that conceptual and perceptual connection-making support leads to better learning of chemistry knowledge. We used a repeated measures ANCOVA with test-time (intermediate test, final posttest) as the repeated, within-subjects factor, conceptual support and perceptual support as between-subjects factors, mental rotation ability and scores on the chemistry knowledge pretest as co-variates, and scores on the chemistry test as the dependent measure.

The main effect of conceptual support was not significant, $F(1,109) = 1.39$, $p > .10$. There was a positive main effect of perceptual support, $F(1,109) = 6.28$, $p < .05$, p. $\eta^2 = .06$. The interaction of conceptual and perceptual support was significant, $F(1,109) = 4.05$, $p < .05$, p. $\eta^2 = .04$, such that perceptual support was effective only if provided in combination with conceptual support (see Fig. 5). To verify the accuracy of this interpretation, we used post-hoc comparisons. Students who did not receive conceptual support had significantly lower learning outcomes if they received perceptual support than without perceptual support, $F(1,110) = 9.34$, $p < .01$, p. $\eta^2 = .08$. Students who received conceptual support had significantly higher learning outcomes if they received perceptual support than without perceptual support, $F(1,110) = 9.34$, $p < .01$, p. $\eta^2 = .08$. Finally, there was a marginally significant advantage of the conceptual / perceptual condition over the no-conceptual / no-perceptual condition, $F(1,110) = 2.69$, $p = .10$, p. $\eta^2 = .05$. In sum, the results indicate that the combination of conceptual and perceptual connection-making support is most effective.

Finally, to investigate whether the effectiveness of conceptual and perceptual support depends on students' mental rotation ability, we used the same ANCOVA model to examine interactions of mental rotation ability with conceptual support and with perceptual support. The interaction was not significant for conceptual support ($F < 1$), but it was significant for perceptual support, $F(1,109) = 7.15$, $p < .01$, p. $\eta^2 = .06$, such that perceptual support was more effective for students with high mental rotation ability than for students with low mental rotation ability.

4 Discussion

We had hypothesized that combining conceptual and perceptual support for connection making would enhance students' learning gains in chemistry. Our results support this hypothesis: we found that combining conceptual and perceptual support leads to the highest learning gains on a domain-knowledge test. This finding is in line with cognitive theories that suggest that both processes play a role in robust learning [9]. Our finding extends prior research on connection-making that has focused only on conceptual support [6, 7] or only on perceptual support [8]. Finally, it extends prior research that found an advantage of combining conceptual and perceptual support in an ITS for fractions learning [10]. We show that this effect generalizes to a different domain, student population, and setting, suggesting that it is indeed a robust effect.

To our surprise, we found that perceptual support was only effective in combination with conceptual support: providing only perceptual support resulted in lower learning gains than providing no connection-making support at all. This finding extends previous research on perceptual support for connection making by showing that the effectiveness of perceptual support depends on whether students also receive conceptual support. To the best of our knowledge, participants in prior research on perceptual support were typically not novices [8]. As part of prior instruction, they may have acquired conceptual understanding of connections. Thus, it is possible that the effectiveness of perceptual support in these studies depended on students' prior conceptual learning. Also to our surprise, the advantage of the conceptual / perceptual condition over the control condition was only marginally significant. It is possible that a longer intervention might have yielded stronger effects. In particular, the amount of practice students need to become perceptually fluent has been found to vary across individuals [3]. Thus, adaptive perceptual support might yield stronger effects.

Furthermore, we found that the effectiveness of perceptual support depends on students' mental rotation ability. Students with high mental rotation ability benefited more from perceptual connection-making support than students with low mental rotation ability. Since perceptual problems ask students to map perceptual features that are not always spatially aligned across representations, students might have to mentally rotate representations when solving perceptual problems. Therefore, students with low mental rotation abilities may particularly struggle with perceptual connection-making problems. Future research should investigate how to tailor perceptual support to the needs of students with low mental rotation ability. Our findings suggest that students with low mental rotation ability might benefit more from perceptual support that provides assistance in mentally rotating representations or that uses examples in which perceptual features are spatially aligned.

One limitation of the experiment is that it was conducted in a lab setting. Chem Tutor is designed to be used as a homework system within undergraduate chemistry courses. In future research, we will investigate whether we find the same effects when students use Chem Tutor in a homework setting. A further limitation is that the majority of participants were non-science majors. These students are likely to have a lower interest in learning chemistry and lower prior knowledge about the domain than science majors. In future research, we will investigate whether our findings generalize to a broader population of undergraduate students.

To conclude, our findings suggest that ITSs should incorporate instructional support for both conceptual and perceptual processes involved in connection making. The fact that a study on undergraduate chemistry learning found the same effect as prior research on elementary-school fractions learning suggests that this effect is robust across domains, student populations, and educational settings. Our findings also have implications for the design of adaptive connection-making support. Case studies suggest that such support can significantly enhance students' learning in STEM [11]. Our findings suggest that a cognitive model that selects appropriate connection-making problems for an individual student at any time during the intervention should reflect conceptual and perceptual skills in making connections. Thus, connection-making support might be most effective if it adapts in real time to students' acquisition of conceptual and perceptual skills. Given that the ability to make connections between representations is critical to students' learning success in many STEM domains, this research has the potential to impact a broad range of educational technologies.

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