Sequencing Support for Sense Making and Perceptual Fluency with Visual Representations: Is There a Learning Progression?

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Abstract: We tend to assume that visuals help students learn. But visuals can impede learning if students lack representational competencies that enable them to understand what the visuals show. We consider two instructional activities that target two qualitatively different representational competencies: explicit sense-making competencies and implicit perceptual fluency. Prior cross-sectional studies showed that students' prior knowledge determines in which sequence they should receive sense-activities and perceptual-activities. This raises the question: is there a learning progression for sense-making competencies and perceptual fluency? In this paper, we address this question with a longitudinal experiment in which 71 students worked with sense-activities and perceptual-activities integrated in six instructional units of a chemistry undergraduate course. For each unit, students either received sense-activities or perceptual-activities first. We assessed learning gains of chemistry knowledge after each unit. Results suggest a learning progression that aligns with results of prior cross-sectional studies.

Keywords: Multiple visual representations, representational competencies, explicit and implicit learning processes, sense making, perceptual fluency

Introduction

Instructors often use multiple visual representations to make content knowledge accessible to students (NRC, 2006). For example, chemistry instruction typically includes the visuals in Figure 1, which emphasize complementary concepts that students need to integrate when learning about atomic structure. Indeed, there is abundant evidence that, compared to learning with a single visual, multiple visuals can help students learn content knowledge because they allow students to form more accurate mental models (Ainsworth, 2006).

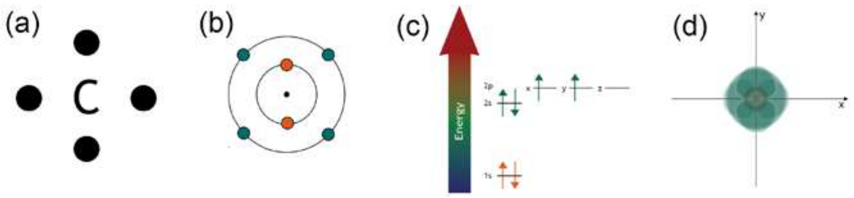

Figure 1. Visuals of atoms: (a) Lewis structure, (b) shell model, (c) energy diagram, (d) orbital diagram.

Yet, visuals can impede learning if students lack *representational competencies:* knowledge about how visuals show information relevant to scientific and professional practices (NRC, 2006). Students need two types of representational competencies (Rau, 2017a). *Sense-making competencies* allow students to explain how visuals show concepts. For example, chemistry students need to explain how the valence electrons shown in Lewis structures (Figure 1a) and inner-shell electrons (Figure 1b) have different energy levels (Figure 1c) because they reside in orbitals (Figure 1d). Students acquire these competencies via *explicit processes* involved in verbal explanation. *Perceptual fluency* allows students to quickly and effortlessly infer more than is shown in a visual. For example, chemistry students need to "mentally see" inner-shell electrons, energy levels, and orbitals based on Lewis structures. Students acquire perceptual fluency via *implicit processes* that are inductive and nonverbal. Analogous to Kahneman's (2003) research on decision making, sense-making competencies correspond to deliberate System 2 thinking, whereas perceptual fluency is similar to intuitive System 1 thinking (Rau, 2017a).

Prior research showed that providing students with activities that support sense-making competencies and activities that support perceptual fluency enhances their learning of content knowledge (e.g., Rau & Wu, 2015). Further, prior cross-sectional studies showed that students' prior content knowledge level determines which sequence of sense-making and perceptual-activities they most benefit from (Rau, 2017b). Students who had low or high prior knowledge benefited most from receiving perceptual-activities first. Students with intermediate prior knowledge benefited most from receiving sense-activities first. These findings evoke a learning progression of sense-making competencies and perceptual fluency for students at various stages of learning.

However, one cannot infer longitudinal effects from cross-sectional studies. Thus, we currently do not know how students' benefit from sense-activities and perceptual-activities changes over the course of longer learning interventions that typically occur in courses in which instruction on a sequence of topics spans multiple weeks.

To address this question, we present a longitudinal experiment that compared sequences of sense-activities and perceptual-activities over the course of a multi-week learning intervention. We chose chemistry as a domain for this research because chemistry instruction heavily relies on multiple visuals, which poses an obstacle to students who fail to acquire key representational competencies (NRC, 2006). At a theoretical level, this experiment provides new insights into how representational competencies develop along with student's learning of content knowledge. At a practical level, the experiment provides recommendations on how to sequence instructional activities that help students learn new content knowledge with visual representations.

Prior research

Research suggests that students need two different types of representational competencies to learn with visual representations. These competencies are acquired via qualitatively different types of learning processes. Hence, they are most effectively supported by different types of instructional activities. While we focus on cognitive learning theories, the following review illustrates the relevance of this research to sociocultural theories.

Instructional activities that support sense making with visual representations

In order to use visuals to learn new content knowledge, students need sense-making competencies: the ability to understand how different visuals show complementary information about a concept (Ainsworth, 2006; Rau, 2017a). For example, when making sense of the visuals in Figure 1, students have to explain that the Lewis structure shows valence electrons (black dots in Figure 1a), which correspond to the four electrons on the outer shell (green dots in Figure 1b), which have higher energy levels than the inner-shell electrons (green arrows in Figure 1c), and which reside in electron clouds that are larger than those of the inner-shell electrons (green shapes in Figure 1d). By making sense of such connections, students learn about domain-relevant concepts. Indeed, sense making is a key part of discipline discourse in STEM (Wertsch & Kazak, 2011). For example, chemists use visuals to discuss concepts and to solve problems (Kozma, Chin, Russell, & Marx, 2000).

Students acquire sense-making competencies by verbally explaining principles by which the visuals depict relevant information (Koedinger, Corbett, & Perfetti, 2012; Rau, 2017a). This process involves mapping visual features (e.g., dots) to abstract concepts (e.g., electron distributions) (Gentner & Markman, 1997). This allows students to distinguish relevant and irrelevant visual features and to determine which information is (or is not) shown in different visuals (Ainsworth, 2006). These sense-making processes are characterized by explicit explanations that students have to willfully engage in (Chi, Feltovitch, & Glaser, 1981; diSessa & Sherin, 2000).

Prior research yields a number of design principles for activities that enhance sense-making competencies. Such *sense-activities* ask students to verbally explain which visual features of different representations show corresponding or complementary information about concepts (Seufert, 2003). Further, sense-activities are most effective if they ask students to actively construct mappings (Bodemer & Faust, 2006). Finally, they should help students attend to relevant visual features (Bodemer & Faust, 2006; Stern, Aprea, & Ebner, 2003).

Instructional activities that support perceptual fluency with visual representations

Research on expertise suggests that students need a second type of representational competency: perceptual fluency, which allows them to quickly and effortlessly translate across representations (Gibson, 2000). Experts "see at a glance" what a given visual shows without any perceived mental effort (Chi et al., 1981; NRC, 2006). For example, chemists quickly see that the Lewis structure in Figure 1a shows the same atom as the shell model in Figure 1b. Experts are so efficient at extracting information from visuals that it seems intuitive. This enables them to effortlessly combine information from multiple visuals (Kellman & Massey, 2013). Cognitive psychology research attributes this high level of efficiency to perceptual chunking: visual features serve to retrieve a corresponding schema that describes related concepts (Richman, Gobet, Staszewski, & Simon, 1996). The sociocultural literature describes perceptual fluency as an important aspect of disciplinary discourse (Wertsch & Kazak, 2011). Perceptual fluency plays an important role in social interactions that involve translating among visuals. For example, Kozma and colleagues (2000) describe how experts' fluency with visuals enables them to communicate efficiently while collaborating on complex problems. Thus, perceptual fluency allows students to infer community-specific ways of thinking beyond what visuals explicitly show (Airey & Linder, 2009).

Students learn perceptual fluency via perceptual-induction processes: they induce connections among visuals without explicit instruction but through experience with many examples (Gibson, 2000; Goldstone, Schyns, & Medin, 1997). Cognitive theories describe perceptual-induction processes as nonverbal and implicit because verbal reasoning is not necessary (Koedinger et al., 2012; Richman et al., 1996) but can interfere with learning (Schooler, Fiore, & Brandimonte, 1997). According to sociocultural theories, community practices allows students to induce a "visual language": students can become fluent with visuals by imitating how experts use them, without explicitly knowing what they show (Airey & Linder, 2009; Wertsch & Kazak, 2011).

Prior research yields several design principles for activities that enhance perceptual fluency. Such *perceptual-activities* provide many simple tasks that ask students to quickly judge what a visual shows (Kellman & Massey, 2013). Effective perceptual-activities draw attention to relevant visual features by varying irrelevant features and contrasting them to relevant features. They should encourage students to rely on perceptual intuitions about what they see rather than explaining what they see. Students should get immediate feedback only on the accuracy of their response without conceptual explanations, to engage implicit rather than explicit processes.

Combining sense-making and perceptual-induction activities

Prior experiments (e.g., Rau, 2017b) tested effects of sense-activities and perceptual-activities on learning of content knowledge. The experiments compared (1) a condition in which students received only sense-activities, (2) only perceptual-activities, or (3) both sense-activities and perceptual-activities to (4) a control condition that received multiple visuals but no sense-activities or perceptual-activities. Only the condition that combined sense-activities and perceptual-activities had significantly higher learning gains than the control condition.

This finding bears a theoretical question about how sense making and perceptual induction interacts in students' learning of content knowledge. This question has practical implications for how sense-activities and perceptual-activities should be sequenced. On the one hand, explicit sense-making competencies involve knowledge about which visual features show conceptually relevant information. This may help students induce meaning from visuals when they work on perceptual-activities. Therefore, doing sense-activities first may help students learn from perceptual-activities (sense-enhancement hypothesis). On the other hand, perceptual fluency involves intuitive knowledge about how to see meaning in visuals. This may reduce cognitive load when students engage in conceptually demanding sense-activities. Therefore, doing perceptual-activities first may help students learn from sense-activities (perceptual-enhancement hypothesis).

Our prior research tested these hypotheses by comparing sequences of sense-activities and perceptual-activities. Results showed that effects depend on prior knowledge and spatial skills (Rau & Wu, 2015). Students with low prior knowledge benefitted most from receiving perceptual-activities before sense-activities. This effect reversed for students with intermediate prior knowledge, who benefitted most from a sense-perceptual sequence—especially if they had low spatial skills. The effect flipped again for students with high prior knowledge, who benefitted most from a perceptual-sense sequence.

These findings invoke a learning progression. It is possible that early in the learning process, the perceptual-sense sequence is most effective because a preliminary level of perceptual fluency helps students make sense of visuals by freeing cognitive capacity for effortful explanations. Later, the sense-perceptual sequence may be most effective because it allows students to focus on understanding how visuals show, which they can then refine in subsequent perceptual-activities that help them see this meaning automatically. Later yet, the perceptual-sense sequence may be most effective because high levels of perceptual fluency may allow students to put their implicit knowledge of visuals at the service of explicitly making sense of how visuals show concepts.

A critical limitation of our prior research is that it has not tested a learning progression. The prior studies were cross-sectional and involved relatively short interventions. That is, prior knowledge was assessed with a pretest and considered to be static for the short duration of the experiment. Hence, they did not consider how students' knowledge level develops over the course of a longer intervention. We address this limitation with a multi-week experiment in which the same students worked through a cohesive curriculum with multiple units.

Research questions

We investigate which sequence of sense-activities and perceptual-activities most enhances students' learning of chemistry knowledge (research question 1). In light of prior findings, we explore if the effect of sequence interacts with students' prior chemistry knowledge and their spatial skills (research question 2). Further, we investigate how the effect of the sequence changes over the course of the intervention (research question 3). Extrapolating from prior cross-sectional studies, we hypothesize that for early units in the learning intervention, students show higher learning gains if they receive perceptual-activities before sense-activities. For units in the middle of the learning intervention, we hypothesize they show higher gains if they receive sense-activities first. For units at the end of the intervention, we hypothesize they show higher gains if they receive perceptual-activities first.

Method

To address these questions, we conducted an experiment as part of an undergraduate chemistry course.

Participants

Seventy-one undergraduate students were in the course. They were assigned to sense-activities and perceptual-activities as part of weekly homework assignments. They received course credit for completing the assignments. The instructor selected the sequence of activities to align with her course schedule.

Instructional activities

Sense-activities and perceptual-activities were implemented in an educational technology for undergraduate chemistry: Chem Tutor (Rau & Wu, 2015). Students were assigned to work on six units that covered different chemistry topics related to electron configurations and atomic structure using the visual representations in Figure 1. As all units relate to periodic table trends, the units are modular in these sense that they could be sequenced in various ways that align with different instructors' course plans. For each unit, students first received two activities that introduced them to how the visuals show key concepts. Next, students received sense-activities and perceptual-activities, sequenced according to their experimental condition.

Sense-Activities

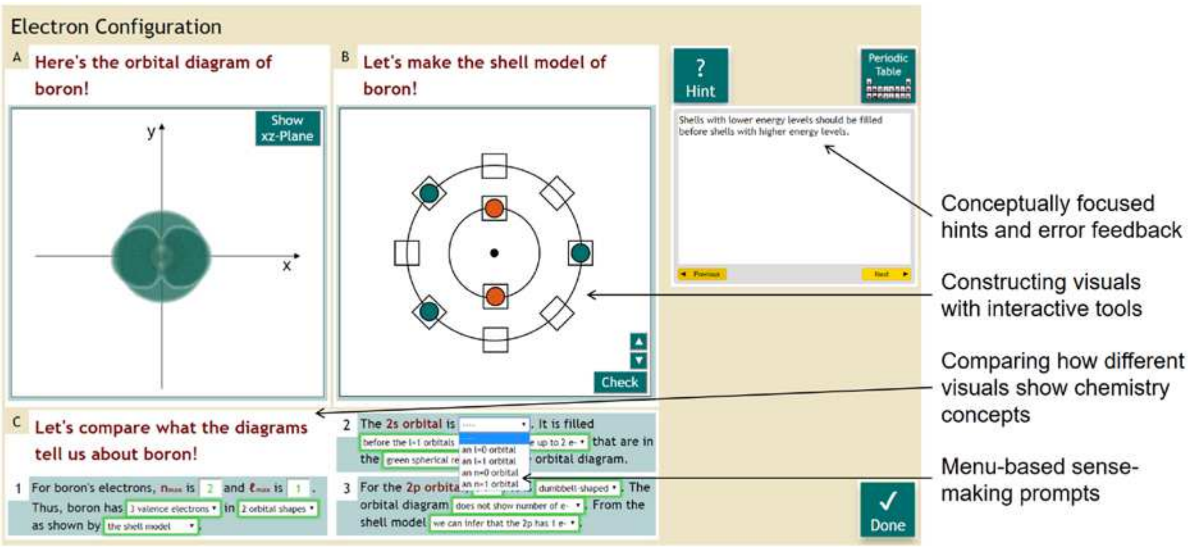

Figure 2. Example sense-activity. Students are given an orbital diagram and construct a shell model of the same atom. Then they receive fill-in-the-blank prompts to make sense of how the two visuals show atoms.

Figure 2 shows an example sense-activity. These activities engage students in verbally mediated explanation-based processes while they work on problem-solving activities that are common in chemistry instruction. To this end, students receive prompts to self-explain differences and correspondences among visuals. They respond to the prompts using menu-based selection. The content of the prompts was generated based on learner-centered studies with novice students and expert chemists. The selection choices were drawn from student-generated explanations. Further, the prompts focus on those concepts and visual features that expert chemists frequently use when using visuals to make sense of atomic structure. Further, Chem Tutor provides error-specific feedback messages and hints on demand that provide conceptual explanations.

Perceptual-Activities

Figure 3 shows an example perceptual-activity. The goal of these activities is to engage students in inductive processes. To this end, students are given one visual and have to select one of four other visuals that shows the same atom. They are prompted to solve this task quickly and intuitively, without overthinking their choices and without being afraid of making mistakes. Students receive many of these one-step problems in a row. The answer choices are designed to direct students' attention to relevant visual features by contrasting relevant visual features. The contrasting cases were selected based on learner-centered studies that investigated which visual features expert chemists pay attention to but novice chemistry students tend to confuse. If students select the wrong visual, Chem Tutor tells them they made an error and asks them to try again. This is in line with perceptual learning research that recommends providing correctness feedback only so as to encourage implicit rather than explicit processes (Kellman & Massey, 2013).

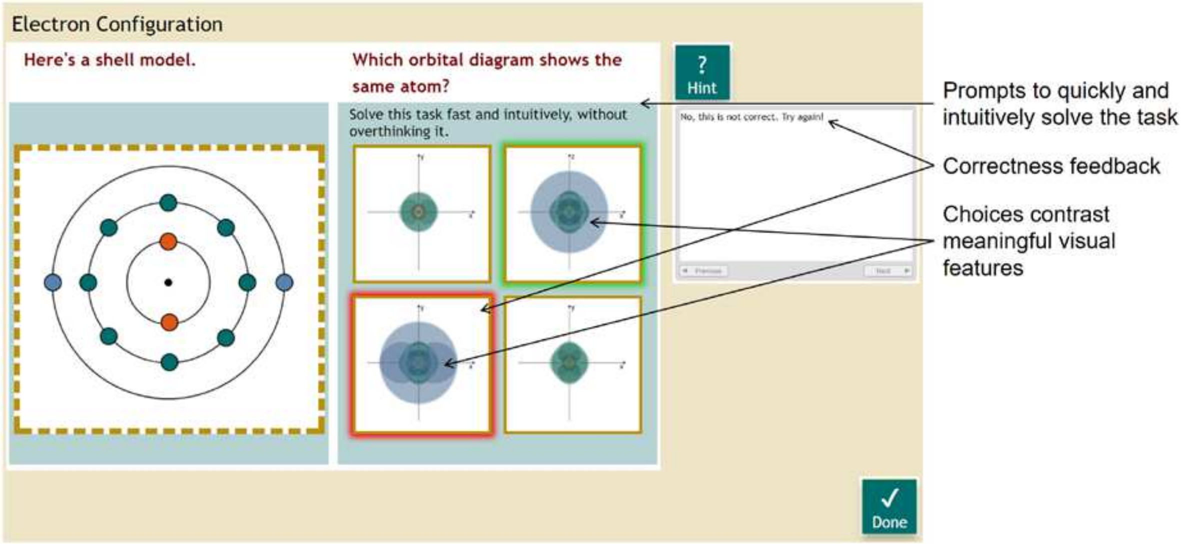

Figure 3. Example perceptual-activity that provides contrasting cases of relevant visual features. Students are prompted to solve them quickly and intuitively. They receive only correctness feedback on their selections.

Experimental design
Students were randomly assigned to one of two experimental conditions for the entire duration of the experiment. The *sense-perceptual condition* received sense-activities before perceptual-activities for each of the six units. The *perceptual-sense condition* received perceptual-activities before sense-activities. For each unit, all students first received two regular activities that introduced how the visuals depict the chemistry concepts covered in that unit. Then, for each unit and in the sequence corresponding to their condition, they received four sense-activities and 36 perceptual-activities. We chose the number of activities based on pilot tests of how many activities yield significant gains on tests of sense-making competencies and perceptual fluency, respectively.

Measures
We assessed students' *spatial skills* with the Vandenberg & Kuse mental rotations test, which is commonly used in research on spatial skills and chemistry learning (e.g., Stieff, 2013). Further, we assessed students' *knowledge of the chemistry concepts* covered in Chem Tutor with pretests and posttests for each unit, developed and evaluated with chemistry experts. Two equivalent test versions were used for the pretests and posttests. For each unit the sequence in which students received the test versions was counterbalanced across pretest and posttest.

Procedure
Students were assigned to work on the Chem Tutor units as a homework assignment for their chemistry course. Students had to complete the six assignments in order to align with the course schedule. The assignments were spread across three consecutive weeks, with two units per week. Students accessed the units online. As with any homework assignment, students could take breaks as needed. For each unit, students first received a pretest, then worked on the activities as per their experimental condition, and then completed the posttest for the unit.

Results
Students were excluded from the analysis if they failed to complete the assignment by the deadline imposed by their course instructor. Of the 71 students, 62 completed units 1 and 2; 69 completed unit 3; 68 completed 4; and 63 completed units 5 and 6. For the following analyses, we consider $p.\eta^2$ as a measure of effect size, $p.\eta^2 \geq .01$ being a small effect, $p.\eta^2 \geq .06$ a medium effect, and $p.\eta^2 \geq .14$ a large effect.

Effects of sequence on learning gains
To test effects of sequence on learning gains (research question 1), we used ANCOVAs with students' posttest scores for the given unit as dependent measure, sequence as independent factor, and pretest scores for the given unit as covariate. To test whether sequence interacts with prior knowledge (research question 2), we added interaction terms for pretest and spatial skills with sequence to the ANCOVA model. In the following, we report results from the model with the interaction effects that were significant. For significant interactions, we exam-

ined the direction of effects with effect slices that compute the effect of sequence for students with low, intermediate, and high prior knowledge, using the 33rd and 66th percentiles as cutoffs. Table 1 shows results by unit.

For unit 1, we found no effect of sequence on posttest scores, $F(1, 60) = 2.51$, $p = .12$, and no interaction between sequence and pretest or spatial skills (Fs < 1). For unit 2, we found no effect of sequence on posttest scores ($F < 1$) and no interaction between sequence and pretest ($F < 1$). There was a significant interaction of sequence with spatial skills, $F(1, 57) = 5.41$, $p = .01$, $p.\eta^2 = .16$. However, effect slices showed no significant effects for students with low, intermediate, or high prior knowledge (ps > .17).

For unit 3, we found a significant effect of sequence on posttest scores, $F(1, 66) = 6.33$, $p = .01$, $p.\eta^2 = .08$, such that students in the perceptual-sense condition had higher learning gains than students in the sense-perceptual condition. There was no interaction between sequence with pretest or spatial skills (Fs < 1).

For unit 4, we found a significant effect of sequence, $F(1, 63) = 4.15$, $p = .05$, $p.\eta^2 = .06$, such that students in the sense-perceptual condition had higher learning gains than students in the perceptual-sense condition. There was no interaction between sequence and pretest ($F < 1$). However, there was a marginal interaction between sequence and spatial skills, $F(1, 63) = 2.89$, $p = .09$, $p.\eta^2 = .04$. Effect slices showed that the advantage of the sense-perceptual condition was more pronounced for students with low spatial skills ($p = .06$) than for students with intermediate ($p = .48$) or high spatial skills ($p = .92$).

For unit 5, we found a marginal effect of sequence, $F(1, 57) = 4.15$, $p = .09$, $p.\eta^2 = .05$, such that students in the sense-perceptual condition had higher learning gains than students in the perceptual-sense condition. There were no interaction between sequence and pretest ($F < 1$) or spatial skills, $F(1, 57) = 2.36$, $p = .13$.

For unit 6, we found a significant effect of sequence on posttest scores, $F(1, 59) = 5.80$, $p = .02$, $p.\eta^2 = .09$, such that students in the perceptual-sense condition had higher learning gains than students in the sense-perceptual condition. There was a significant interaction with pretest, $F(1, 59) = 4.20$, $p = .05$, $p.\eta^2 = .07$. Effect slices showed that the advantage of the perceptual-sense sequence was more pronounced for students with low ($p = .01$) and intermediate prior knowledge ($p = .06$) than for students with high prior knowledge ($p = .76$). There was no interaction of sequence with spatial skills ($F < 1$).

Examining Table 1 allows us to answer how the effect of the sequence changed throughout the intervention (research question 3). Counter to our hypotheses, we did not see differences between conditions in early units. However, the results for units 3-6 match our hypotheses in the sense that students show a benefit for the perceptual-sense sequence in units 3 and 6 (i.e., in the first half of the intervention and at the end of the intervention) and a benefit for the sense-perceptual sequence in units 4 and 5 (i.e., in the middle of the intervention).

Table 1: Overview of sequence effects by unit. (*) indicates effects with $p < .10$; * $p < .05$; ** $p < .01$

	Effect on posttest	**Direction of interaction effects**
Unit 1	-	-
Unit 2	-	-
Unit 3	Perceptual-sense > Sense-perceptual **	-
Unit 4	Sense-perceptual > Perceptual-sense *	Especially for low spatial skills
Unit 5	Sense-perceptual > Perceptual-sense (*)	-
Unit 6	Perceptual-sense > Sense-perceptual *	Especially for low and intermediate pretest

Discussion

Prior research showed that students most benefit from interventions that combine activities designed to support for sense-making competencies and perceptual fluency. Further, prior cross-sectional studies showed that students' prior knowledge seems to determine in which sequence sense-activities and perceptual-activities should be combined. These findings invoked a learning progression that had not been tested. Our findings from this longitudinal study match previous findings from cross-sectional studies. Based on our results, we tentatively put forward the following progression with, roughly, four phases. In the first phase (units 1-2), we found no difference between sequences. It is possible that at this early stage, students familiarize themselves with how the visuals show concepts, which is considered to be an important learning process that occurs before students learn to make connections among different visuals (Ainsworth, 2006; Rau, 2017a).

In a second phase (unit 3), students benefited from receiving perceptual-activities before sense-activities. This finding is consistent with the theory that perceptual fluency frees cognitive capacity that students can invest in effortful explanation-based processes while working on sense-activities. It is possible that this mechanism is important at this earlier stage because the cognitive load of explanation-based sense-activities would be too high and could impede students' learning if they lack a preliminary level of perceptual "intuitions" about what the visuals show and inhibits their ability to participate in disciplinary discourse with these visuals.

In a third phase (units 4-5), students benefited from receiving sense-activities before perceptual-activities. This finding is consistent with the theory that sense-activities help students attend to relevant visual features while they work on perceptual-activities. It is possible that this mechanism is important in this middle stage because students have sufficient knowledge so that sense-activities are not so cognitively demanding that it would impede learning. Further, first focusing on how visuals show particular concepts allows students to refine their understanding of domain-relevant concepts. Subsequent perceptual-activities can then serve to refine these connections between visuals and concepts, allowing students to automatically "see" concepts in visuals.

In a fourth phase (unit 6), students again benefited from receiving perceptual-activities before sense-activities. This finding again aligns with the theory that perceptual fluency frees cognitive capacity that students can invest in effortful explanation-based processes. It is possible that this mechanism becomes important again at this late stage because now the main benefit of perceptual fluency is to put intuitive knowledge about visuals at the service of explaining how visuals show concepts—which is afforded by the perceptual-sense sequence

Our experiment makes important novel contributions to the literature on representational competencies. We expand theory by providing new evidence that there is a learning progression of representational competencies. Specifically, our focus was on learning of content knowledge. We found that students' acquisition of content knowledge is best supported if they receive activities that focus on implicit, then explicit, and then implicit knowledge about visuals. Our findings also have practical implications for the sequence of these instructional activities that support representational competencies in chemistry. Our findings show that if sense-activities and perceptual-activities are sequenced in a way that matches the hypothesized learning progression, they achieve higher learning gains of content knowledge.

Limitations and future directions

Future research should address a number of limitations of our study. First, our study provided chemistry content in particular sequence, which matched the schedule of the course in which we situated our experiment. Therefore, future research should test whether the findings of a learning progression remain when sense-activities and perceptual-activities are added to a different sequence of content-focused instruction. Second, while we consider the fact that our experiment was embedded in a real chemistry course a strength by enhancing its external validity, this choice could reduce the internal validity of our experiment. Students received instruction on the chemistry content outside our intervention—even though this instruction was the same for all students, it is possible that it interacted with our intervention in an unknown way. Therefore, future research should investigate the effects of sequencing sense-activities and perceptual-activities in more controlled contexts. Third, while we had sufficient statistical power to detect small effect sizes of main effects, our sample may have been too small to detect small interaction effects between sequence and prior knowledge. Therefore, future research should use a larger sample to investigate potentially undetected effects. Fourth, our study did not include control conditions that received only sense-activities, only perceptual-activities, or only regular activities without support for representational competencies. While our prior studies showed that students benefit from the combination of sense-activities and perceptual-activities, those prior studies included short interventions and did not consider progressions across longer learning interventions. Therefore, future studies should test whether the combination of sense-activities and perceptual-activities is indeed most effective throughout the learning progression. In particular, it would be interesting whether in the first stage of our tentative learning progression where we did not find a difference between conditions, students might benefit from regular activities alone, so that they can familiarize themselves with one visual at a time. Finally, future work should investigate how to translate our findings into sequences of sense-activities and perceptual-activities. Specifically, we need to know when a student has reached a level of proficiency that requires a switch in the sequence of these activities. We plan to address this question in our own work by examining how real-time data on students' problem-solving performance can be used to predict which particular sequence an individual student would most benefit from.

Conclusion

To conclude, our research is, to the best of our knowledge, the first to demonstrate that there may indeed be a learning progression of explicit and implicit representational competencies. Our findings demonstrate that providing activities that support these competencies in a sequence that matches this learning progression has a significant impact on students' learning of content knowledge. This finding is striking because all students received the same instruction; only the sequence differed. Even when embedded in an existing chemistry course that provided instruction beyond our intervention, the sequence of sense-activities and perceptual-activities affected students' learning of content knowledge with medium to large effect sizes.

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