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Visual Representations in MINT Education: Pitfalls, Benefits, and How to Help Students Make the Most Out of Visualizations

Visual representations are ubiquitous in education in mathematics, informatics, natural sciences, and technical (MINT) domains (Ainsworth, 2008; Gilbert, 2008; NRC, 2006). Formally, representations are objects that stand for something else. Visual representations are objects that have similarity-based mappings to their referent (in contrast to symbolic representations that have arbitrary mappings to their referent) (Rau, 2017a; Schnotz, 2014). We use visual representations to teach students about chemical molecules, to instruct students about the laws of physics, and as scientists more broadly to illustrate our findings to colleagues. Visual representations serve as communication tools, problem-solving tools, and as teaching tools in educational, professional, and scientific communities.

On the one hand, we tend to assume that visual representations make content easily accessible to students (Rau, 2017a). On the other hand, using visual representations requires students to navigate multiple complex learning processes at the same time, because students need to use visual representations they do not know to learn concepts they do not know (Rau, 2017a). This conundrum is known as the representation dilemma (Dreher & Kuntze, 2015). Thus, to use visual representations to learn content knowledge, students also need to acquire representational competencies: the knowledge and skills that allow students to use representations to reason and solve tasks (Rau, 2017a).

Importance of Representational Competencies

Scientific visual representations developed historically to support communication among scientists (Donald, 1991; Latour, 1986). Yet, when we use these visual representations as teaching tools, they can lead to student confusion (Schönborn & Anderson, 2006). An illustrative example regards the use of arrows in visual representations that are commonly used in chemistry. As illustrated in Fig. 1, different types of visual representations use different types of arrows, which carry different meanings. What stands out in this example is that, with the exception of Fig. 1D, the arrows are not labelled.

As pointed out by Dorris and Rau (2022), the meaning of arrows is often left implicit in instructional materials. An interview study found that undergraduate students working with atomic energy diagrams (e.g., Fig. 1C) exhibited severe misconceptions about the meaning of arrows (Dorris & Rau, 2022). For instance, they falsely interpreted the direction of the arrows as indicating whether an electron moves towards or away from the nucleus.

This example illustrates that a lack of representational competencies (e.g., a lack of understanding arrows in a visual representation) can result in misconceptions about domain-relevant concepts (e.g., about electron behavior). To address and prevent such issues, instruction should support students' learning of representational competencies, which they likely acquire in an iterative process (Rau, 2017a): As students use visual representations to understand domainrelevant concepts, they also learn about how the visual representations depict these concepts, which in turn allows them to refine their understanding of the concepts, which then allows them to refine their interpretation of the visual representations, etc.

The goal of this paper is to present emerging research on how to support students' representational competencies alongside their learning of content knowledge.

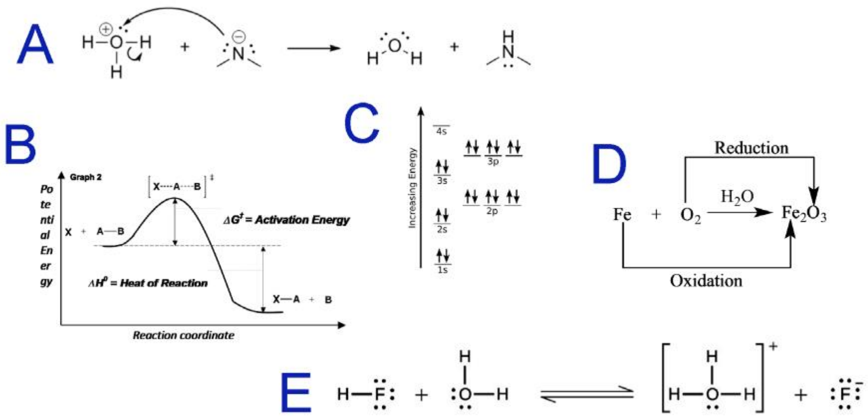

Fig. 1. Chemistry visualizations that use various types of arrows. A: Curved arrows illustrate movement of electrons. B: Double-headed arrows indicate a difference in potential energy. C: Small arrows denote electron spin states. D: Bracketed arrows stand for reduction and oxidation processes. E: Double arrow implies a chemical equilibrium.

Understanding Discipline-Specific Representational Use

Designing instructional supports for representational competencies necessitates an understanding of how visual representations are used in a given discipline (Rau, 2017b). While prior frameworks focused on aligning instructional interventions with broader instructional goals (e.g., Molenda et al., 1996; van Merrienboër et al., 2002), a framework by Rau (2017b) focuses on aligning instruction with discipline-specific uses of visual representations. First, text-book reviews, instructor interviews, and classroom observations can serve to identify how instructors use visual representations in their teaching. Second, interviews with students and instructors as well as observations of student problems solving can help identify difficulties students have in working with visual representations. Third, cognitive tasks analyses and user-centered studies can be used to determine which representational competencies students need to overcome these difficulties.

Building on research that followed the framework by Rau (2017b), Rau (2017a) provides a taxonomy of representational competencies that emerged from empirical research across several disciplines that followed the steps just described. While representational competencies are always specific to the representations used and the concepts taught in the given discipline, Rau (2017a) distinguishes two qualitatively different types of representational competencies that appear to play an important role across disciplines.

First, *sense-making competencies* describe students' ability to explain relationships between visual representations and discipline-specific concepts. For example, chemistry students typically work with not just one but multiple visual representations. In this context, a proficient student should be able to explain which visual features of the visual representations correspond to one another because they depict similar or complementary aspects of the underlying chemistry concept. Students acquire sense-making competencies through analytical learning processes that involve explicit reasoning about conceptual relationships. These processes are verbally mediated and require significant cognitive effort. Much prior research has investigated how to support sense-making competencies effectively through prompts that encourage reflection and student explanations while providing conceptual feedback on those explanations (Ainsworth, 2006; Berthold & Renkl, 2009; Bodemer et al., 2005; van der Meij & de Jong, 2011). For example, chemistry students working with the two visual representations in Fig. 2 may receive prompts to explain why the Lewis structure of the ammonium ion shows a formal positive charge by the nitrogen atom, whereas the electrostatic potential map shows a partial negative charge by the nitrogen atom.

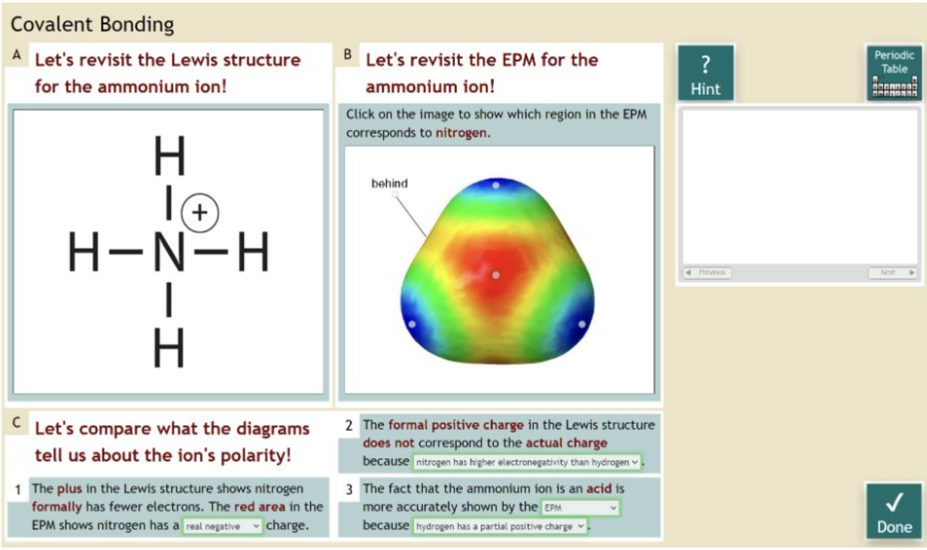

Fig. 2. Example problem-solving activity that supports sense-making competencies.

Second, *perceptual fluency* describes students' ability to efficiently extract information from visual representations. Often overlooked in educational contexts (Kellman et al., 2008), perceptual fluency allows students to immediately see meaning in visual representations and to translate between different types of visual representations so quickly that it seems automatic. Such efficient processing has been linked to expert performance in high-level tasks (Goldstone et al., 2010). On the flipside, lack of perceptual fluency has been associated with poor performance, for instance in chemistry courses (Anderson & Bodner, 2008). The learning processes through which students acquire perceptual fluency fundamentally differ from those processes that lead to sense-making competencies because they are inductive, implicit, nonverbal, automatic, and therefore not under the direct control of the students. Prior research has investigated how to support perceptual fluency (Kellman & Massey, 2013; Wise et al., 2000). This research suggests that students should receive short classification tasks where they have to quickly sort visual representations. The visual representations should repeat information-carrying features while varying irrelevant features. Students should receive immediate feedback on their responses, but this feedback should be nonverbal because verbalization can disrupt perceptual processing (Schooler & Engstler-Schooler, 1990). For example, a chemistry student might be asked to quickly decide which of four ball-and-stick models depict the same molecule as a given wedge-dash Lewis structure, as illustrated in Fig. 3.

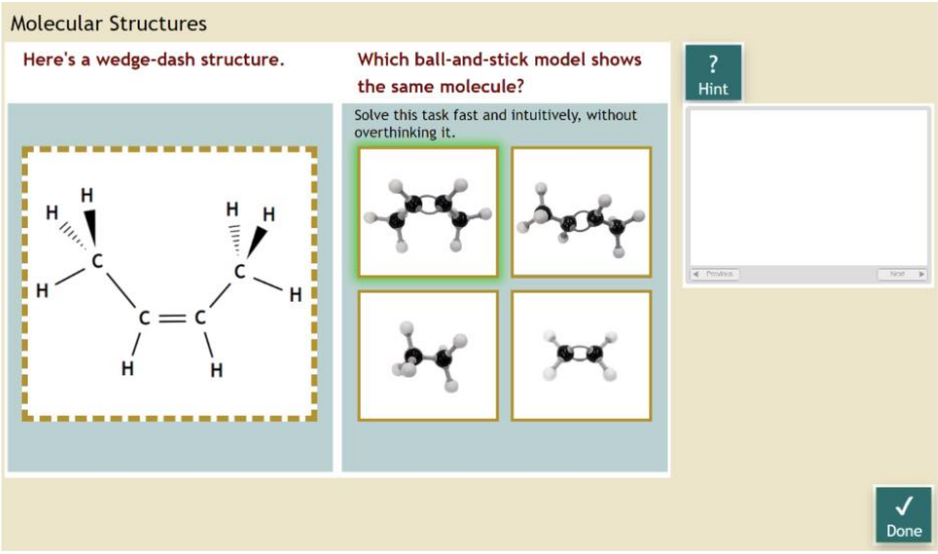

Fig. 3. Example problem-solving activity that supports perceptual fluency.

Effects of Representational-Competency Supports on Learning of Content Knowledge

Much research has documented that supporting students in making sense of how visual representations depict domain-relevant concepts enhances students' learning of content knowledge in domains such as physics (Berthold et al., 2008; van der Meij & de Jong, 2011), biology (Seufert, 2003), and mathematics (Berthold & Renkl, 2009; Cobb & McClain, 2006). In contrast, less research has focused on the role of perceptual fluency in learning. A few studies document a benefit of interventions that engage students in intuitive, inductive processing of visual information (Kellman et al., 2008; Wise et al., 2000), sometimes through game-based interventions (Moreira, 2013; Welsh, 2003).

However, this research left open the question of whether combining instructional support for sense-making competencies and perceptual fluency enhances students' learning of content knowledge. Rau and Wu (2018) addressed this question in an experiment with undergraduate students learning about atomic structure. Students participated in the experiment in a research laboratory but were recruited from an introductory chemistry course for non-science majors. All students first received a pretest assessing their content knowledge. Then, they worked on instructional problem-solving activities that were presented on a computer. At the end, all students received a posttest assessing their content knowledge. The tests included items with and without visual representations as well as multiple-choice and open-ended response items. During a first instructional phase, all students first received regular problem-solving activities where students used visual representations to learn about chemistry concepts without representational-competency supports. Then, during a second instructional phase, students were randomly assigned to either (1) a *control condition* that provided students with more regular problem-solving activities, (2) a *sense-only condition* that provided sense-making activities (see Fig. 2), (3) a *perceptual-only condition* that provided perceptual-fluency activities (see Fig. 3), or (4) a *combined condition* that provided sense-making activities followed by perceptual-fluency activities. All conditions received instruction on the same chemistry concepts, were exposed to the same visual representations, and solved the same number of problemsolving steps to ensure that average instructional time was equivalent across conditions. Results of N = 117 students showed that neither the sense-only condition nor the perceptualonly condition significantly outperformed the control condition. Only students in the combined condition showed significantly higher learning outcomes on the content knowledge posttest compared to the control condition. Eye-tracking data and verbal reports provided additional insights into this finding. Students in the perceptual-only condition showed reduced conceptual engagement with the visual representation, which might explain the low learning outcomes of this condition. Sense-making activities helped students notice meaningful features of the visual representations, and (when combined with sense-making activities) perceptual-fluency activities helped students efficiently extract this meaning, which made it usable on the posttests.

In sum, this study shows that students' learning of content knowledge through visual representations can be enhanced by combining instructional support for sense-making competencies and perceptual fluency.

Effects of Representational-Competency Supports on Future Learning Experiences

While the results from the previously described study are encouraging, students may not always have access to representational-competency supports. Little research has investigated long-term effects of representational-competency supports, and the few existing studies were carried out from the perspective of a traditional transfer paradigm. The traditional transfer paradigm tests whether instructional interventions increase students' performance on novel problem-solving activities (Nokes-Malach & Mestre, 2013; Schwartz et al., 2005). Following this paradigm, Cromley and colleagues (2013) found that supporting students' representational competencies improved their ability to solve novel tasks on a transfer posttest.

In contrast to the traditional transfer paradigm, research on preparation for future learning examines whether instructional interventions help students make better use of resources they receive in subsequent instruction (Nokes-Malach & Mestre, 2013; Schwartz et al., 2005). Research on preparation for future learning documents that this paradigm is more sensitive to educationally meaningful differences between students than the traditional transfer paradigm (Schwartz et al., 2005; Schwartz et al., 2007): Students who perform similarly on a traditional transfer test may perform differently after having received additional instruction on a new topic. However, this line of research has not investigated whether representational-competency supports enhance students' ability to learn from future instruction.

To address this question, Rho and colleagues (2022) tested whether the effects of representational-competency supports enhance students' benefit from future learning experiences. The experiment was carried out as part of an undergraduate engineering course on signal processing. In a first instructional phase, which lasted four consecutive course meetings, students learned about sinusoids using the visual representations shown in Fig. 4. During this phase, students were randomly assigned to one of four experimental conditions that were similar to the conditions described above. (1) A *control condition* received regular problem-solving activities without representational-competency supports. (2) A *sense-only* condition received sense-making activities that prompted students to explain relationships between visual representations based on concepts related to sinusoids. (3) A *perceptual-only condition* received perceptual-fluency activities where students had to quickly find matching visual representations. (4) A *combined condition* received sense-making activities followed by perceptual-fluency activities.

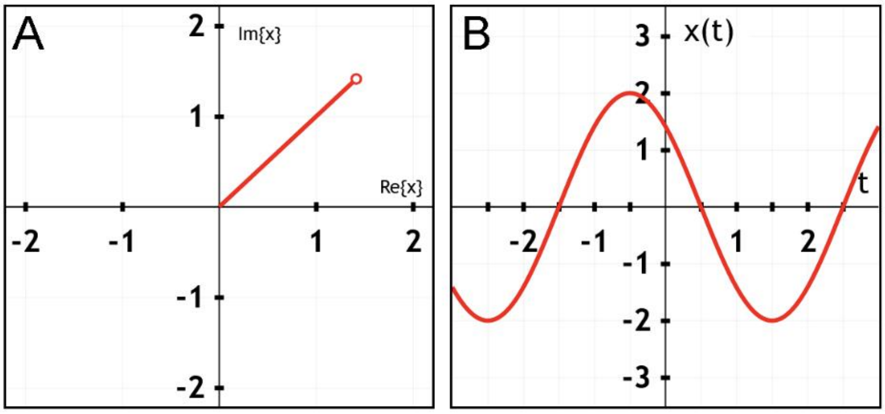

Fig. 4. Visual representations used to introduce students to concepts related to sinusoids. A: Phasor graph. B: Time-domain graph.

A second instructional phase, which was identical for all students, provided instruction on a new topic related to phasor addition, using a new visual representation that students had not encountered before. Students' learning from the second instructional phase was assessed with a pretest that students completed prior to instruction and a posttest that they completed following the instruction. The tests assessed students content knowledge and included test items with and without visual representations.

Results of N = 120 students showed that neither the sense-only condition nor the perceptualonly condition outperformed the control condition. Only students who had received the combination of both sense-making and perceptual-fluency activities outperformed students in the control condition. This finding suggests that students' learning from future lessons can be enhanced by combining support for sense-making competencies and perceptual fluency.

Sequencing Support for Sense-Making Competencies and Perceptual Fluency

While the previous findings suggest that support for sense-making competencies and perceptual fluency should be combined, open questions remained about how best to combine support for these representational competencies. While prior research had investigated sequences between sense-making activities and other types of activities (e.g., activities that focus on procedural learning; Rittle-Johnson et al., 2001), prior research had not examined how best to sequence sense-making activities and perceptual-fluency activities.

To address this question, a series of experimental studies compared the effects of providing sense-making activities followed by perceptual-fluency activities or vice versa (Rau, 2018).

Three experiments were carried out in the context of undergraduate chemistry learning. In these experiments, students first received a pretest, then worked on instructional activities that either (1) presented sense-making activities followed by perceptual-fluency activities or (2) presented perceptual-fluency activities followed by sense-making activities. Experiments with different samples yielded conflicting results. A lab experiment with $N = 48$ undergraduate students who were recruited from a chemistry course for non-science majors found that students with low prior knowledge benefited from receiving perceptual-fluency activities first, whereas students with high prior knowledge benefited from either sequence. Similarly, a class experiment with $N = 607$ undergraduate students enrolled in an introductory chemistry course for science majors found a benefit for providing perceptual-fluency activities first for students with low prior knowledge, whereas students with high prior knowledge benefited from receiving sense-making activities first. In contrast, a class experiment with N = 74 undergraduate science majors found that students with low prior knowledge benefited from receiving sense-making activities first, whereas students with high prior knowledge benefited from receiving perceptual-fluency activities first. To gain deeper insights into these divergent effects, Rau (2018) conducted causal path analyses of errors students made while working on sense-making activities and perceptual-fluency activities.

The patterns of student mistakes suggested that students with low prior knowledge struggled when switching from one type of activity to another. For example, when switching from sense-making activities to perceptual-fluency activities, low-prior-knowledge students made more errors when working on the perceptual-fluency activities, compared to low-priorknowledge students who had not previously received sense-making activities. These difficulties were associated with lower learning outcomes at the posttests and were apparent regardless of the sequence in which students received the two types of activities. By contrast, for students with high prior knowledge, the previous type of activity seemed to prepare them to learn from the second type of activity.

For example, when switching from sense-making activities to perceptual-fluency activities, high-prior-knowledge students made fewer errors when working on the perceptual-fluency activities, compared to high-prior-knowledge students who had not previously received sense-making activities. This pattern was associated with higher learning outcomes at the posttests and was apparent regardless of the sequence in which students received the two types of activities.

In sum, this research suggests that students with different levels of prior knowledge may need different sequences of sense-making and perceptual-fluency activities at different times during their learning trajectory. Adaptive educational technologies lend themselves to addressing such interdependencies between instructional needs and prior knowledge levels.

Adaptive Support for Representational Competencies

Abundant research has investigated whether adaptive support for problem-solving skills enhances learning outcomes (Koedinger & Corbett, 2006; VanLehn, 2011). However, this research typically focused on adapting instruction to students' current level of content knowledge. The question of whether adapting instruction to students' current level of representational competencies remained open. To address this question, Rau and colleagues (2021) investigated whether adaptively assigning sense-making competencies or perceptual-fluency activities based on students' learning progress would enhance students' learning of content knowledge.

Designing adaptive representational-competency support.

The first step was to create an algorithm that carries out the adaptive selection procedure. To this end, the authors conducted a pre-study with N = 129 undergraduate students who were enrolled in an introductory chemistry course for science majors. The study was carried out over ten weeks where students worked through ten units of instructional materials on atomic structure and chemical bonding. Each week, students received a pretest, then worked on instructional activities, and then took a posttest. One week later, students took a delayed posttest. The tests assessed students' content knowledge.

Instruction for each week involved two phases. During the first instructional phase, all students received regular problem-solving activities without representational-competency supports. In the second instructional phase, students were randomly assigned to one of five conditions: (1) A *control condition* received more regular problem-solving activities. (2) A *sense-only condition* received sense-making activities that prompted students to explain relationships between visual representations based on concepts related to sinusoids. (3) A *perceptual-only condition* received perceptual-fluency activities where students had to quickly find matching visual representations. (4) A *sense-perceptual condition* received sense-making activities followed by perceptual-fluency activities. (5) A *perceptual-sense condition* received perceptual-fluency activities followed by sense-making activities.

To create the adaptive algorithm, the authors used learning analytics methods. Specifically, the log data obtained during the first instructional phase was used to predict which condition the given student would most benefit from during the second instructional phase. This analysis identified mistakes students might make during the regular problem-solving activities during the first instructional phase of each unit that were indicative for whether the student might benefit from receiving more regular activities, sense-making activities, or perceptual-fluency activities during the second instructional phase of the unit. These insights were then implemented as if-then rules in the adaptive algorithm: IF the student makes mistake x, THEN the algorithm will assign activity.

Evaluating the adaptive representational-competency supports.

To investigate whether adaptive representational-competency supports enhance students' learning outcomes, the authors conducted an experiment as part of an undergraduate chemistry course for science majors enrolling N = 45 students. The experiment was carried out over ten weeks where students worked on ten units of instructional materials about atomic structure and chemical bonding. Each week, students received a pretest, instructional activities, and a posttest. One week later, students took a delayed posttest. The tests assessed students' content knowledge.

Like the pre-study, instruction for each week was delivered in two phases. During the first phase, all students received regular problem-solving activities without representational-competency supports. During the second phase, students were randomly assigned to one of two experimental conditions. (1) Students in a *static condition* received sense-making activities followed by perceptual-fluency activities in the second phase, which corresponded to the most effective sequence for the given population of students, as determined by the previous experiments described above (Rau, 2018). (2) For students in an *adaptive condition*, the adaptive algorithm described above used students' log data from the first instructional phase of the given unit to determine whether students should receive regular activities, sense-making activities, or perceptual-fluency activities during the second instructional phase of the unit. As illustrated in Fig. 5, results showed that students in the adaptive condition showed significantly higher learning outcomes at the posttests while also making significantly fewer errors on the instructional problem-solving activities. Furthermore, an analysis of reflection papers that students enrolled in the course had to submit every week revealed that students in the adaptive condition voiced less confusion about the visual representations covered in the course.

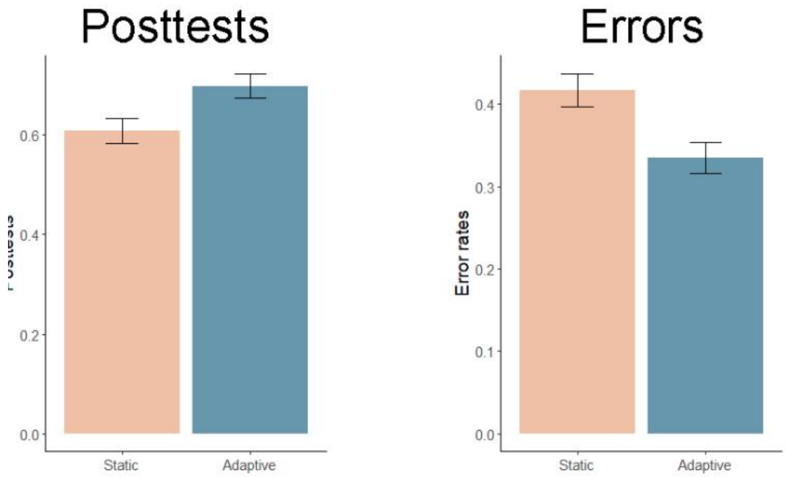

Fig. 5. Estimated marginal means of condition effects. Error bars show standard errors of the mean. Left: Condition effect on posttest scores, averaged across the ten units for posttest and delayed posttest. Right: Condition effect on error rates during problem solving, averaged across the ten units.

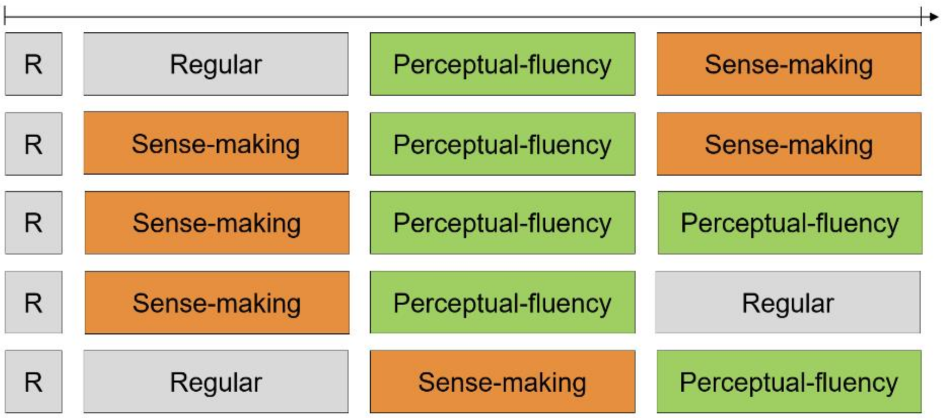

Fig. 6. Schematic depiction of the sequence of instructional activities in the adaptive condition over the course of ten weeks.

Additionally, the authors analyzed how the adaptive algorithm assigned regular, sense-making, and perceptual-fluency activities over the course of the ten weeks. As illustrated in Fig. 6, all students in the adaptive condition received regular instructional activities or sense-making activities before they received perceptual-fluency activities. Further, all students received a combination of sense-making and perceptual-fluency activities. In sum, these findings indicate that adaptive support for representational competencies can significantly enhance students' learning outcomes in a chemistry course. Further, the analysis of the adaptive assignment of instructional activities provides further evidence that combining support for both sense-making competencies and perceptual fluency is important. Finally, the pattern of adaptive assignments suggests that students require some experience with the visual representations before they can benefit from activities that support perceptual fluency.

Alternative Supports for Representational Competencies

The studies presented thus far supported representational competencies through sophisticated educational technologies. However, such technology-based representational-competency supports are not available for all topics of instruction, and even if they were, not all students would have access to them. Therefore, it is important that research also investigates how to support representational competencies in a light-weight fashion, without the use of technologies.

Supporting Sense-Making Competencies through Collaboration.

When students collaborate, they naturally engage in explanation-based processes that can support sense-making competencies. When students collaborate on activities that involve visual representations, they may realize that they interpret visual representations differently, which can prompt students to jointly make sense of how the visual representations depict information (Strickland et al., 2010).

Yet, prior research suggests that students tend not to spontaneously engage in productive collaborative behaviors (Lou et al., 2001). Therefore, much research has investigated how to support productive collaboration. This research suggests that students should actively construct meaning by discussing their different viewpoints (Miyake & Kirschner, 2014). Collaboration scripts that prompt students to engage in productive collaborative behaviors have been shown to enhance collaboration quality (Walker et al., 2009; Weinberger et al., 2005). However, this research had not focused on supporting students to collaboratively engage in sense making of visual representations and the resulting effects on students' learning outcomes. To close this gap, Rau and colleagues (2017) investigated whether a collaboration script that prompts students to jointly make sense of visual representations would enhance their learning of content knowledge. A quasi-experiment with N = 61 undergraduate students enrolled in an accelerated introductory chemistry course compared (1) a *control condition* in which students collaborated without the support of a collaboration script to (2) an *intervention condition* in which students received a collaboration script that prompted them to discuss visual representations with their partner. Results demonstrated a significant advantage of the intervention condition on a posttest assessing their content knowledge immediately after the intervention as well as on complex knowledge questions on a midterm exam that was delivered three weeks after the intervention. This finding suggests that supporting students' collaborative sense making via collaboration scripts can enhance students' learning outcomes.

Supporting Sense-Making Competencies Through Drawing.

The sense-making activities discussed thus far have focused on verbally mediated sense-making processes. However, the visuo-spatial concepts depicted in visual representations can be difficult to explain verbally (Bobek & Tversky, 2014; Vosniadou, 1994). To address this issue, research has investigated whether drawing can serve as a nonverbal means to support sense-making processes. Indeed, empirical research suggests that prompting students to draw their own visual representations can enhance their learning outcomes (Prain & Tytler, 2012; Van Meter & Garner, 2005). However, this research had not investigated whether drawing prompts might enhance students' benefit from instruction that focuses on verbal sense making of visual representations. A further open question remained about how often students should be prompted to draw. While some prior studies had investigated the effects of providing drawing prompts only before and after instruction (Gadgil et al., 2012; Mason et al., 2013), other studies had examined the effects of providing drawing prompts throughout instruction (Leopold & Leutner, 2012; Schmeck et al., 2014). However, this research had not contrasted effects of providing drawing prompts only before and after versus throughout instruction.

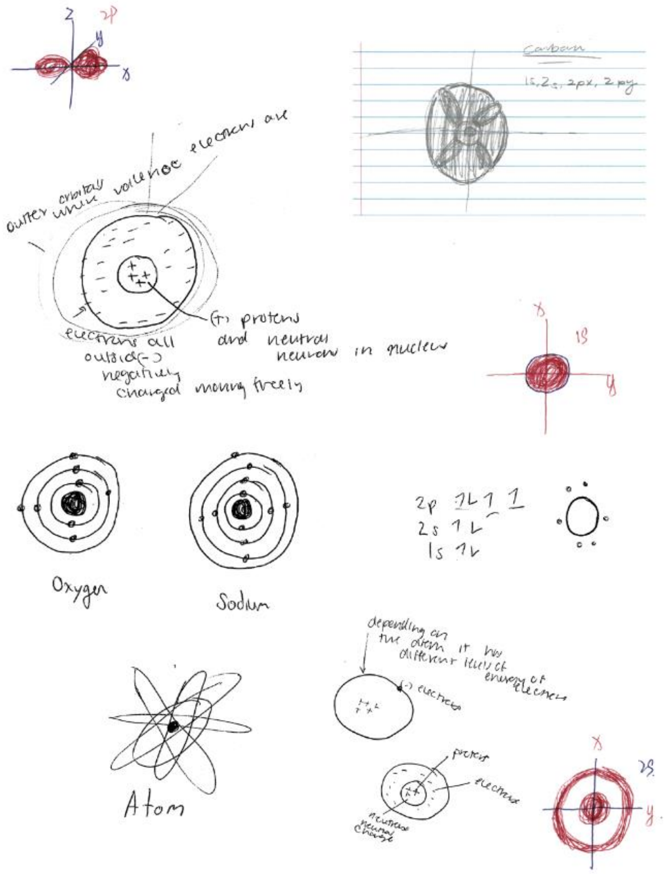

Fig. 6. Example drawings from Wu and Rau (2018).

To address these open questions, Wu and Rau (2018) conducted a laboratory experiment with N = 72 undergraduate students. Students received a pretest, instructional activities about atomic structure, a posttest, and a delayed posttest that was delivered one week later. The tests assessed students' content knowledge. During the instructional phase, students were randomly assigned to either (1) a *control condition* that did not receive drawing prompts, (2) a *before-after condition* that was prompted to draw before the instructional intervention and after the instructional intervention, or (3) a *throughout condition* that received drawing prompts before, during, and after the intervention. The intervention consisted of sense-making activities that asked students to explain relationships between visual representations based on chemistry concepts. To accommodate the extra time needed for drawings in the before-after and the throughout conditions, the number of instructional activities in these conditions was reduced compared to the control conditions. This reduction of instructional activities ensured that the average instructional time was equivalent across conditions. Results showed an advantage of providing drawing prompts compared to the control condition. Further, the study revealed an advantage of providing drawing prompts throughout the instructional intervention over providing drawing prompts only before and after instruction. Finally, a qualitative analysis of students' drawings (e.g., see Fig. 6) suggested that students who were prompted to draw throughout instruction produced higher-quality drawings. In sum, this study suggests that prompting students to draw their own visual representations can serve as a nonverbal means to support sense making that enhances their learning outcomes.

Game-Based Support for Perceptual Fluency.

As mentioned above, existing perceptual fluency interventions often engage students with visual representations in a game-like fashion, for example through card games (Moreira, 2013; Welsh, 2003). With the increased use of educational video games for instructional purposes, the question arises whether these rich, highly visual environments lend themselves to supporting representational competencies. Indeed, educational video games are typically highly visual (Virk et al., 2015) and seek to engage students in authentic scientific practices that involve visual representations (Clark et al., 2009; Clark & Sengupta, 2020). However, prior research on representational-competency supports have focused on structured learning environments rather than educational video games. Hence, the question of whether these types of games are a useful platform for supporting sense-making competencies and perceptual fluency remained open. Herder and Rau (2022) sought to close this gap by investigating whether providing support for students' sense-making competencies and perceptual fluency would enhance their learning from an educational video game for astronomy (Fig. 7). In the game, students serve as a contractor who flies to various planets to obtain data, which they then analyze using visual representations that are commonly used as tools for data analysis by astronomers. In a laboratory experiment, N = 115 undergraduate students took a pretest, played the astronomy game, and then took a posttest. The tests assessed students' understanding of the astronomy concepts covered in the game as well as sense-making competencies and perceptual fluency. During game play, students were randomly assigned to one of four experimental conditions. (1) In a *control condition*, students played the game without receiving support for representational competencies. (2) In a *sense-only condition*, students received support for sense-making competencies in the form of an instructional video that modeled sense making in the game as well as prompts that were delivered prior to game play as well as reminders throughout the game. (3) In a *perceptual-only condition*, students received support for perceptual fluency in the form of an instructional video that modeled intuitive processing of the visuals in the game as well as through prompts that were delivered prior to and during game play. (4) In a *combined condition*, students received support for sense-making competencies in the first half of the game and support for perceptual fluency in the second half of the game.

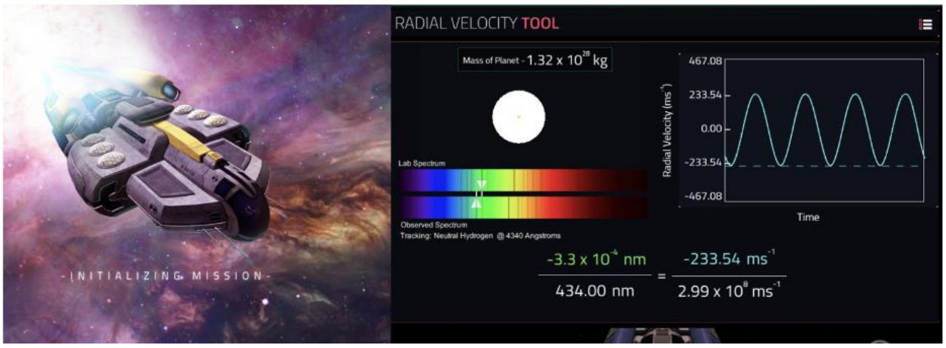

Fig. 7. Educational astronomy video game. Left: Students fly to various planets. Right: Students use disciplinary visual representations to analyze data obtained from the planets.

Results showed no evidence that sense-making support failed to enhance students' sense-making competencies and did not result in gains in terms of content knowledge. By contrast, support for perceptual fluency significantly enhanced students' perceptual fluency as well as their learning of content knowledge. However, students with high prior knowledge showed higher benefits from perceptual-fluency supports. In sum, this finding suggests that the game supported students' perceptual fluency, whereas it did not support sense-making competencies. Importantly, Herder and Rau (2022) were careful to point out that their findings do not imply that games cannot be used to support sense-making competencies, but that future research is needed to examine other types of educational video games that may have different implications for representational competencies. The finding that students with high prior knowledge showed higher benefits from this game aligns with the previously mentioned findings (Rau et al., 2021) that support for perceptual fluency is most suitable for students who already have a certain level of experience with the content and the visual representations.

Conclusion

The research presented in this paper demonstrates that instructional supports for representational competencies can enhance students' learning of content knowledge. Future research should further examine opportunities for designing representational-competency supports in ways that can easily be integrated with existing instructional materials that use visual representations to depict domain-specific concepts. Recent research suggests that collaborative activities, drawing, as well as educational games might be promising platforms to engage students with visual representations in a meaningful and productive way.

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