Social, Perceptual, and Conceptual Factors of Learning With Multiple External Representations in Educational Technologies

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Introduction

Students learn with visual representations (e.g., pie charts and graphs in math; Lewis structures and ball-and-stick models in chemistry). Instruction in science, technology, engineering, and math (STEM) domains use visual representations to make abstract concepts accessible to students. However, visual representations can also confuse students; for instance, if students do not understand how the representation depicts concepts, or how to translate among representations. Thus, students need **representational competencies:** knowledge and skills that enable them to construct, interpret visual representations, and to translate between them. My goal is to establish effective ways to support students' representational competencies to help them succeed in STEM. To this end, I conduct empirical research that investigates (1) which representational competencies are key to STEM learning, (2) through which processes students acquire them, and (3) best to support them in instruction.

Theoretical framework

Based on my findings, I am developing a theory of the **S**ocial, **P**erceptual, and **C**onceptual factors of learning with **E**xternal **R**epresentations (**SPACER**). The SPACER theory makes three central claims.

Claim I states that STEM learning involves two types of representational competencies that require different types of instructional support because they involve different types of learning processes. *Conceptual competencies* involve the ability to map visual representations to concepts, to make inferences based on representations, and to choose appropriate representations for a given task. Students acquire conceptual competencies via conceptual processes—verbally mediated, explanation-based processes. Conceptual processes are roughly analogous to Kahneman's popular description of "deliberate" or "System 2" thinking. To support conceptual processes, instruction needs to actively engage students in making sense of visual representations.

By contrast, *perceptual competencies* involve the ability to effortlessly and efficiently see meaning in visual representations. Analogous to bilinguals who are fluent in two languages, perceptual competencies involve fluency in understanding and translating between representations. Students acquire perceptual competencies via perceptual processes—automatic processes involved in pattern recognition that are non-verbal, implicit, and inductive. Perceptual processes are analogous to Kahneman's "fast" or "System 1" thinking. To support perceptual processes, instruction can expose students to numerous varied examples of visual representations.

Claim II states that students' acquisition of conceptual and perceptual competencies follows a learning progression; that is, students acquire these competencies in a particular sequence because the acquisition of one competency helps them acquire another competency and vice versa. On the one hand, conceptual competencies can enhance the acquisition of perceptual competencies because students know which visual features show domain-relevant concepts. On the other hand, perceptual competencies can enhance the acquisition of conceptual competencies because "fluency" with visual representation frees cognitive resources that students can invest in willful, deliberate thinking. Thus, support for representational competencies is most effective if it takes into account how conceptual and perceptual competencies build on one another in a learning progression.

Claim III states that, because individual students learn at different rates, they may have different needs for conceptual and perceptual support. Therefore, support for representational competencies is most effective if it adapts to the individual student's needs in real time.

Educational technologies

Educational technologies have the capability to adapt to the individual student's needs. They do so based on a computational model that infers the student's knowledge level based on interactions with the technology. Therefore, I situate my research on the SPACER theory in educational technologies. Specifically, I seek to augment regular learning activities with educational technologies that provide individualized support for representational competencies. Imagine a student visualizing a fraction with an interactive computer-based pie chart, or two chemistry students building a ball-and-stick model. The technology may alert the math student to having confused numerator and denominator of the fraction in the pie chart; or it may prompt the chemistry students to compare their model to a virtual representation and to discuss mismatches. I refer to this use of educational technologies as **V**isual **E**xternal **R**epresentations with **I**ndividualized **T**echnologies (**VERITs**).

Empirical research

My research on the SPACER theory and my research on VERITs iteratively build on one another. On the one hand, I use VERITs to test the SPACER theory. Second, VERITs can assess students' conceptual and perceptual competencies as they develop over time. This provides insights into the nature and relationships among these competencies. In the following, I describe how VERITs have served to test and refine the SPACER theory in my current research.

My first step was to establish a methodology for developing VERITs that align with the educational practices of the given target domain. I applied this methodology to design a VERIT for college chemistry (VERIT-Chem). VERIT-Chem features conceptual and perceptual support for representational competencies and yields significant learning gains when used as part of college chemistry courses. My current research uses VERIT-Chem to investigate specific claims of the SPACER theory.

With respect to **Claim I**, my work has yielded several **instructional design principles** for conceptual and perceptual supports. *Conceptual supports* are effective if they prompt students to compare multiple representations to one another, if they engage students in discussions about how visual representations depict information, or if they ask students to construct their own representations. Further, my research describes *social contexts* that can enhance the effectiveness of conceptual supports. Conceptual supports are particularly effective if they are integrated in collaborative activities and if students receive assistance from an instructor.

By contrast, *perceptual support* should be embedded in *individual contexts* because verbalization—as common in social contexts—interferes with non-verbal perceptual processes. Instead, perceptual support should provide classification tasks with a variety of visual representations, provided in an interleaved sequence. These sequences should draw students' attention to visual features they tend to confuse. I currently investigate how to trace students' level of perceptual competencies over time so as to provide more effective visual feedback.

I also tested the **hypothesis** that providing students with conceptual and perceptual support enhances their learning. I had found initial evidence for this prediction in my research on elementary-school fractions. I then investigated whether these findings generalize to a drastically different domain and population: college-level chemistry. Lab and field experiments show that combining conceptual and perceptual support leads to higher learning outcomes, compared to either support alone, and compared to "business-as-usual" control conditions without such support.

With respect to **Claim II**, I tested the **hypothesis** that students' benefit from conceptual versus perceptual support depends on their current level of conceptual and perceptual competencies, respectively. I had found initial evidence for this claim in a lab experiment on fractions learning. Lab and field experiments with VERIT-Chem provide support for this claim in college chemistry. To my surprise, recent results even reveal potential "dangers" of providing supports in a way that misaligned with the learning progression. For example, students with low conceptual competencies who received perceptual support (instead of conceptual support) showed lower learning gains than students who received neither type of support.

Future research plans

My plan for the immediate future is to test additional hypotheses of the SPACER theory using VERITS-Chem. Specifically, I will test whether conceptual support is most effective when it is "spaced" across different social contexts (e.g., collaborative wet-labs for conceptual support, individual homework assignments for perceptual support) (Claim I). I will also examine the proposed learning progression over the course of a semester-long chemistry course (Claim II). Finally, I will test whether support that adapts to the individual student's level of representational competencies is more effective than static forms of support (Claim III).

My long-term plan is to expand my research to other domains than chemistry. I will investigate whether the SPACER generalizes to other STEM domains and refine it based on my findings. Specifically, I will investigate how the type of visual representation affects students' learning. For example, some domains tend to use visual representations with iconic features (e.g., physics, computer science, whereas other domains often use realistic photos (e.g., medicine, biology). Further, I will investigate domain-specific practices. For example, in some domains, visual representations play a "training wheel" role (e.g., math), whereas in other domains, they play an "end-in-itself" role: (e.g., chemistry, medicine).

In sum, my work addresses several issues. First, existing interventions, including educational technologies, tend not to take students' representational competencies into account. Second, they can adapt only to verbally mediated forms of knowledge (e.g., conceptual competencies), but not to non-verbal forms of knowledge (i.e., perceptual competencies). Third, they do not take into account how the social context affects learning with representations. Thus, my research bridges social, perceptual, and conceptual factors of learning with external representations.

