Sequencing Sense-Making and Fluency-Building Support for Connection Making between Multiple Graphical Representations

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Abstract: Multiple graphical representations can significantly improve learning, provided that students make connections between them. In doing so, they need to engage in sense-making processes to build up conceptual understanding of the connections, and in fluency-building processes to fast and effortlessly use perceptual properties to make connections. We investigate how these learning processes interact, and consequently, which learning process should be supported first. We contrast two hypotheses: (1) conceptual understanding facilitates fluency-building processes, and (2) fluency enhances sense-making processes. We conducted an experiment to investigate whether students learn better if they receive sense-making before fluency-building support, or fluency-building before sense-making support. We assessed students' learning outcomes, problem-solving behaviors, conceptual reasoning, and visual attention. Our results show an advantage for supporting sense-making processes before fluency-building processes rather than vice versa. We conclude that instructional materials with multiple representations should first support sense-making processes and then support fluency-building processes in connection making.

Introduction

Instructional materials in science, technology, engineering, and mathematics (STEM) domains often employ multiple graphical representations (e.g., circles and number lines of fractions, ball-and-stick figures and skeleton drawings of molecules), which use visual and perceptual elements rather than symbols to communicate information. A vast literature documents that multiple representations can enhance students' learning, provided that students make connections between them (Ainsworth, 2006; Bodemer & Faust, 2006). However, students tend not to spontaneously make connections, but they need to be supported in doing so (Bodemer & Faust, 2006).

In any domain, learning is likely to include sense-making processes and fluency-building processes. Sense-making processes are learning processes that lead to conceptual understanding by explicit and verbal reasoning. Fluency-building processes lead to more automatic knowledge that can be used fast and effortlessly. Accordingly, with respect to connection making between multiple graphical representations, we distinguish between sense-making processes that lead to conceptual understanding of the connections between graphical representations, and fluency-building processes that lead to the ability to fast and effortlessly make connections between them based on their perceptual characteristics.

Most prior research exclusively focused on supporting *sense-making processes* involved in students' conceptual understanding of connections between multiple representations. This research shows that supporting students to make connections based on elements that – across representations – correspond to one another enhances their learning (e.g., Bodemer & Faust, 2006; Seufert & Brünken). Recent research on perceptual learning has investigated the effects of support for *fluency-building processes* in connection making on students' learning (Kellman, Massey, & Son, 2009). In these studies, students learned to find corresponding representations while focusing on perceptual characteristics of the representations, without conceptually reflecting on the connections. Students who received fluency training showed significantly higher learning gains compared to students who did not receive such training (Kellman et al., 2009). However, Kellman and colleagues did not investigate interactions between conceptual understanding of connections and perceptual fluency.

In a prior experiment, we found that both sense-making and fluency-building support is necessary for students' learning from multiple graphical representations of fractions (Rau, Scheines, Aleven, & Rummel, 2013): neither sense-making or fluency-building support alone were effective, but only the combination of sense-making and fluency-building support significantly enhanced students' learning of fractions (compared to a single-representation control group). To gain further insight into the mechanisms of the interaction between sense-making and fluency-building support, we conducted a mediation analysis based on errors students made during the learning phase (Rau et al., 2013). Our findings indicate that conceptual understanding of connections enhanced students' benefit from fluency-building support. We did not, however, find any evidence that fluency in connection making enhanced students' benefit from sense-making support. This prior research leads to the hypothesis that instruction is most effective if we provide students with sense-making before fluency-building support (*understanding-first hypothesis*). By contrast, if fluency enhances students' benefit from sense-making support, we should provide fluency-building before sense-making support (*fluency-first hypothesis*).

In support of the *fluency-first hypothesis*, one might argue that fluency in connection making between representations reduces cognitive load during learning activities with multiple representations (Koedinger et al., 2012). Indeed, Kellman and colleagues (2009) argue that fluency results from automating the perceptual task of connection making, thereby freeing cognitive resources for subsequent activities. Thus, supporting fluency-building processes first may free cognitive resources that students can then invest in making sense of connections between graphical representations. Thus, the fluency-first hypothesis predicts that instruction is most effective if it provides fluency-building support before sense-making support (fluency-sense condition).

By contrast, the *sense-first hypothesis* proposes that conceptual understanding is necessary for students to attend to relevant features of the graphical representations while they work on fluency-building support. Not having conceptual understanding might lead students to employ inefficient learning strategies (e.g., trial and error), which might impede their benefit from fluency-building support. Indeed, education practice guides seem to implicitly agree with this view. For example, according to the NCTM (2010), understanding of fractions representations is expected by grade 5, but the ability to efficiently work with fractions representations is expected later: by grade 8. In sum, the understanding-first hypothesis predicts that instruction is most effective if it provides sense-making support before fluency-building support (sense-fluency condition).

In our prior study (Rau et al., 2013), we consistently provided sense-making support before fluency-building support. Therefore, the understanding-first and fluency-first hypotheses remain untested. Yet, we expect that the temporal sequence of sense-making and fluency-building support should maximize students' benefit from activities designed to support connection making. This question of optimal sequence is of broad relevance because connection making between multiple graphical representations is critical to students' learning of robust domain knowledge in many STEM domains. Furthermore, in investigating this question, our research helps close the gap between studies that have exclusively focused on sense-making support (e.g., Bodemer & Faust, 2006) or exclusively on fluency-building support (e.g., Kellman et al., 2009). In this paper, we present a lab experiment that contrasts the fluency-first hypothesis and the understanding-first hypothesis.

Experimental Study

Experimental Design and Procedure

To investigate these hypotheses, we conducted a lab experiment that contrasted different sequences of sense-making and fluency-building support. We conducted the experiment within the context of the Fractions Tutor: an intelligent tutoring system for fractions (fractions.cs.cmu.edu). The Fractions Tutor supports learning through problem solving with a variety of interactive graphical representations (Figure 1).

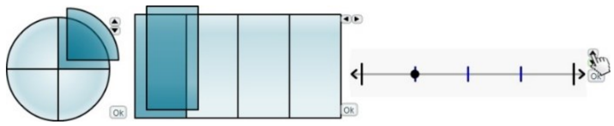

Figure 1. Interactive graphical representations used in the Fractions Tutor: circle, rectangle, and number line

Seventy-four students from grades 3-5 participated in the experiment. Table 1 details the sequence of activities for each condition. Students were randomly assigned to the sense-fluency and the fluency-sense conditions. Both conditions contained the same tutor problems, but they were provided in different orders. Students in the *sense-fluency condition* received sense-making support before fluency-building support. This procedure was implemented for each topic (i.e., equivalence and comparison; see Table 1). By contrast, students in the *fluency-sense condition* received fluency-building support before sense-making support, again for each topic.

The experiment was conducted in two phases. Due to delayed arrival of eye-tracking equipment, 38 students participated in phase 1 of the experiment, without eye tracking. The remaining 36 students worked with the SMI RED 250 remote eye-tracking system. The procedure for phases 1 and 2 was identical except for the collection of interview data (detailed below) and a calibration procedure (1-2 minutes prior to the pretest).

Table 1: Sequence of activities by experimental condition

Activity Type	Sense-fluency condition	Fluency-sense condition
1. Test	Pretest: near / far transfer	Pretest: near / far transfer
2. ***Tutor: equivalence***	***Sense-making support:*** 4 tutor problems	***Fluency-building support:*** 4 tutor problems
	Fluency-building support: 4 tutor problems	***Sense-making support:*** 4 tutor problems
3. Quiz: equivalence	Reproduction-understanding, reproduction-fluency	Reproduction-understanding, reproduction-fluency
4. ***Tutor: comparison***	***Sense-making support:*** 4 tutor problems	***Fluency-building support:*** 4 tutor problems
	Fluency-building support: 4 tutor problems	***Sense-making support:*** 4 tutor problems
5. Quiz: comparison	Reproduction-understanding, reproduction-fluency	Reproduction-understanding, reproduction-fluency
6. Test	Posttest: transfer of fractions knowledge	Posttest: transfer of fractions knowledge
7. Interview	Retrospective interview on tutor problems	Retrospective interview on tutor problems

Materials

Students worked with the Fractions Tutor's units on equivalent fractions and fraction comparison topics. Each tutor activity was designed to support either sense-making or fluency-building processes. *Sense-making support* first presented students with a worked example that used a familiar graphical representation (i.e., circle or rectangle) to illustrate how to solve a problem. Students completed the last step of the worked-example problem themselves. Next, with the worked example still on the screen, students solved an analogous problem with a less familiar representation (i.e., the number line). At the end of the problem, students were prompted to relate the two representations to each other. *Fluency-building support* was similar to Kellman and colleagues' (2009) fluency training for perceptual expertise in connection making. Students were presented with a variety of graphical representations and, using drag-and-drop, had to sort them into sets of equivalent fractions, or order them from smallest to largest. Students were encouraged to solve the problems visually rather than computationally.

Assessments

We assessed learning outcomes with respect to reproduction of conceptual understanding, reproduction of fluency, and transfer of fractions knowledge. *Understanding-reproduction* quiz items assessed students' conceptual understanding of connections between graphical representations. *Fluency-reproduction* quiz items assessed students' fluency in making connections. We assessed students' *transfer of fractions knowledge* based using pretests and posttests. The transfer test included test items without graphical representations.

In addition, we assessed *conceptual reasoning* using retrospective interviews. For all students, we randomly selected one problem of each type for retrospective interviews. In phase 1, the interviewer asked the student immediately after completing the problem how he/she solved each problem step. In phase 2, we used eye-gaze recordings as cues for the interviews. Protocols obtained from retrospective interviews were coded for conceptual and surface-level processing of connections between multiple graphical representations, and for conceptual reasoning about fractions (independent of graphical representations), based on a coding scheme used in our prior research (Rau, Rummel, Aleven, Pacilio, & Tunc-Pekkan, 2012).

Further, we assessed visual attention behaviors during the learning phase using eye tracking. To analyze the eye-tracking data, we created areas of interest (AOIs) for each representation presented in the Fractions Tutor problems. We considered *frequency of switching* between different AOIs, which has been used to indicate perceptual integration (e.g., Johnson & Mayer, 2012). We computed the frequency of switching between graphical representations as the number of times a fixation on one AOI was followed by one on a different AOI. Second, we considered the duration of fixation after the first inspection of an AOI. The first inspection of an AOI is considered to indicate initial processing of material (e.g., Mason et al., 2013). The duration of fixations after the first inspection is considered to reflect intentional processing to integrate the information with other information (e.g., Mason et al., 2013). We computed the *duration of second-inspection fixations* on each AOI as the sum of fixations that occurred after the first fixation on AOIs for area models and number lines.

Finally, we collected *errors rates* while students worked with the tutor based on the tutor logs. We considered a step to be correct if the student solved it without hints or errors. We computed error rates separately for equivalence-sense, equivalence-fluency, comparison-sense, and comparison-fluency problems.

Results

Table 2. Frequencies of utterances coded as representation connections and conceptual reasoning

	Sense-fluency condition	**Fluency-sense condition**
1.1. Representation-surface	1	0
1.2. Representation-concept-incorrect	6	2
1.3. Representation-concept-correct	17	14
2. Representation-fluency	108	94
3. Concept-correct	305	245

Five students were excluded because they did not complete the Fractions Tutor or were statistical outliers at the pretest. Thus, we analyzed data from $N = 69$ students ($n = 37$ in sense-fluency, $n = 32$ in fluency-sense).

First, we consider the effects on learning outcomes. The *understanding-first hypothesis* predicts that the sense-fluency condition will outperform the fluency-sense condition on measures of fluency in making connections. We conducted repeated measures ANCOVAs with transfer pretest score and time spent on the Fractions Tutor as covariates and performance on the *reproduction-fluency* quiz, averaged across equivalence and comparison topics, as dependent measure. There was a significant advantage of the sense-fluency condition over the fluency-sense condition, $F(1,65) = 4.52$, $p < .05$, $\eta^2 = .07$. The *fluency-first hypothesis* predicts that the fluency-sense condition will outperform the sense-fluency condition on measures of conceptual understanding of connections. Using performance on the *reproduction-understanding* quiz averaged across equivalence and comparison topics as dependent measure, we found no significant effect of condition ($F < 1$). Both hypotheses predict that the optimal sequence of sense-making and fluency-building support will enhance students' performance on the *transfer test*. Using performance on the *transfer test* as dependent measure, we found a marginally significant interaction of test time with condition, $F(1,66) = 3.76$, $p < .10$, $\eta^2 = .05$, but no significant main effects of condition or test (Fs < 1). A posthoc comparison showed a marginal advantage of the sense-fluency condition at the posttest, $F(1,65) = 3.05$, $p < .10$, $\eta^2 = .05$.

Second, we consider the effects on conceptual reasoning, based on retrospective interviews. Table 2 depicts the number of utterances of representation connections and conceptual reasoning. Interrater reliability between two independent coders on 33% of the transcripts was substantial ($\kappa = .66$). To investigate the effects on the interview measures, we computed chi-square tests. The *understanding-first hypothesis* predicts that the sense-fluency condition will make more connections while reflecting on fluency-building problems than the fluency-sense condition. Using frequency of *representation-fluency* utterances as the dependent measure, we found no significant difference between conditions ($\chi^2 < 1$). The *fluency-first hypothesis* predicts that the fluency-sense condition will make more connections while reflecting on sense-making problems than the sense-fluency condition. Since there were almost no utterances coded as representation-concept-correct connections (see Table 2), a chi-square test on representation-sense utterances was not warranted. Both hypotheses predict that the optimal sequence of sense-making and fluency-building support will result in more *conceptual reasoning* about fractions. Using concept-correct utterances as dependent measures, we found a significant difference between conditions, $\chi^2(1, N = 550) = 6.55$, $p < .05$, with the sense-fluency condition exhibiting more conceptual reasoning than the fluency-sense condition. Finally, fluency-building problems elicited significantly more connection-making utterances than the sense-making problems did, $\chi^2(1, N = 241) = 110.25$, $p < .01$.

Third, we consider effects on visual attention behaviors. Four students were excluded due to a tracking ratio below 70%. Thus, we analyzed data from $N = 24$ students from phase 2 ($n = 12$ in each condition). We conducted repeated measures ANCOVAs with transfer pretest and time spent on the tutor as covariates and visual attention measures on equivalence and comparison problems as dependent variables. The *fluency-first hypothesis* predicts that the fluency-sense condition will exhibit more integrative eye-gaze behaviors while working on sense-making problems. Using frequency of switching as dependent measures, we found no main effect of condition, $F(1, 21) = 1.11$, $p > .10$, but a significant main effect of topic, $F(1, 21) = 11.19$, $p < .01$, $\eta^2 = .35$, and a marginal interaction of topic with condition, $F(1, 21) = 4.09$, $p < .10$, $\eta^2 = .16$. Post-hoc comparisons showed that the fluency-sense condition switches marginally more frequently between representations on equivalence-sense problems, $F(1, 21) = 3.53$, $p < .10$, $\eta^2 = .14$, but not on comparison-sense problems ($F < 1$). Using duration of second-inspection fixations as dependent measures, we found a significant main effect of condition, $F(1, 21) = 4.43$, $p < .05$, $\eta^2 = .17$, and a significant interaction of topic with condition, $F(1, 21) = 7.09$, $p < .05$, but no significant main effect of topic ($F < 1$). Post-hoc comparisons showed that the sense-fluency condition exhibits significantly longer second-inspection fixations on area models on comparison-sense problems, $F(1, 21) = 5.95$, $p < .01$, $\eta^2 = .22$, but not on equivalence-sense problems, $F(1, 21) = 1.43$, $p > .10$. There were no significant effects of condition on duration of second-inspection fixations on number lines (ps > .10). The *understanding-first hypothesis* predicts that the sense-fluency condition will exhibit more integrative eye-gaze behaviors while working on the fluency-building problems. Using eye-gaze measures collected while students worked on fluency-building problems, we found no significant differences between conditions (Fs < 1).

Finally, to better understand the effects on visual attention behaviors, we computed correlations with the error rates on equivalence-sense and comparison-sense problems. Frequency of switching on equivalence-sense problems correlated positively with students' error rates ($r = .358$, $p < .10$), indicating that a higher frequency of switching is associated with lower problem-solving performance. Duration of second-inspection fixations on area models on comparison-sense problems correlated negatively with students' error rates ($r = -.357$, $p < .10$), indicating that shorter fixations are associated with higher problem-solving performance.

Discussion and Conclusion

We conducted an experiment to contrast the *understanding-first* and the *fluency-first hypotheses.* Results from the *learning outcomes* provide some support for the understanding-first hypothesis. The sense-fluency condition significantly outperformed the fluency-sense condition on the reproduction-fluency quiz and marginally on the transfer posttest. By contrast, our results do not support the fluency-first hypothesis.

The analysis of *process-level measures* provides insights into the mechanisms that may underlie the advantage of the sense-fluency condition. First, the analysis of the *retrospective interviews* shows that the sense-fluency condition engages in more conceptual reasoning than the fluency-sense condition. We also found that fluency-building support elicits significantly more connection-making utterances than sense-making support. (These types of activities involve a large number of representations, and may simply afford greater opportunity for connection making.) A reasonable interpretation of these findings may be that the combination of sense-making and fluency-building support is effective because fluency-building support aids students in making a large number of explicit connections between graphical representations. However, only when students receive sense-making support *before* fluency-building support might they be able to take advantage fluency-building support because they can integrate the perceptual knowledge with conceptual understanding.

The analysis of the *eye-tracking data* provides somewhat less conclusive insights. We found differences only on sense-making problems, not on fluency-building problems. Seemingly consistent with the fluency-first hypothesis, students in the fluency-sense condition (compared to the sense-fluency condition) switched more frequently between representations on equivalence-sense problems. Although frequency of switching is often considered to indicate integrative processing (e.g., Johnson & Mayer, 2012), we found that frequency of switching is (marginally) associated with lower performance on these problems. Rather than indicating integration across representations, frequency of switching may indicate confusion. Inconsistent with the fluency-first hypothesis, the fluency-sense condition shows shorter second-inspection fixations on area models than students in the sense-fluency condition on comparison-sense problems. Shorter second-inspection fixations on area models were associated with lower performance on these problems. This finding might indicate that receiving fluency-building support before sense-making support inhibits students' integration of new information with the area models. These interpretations of the eye-tracking data remain speculative, but they illustrate that we do not yet fully understand which measures of visual attention to consider, or whether they indicate productive or unproductive learning processes. It is crucial, therefore, that we explore the relationship between measures of visual attention and measures of other learning processes, such as the error rates we collected in our study.

In summary, our findings provide some support for the understanding-first hypothesis. Although our results were not uniformly strong, a reasonable interpretation may be that understanding of connections between representations *is necessary* for students' benefit from fluency-building support because it enables students to relate connections between representations to conceptual knowledge about fractions. Thus, we cautiously recommend that instructional designers of multi-representational learning materials provide sense-making *before* fluency-building support to enhance students' acquisition of fluency in connection making and of robust domain knowledge that transfers to novel task types. Whether or not these conclusions hold for other domains than fractions learning remains to be empirically tested. We consider our study to be a first step towards closing the gap between research that has exclusively focused on sense-making processes in connection making (e.g., Bodemer & Faust, 2006) and studies that have mainly focused on perceptual fluency in connection making (e.g., Kellman et al., 2009). Since many STEM domains employ multiple graphical representations and emphasize the importance of both conceptual understanding of the connections between these representations as well as the ability to fluently make connections between them, we anticipate that future research that investigates the interaction between sense-making and fluency-building processes will have broad impact to many domains.

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