Representational-Competency Supports in an Educational Video Game

Tiffany Herder*, Martina Rau

Department of Educational Psychology – Learning Sciences, University of Wisconsin-Madison, Madison, United States

*Corresponding author. Department of Educational Psychology – Learning Sciences, University of Wisconsin-Madison: 1025 W Johnson St, Madison, WI 53706, United States. Email address: therder@wisc.edu (T. Herder)

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Representational-Competency Supports in the Context of an Educational Video Game

Abstract: Educational video games can engage students in authentic STEM practices, which often involve visual representations. Specifically, because most interactions within video games are mediated through visual representations, video games provide opportunities for students to experience disciplinary practices with visuals. However, prior research has not investigated how students learn from visuals within games. Prior research on learning with visuals in non-game contexts suggests that visuals may confuse students if they lack prerequisite representational competencies which include sense-making competencies and perceptual fluency. Sense-making competencies allow students to relate visual features of a representation to the discipline-specific concepts they show and to explain connections between multiple visuals based on conceptual mappings. Perceptual fluency allows students to quickly and effortlessly extract relevant information from visuals and to fluently translate among different representational systems. To address this gap, we investigated the role of representational competencies for students' learning from educational video games. We conducted a 2x2 factor experiment with 120 participants to investigate the effects of sense-making and perceptual-fluency supports within the context of an educational video game. Results showed that sense-making supports did not enhance players' content learning. Further, perceptual-fluency supports enhanced players' content learning outcomes but only when they had high prior astronomy knowledge. Hence, interventions that support representational competencies in non-game environments may work differently in the context of educational video games. This suggests that designers of educational games may need to develop new strategies to support students' learning with disciplinary visual representations.

Keywords: representational competencies, educational video games, sense-making

1. Introduction

Educational video games are powerful tools that can engage students in authentic practices of STEM disciplines (Clark et al, 2009). These practices often include the use of visual representations to solve problems and communicate with others (Airey & Linder, 2009). Prior research shows that visual representations can confuse students unless they have prerequisite representational competencies (Ainsworth, 2006; Kozma & Russell, 2005; Rau, 2017). These competencies include the ability to make sense of how visual representations show relevant information and to fluently perceive disciplinary-relevant information in them (Rau, 2017). Further, this line of research shows that students' learning of disciplinary knowledge can be enhanced if they receive instructional support for these representational competencies while interacting with visuals (Bodemer, Ploetzner, Bruchmüller, & Häcker, 2005; Rau, 2017).

However, prior research on representational competencies focused on highly structured learning environments, whereas video games are informal learning environments (National Research Council, 2011). Structured environments are designed to purposefully engage students with visuals in ways that encourage reflection, whereas video games aim to intuitively engage students with visuals without requiring reflection (Virk, Clark, & Sengupta, 2015). Further, structured environments often incorporate multiple visual representations in a primarily non-visual environment such as a classroom or textbook, whereas video games are multi-representational at their core (Virk, Clark, & Sengupta, 2015). Therefore, it is unclear whether findings from this prior research generalize to educational video games. Indeed, we found few studies that investigated the role of representational competencies for students' learning with visuals in video games or whether students need support for these competencies to enhance their learning from video games. We summarize these studies in section 2.1.

To address this gap, we conducted a lab experiment that investigated whether an intervention shown to enhance learning with visuals in non-game contexts would enhance students' learning of representational competencies and content knowledge from the game. Our findings yield novel insights into how representational competencies affect learning in informal educational contexts and have implications for the design of educational video games.

2. Theoretical background

In the following, we briefly review prior research on visual representations in educational video games and in non-game structured learning environments to highlight the gap we seek to address.

2.1 Visual representations in educational video games

Defining educational video games is not straightforward, in part, because platforms differ in terms of their game-like features (De Freitas & Oliver, 2006). For our study, we define *games* as interactive experiences that model disciplinary phenomena of interest, allow students to take actions that impact aspects of the phenomena, and incorporate goals and ongoing feedback for measuring progress (Clark et al, 2009). Further, we focus on *video* games that are played via computers, gaming platforms (e.g., Xbox), or other digital devices (e.g., smart phones) (Gee, 2003). Finally, we focus on *educational* video games that are specifically designed to achieve learning goals, as opposed to recreational games designed purely for entertainment (Belanich et al, 2009).

By definition, video games are highly visual, and one of their strengths is that they can engage students in disciplinary practices that involve interactions with visuals (Clark et al, 2009). Many STEM disciplinary practices centrally involve the ability to use visual representations to solve problems and communicate with others both verbally and non-verbally (Airey & Linder, 2009; Rau, 2017). Indeed, scientists in multiple disciplines use visuals to make abstract concepts visible, predict and explain scientific phenomena, and communicate ideas within their community of practice (Gilbert, 2008; Kozma & Russel, 2005). For example, astronomers use visual tools, such as line emission spectra (see Figure 1) to determine the compounds present in celestial bodies. Hence, an important goal of educational video games is to immerse students in disciplinary practices with visuals (Virk, Clark, & Sengupta, 2015). The present study focuses on those visuals within games that serve as disciplinary tools (e.g., line emission spectra), as opposed to visuals that purely serve to engage students with the game environment (e.g., a spaceship) or to navigate the game (e.g., a map of the environment).

Figure 1. Line Emission Spectrum: The series of lines indicate the elemental composition of the material streaming off a comet.

While little prior research specifically focused on the role of disciplinary visuals in educational video games, our review of the literature identified several ways in which visuals may enhance students' learning within games. First, we found that educational video games include visuals that allow students to see and interact with abstract concepts within the discipline (e.g., speed of light; Kortemeyer, Tan, & Schirra, 2013). Second, visuals support students' deep conceptual understanding and development of flexible mental models related to disciplinary phenomena (e.g., DNA encoding; Corredor, Gaydos, & Squire, 2014). Third, because the visuals mimic tools used within the discipline, they serve to enculturate students into disciplinary practices (e.g., modeling physical phenomena based on data; Sengupta, Krinks, & Clark, 2015).

Our review also identified several obstacles that could reduce students' ability to achieve these learning goals. First, some games (e.g., Anetta et al, 2013) place high demands on students to learn gameplay conventions and navigation, which may impede their ability to invest cognitive effort into making sense of disciplinary visuals. Second, prior research suggests that this multitude of visuals may cause students difficulties to distinguish between visuals relevant to disciplinary learning and visuals that purely support gameplay (e.g. Lim, Nonis, & Hedberg, 2006). Finally, in some games, disciplinary visuals are incorporated into passive components of the game (e.g., students may view but not interact with an animation), which have been shown to be less effective than disciplinary visuals that students actively manipulate (e.g., Anderson & Barnett, 2013).

2.2 Visual representations in structured learning environments

Our review of visual representations in educational video games parallels findings from prior research on visuals in structured learning environments. That is, this research shows that visual representations can enhance students' learning because they visualize abstract concepts, allow for modeling of discipline-relevant processes, and enable students to participate in disciplinary practices (Gilbert, 2008; Rau, 2017).

This line of prior research also identified several obstacles that could impede students' learning with visuals, which also parallel our review. Specifically, making sense of visuals is cognitively demanding, especially when students must connect multiple visuals (Ainsworth, Bibby, & Wood, 2002; Rau, 2017). Further, students tend to have difficulties distinguishing relevant visual features from irrelevant ones (Goldstone & Son, 2005). Finally, students tend not to make sense of visuals unless they must actively manipulate them (Bodemer et al., 2005).

In contrast to the video games literature, this line of research has investigated how students could overcome these obstacles. Several studies show that a lack of learning from visual representations is, to a large part, caused by a lack of representational competencies (Ainsworth, 2006; Rau, 2017). Specifically, students need two broad types of representational competencies—sense-making competencies and perceptual fluency (Kellman & Massey, 2013; Rau, 2017).

Sense-making competencies allow students to relate visual features of a representation to the discipline-specific concepts they show and to explain connections between multiple visuals based on conceptual mappings (Ainsworth, 2006; Seufert, 2003). For example, when learning about radial velocity in astronomy, students must understand the concepts underlying each visual representation and connect multiple visual representations as illustrated in Figure 2. In this case, students must understand that the given equation for the doppler shift models the relationship between the blueshift and redshift illustrated in the electromagnetic spectrum and the distance towards or away from a point in space illustrated in the graph (Franknoi, Morrison, & Wolff, 2017). Students gain these sense-making competencies through verbally mediated processes such as self-explanations (Rau, 2017). Students engage in these sense-making processes when they actively explain the relationships between visual representations and relevant disciplinary concepts (Chi et al, 1989; Koedinger, Corbett, & Perfetti, 2012).

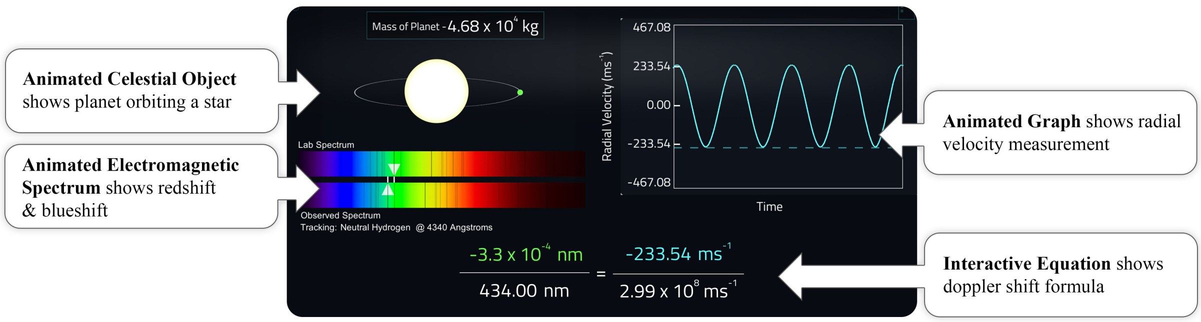

Figure 2. Multiple representations showing radial velocity.

In contrast, perceptual fluency allows students to quickly and effortlessly extract relevant information from visuals and to fluently translate among different representational systems (Kellman & Massey, 2013; Rau, 2017). For instance, in astronomy, students must gain proficiency matching observed spectra with lab spectra to determine critical properties of celestial bodies. Figure 3 illustrates an example of matching spectra to identify a corresponding element. Perceptual fluency is a skill that is not often addressed in educational contexts (Kellman & Massey, 2013). Nevertheless, this skill is critical to enable students to automatically process visuals and free up cognitive resources for more complex thinking processes such as problem solving (Goldstone & Barsalou, 1998; Richman, Gobet, Staszewski, & Simon, 1996) and, subsequently, enhance disciplinary learning (Gilbert, 2005; Taber, 2014).

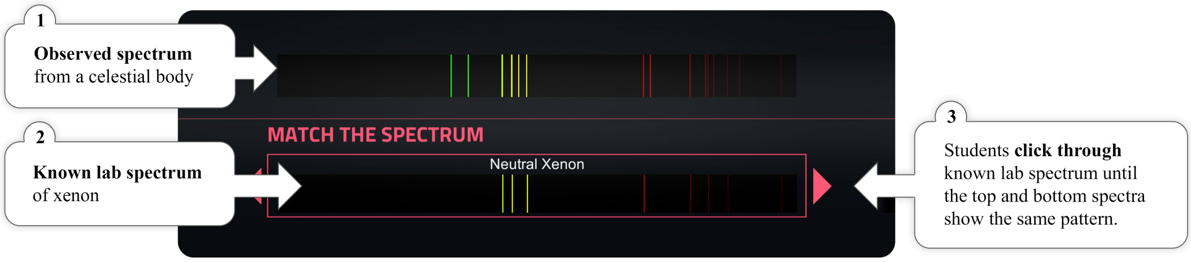

Figure 3. Spectra Visual Representations: 1) Students view a spectrum observed from a celestial body which contains multiple elements. 2) Because each element has a unique signature, they can then select a lab spectrum that matches the observed spectrum to 3) identify an element present in a celestial body. In this case, the matching spectra indicate there is Xenon present in the Crab Nebula.

Students gain perceptual fluency through non-verbal, inductive learning processes that rely on pattern recognition (Rau, 2017), which is fundamentally different from the effortful and conscious processes that lead to sense-making competencies, described above. Further, the verbal processing and explicit thinking that goes along with students' sense-making processes may disrupt students' perceptual learning processes (Rau, 2017; Schooler, Fiore, & Brandimonte, 1997). Thus, cognitive learning theories show that students engage in perceptual-fluency processes when they attempt to quickly and efficiently recognize and classify disciplinary content shown in visual representations (Kellman & Garrigan, 2009). Alternatively, disciplinary practice theories argue that students engage in perceptual-fluency processes while observing and participating in communication practices such as through nonverbal gestures (Singer, 2017) or the use of visual representations for verbal communication (Braden & Hortin, 1982). By participating in this discourse, students are immersed multimodally into a discipline (Airey & Linder, 2009; Schonborn & Anderson, 2006) and, thus, induce patterns of practice and relationships among visual representations and disciplinary problems (Rau, 2017; Wertsch & Kazak, 2011).

Further, this line of prior research has established design principles for the support of these representational competencies. To support sense-making competencies, instruction should encourage students to actively establish mappings between visual representations and the concepts they show while explaining these connections (Bodemer et al., 2005; Seufert, 2003). This can be accomplished through reflective prompts, prompts to draw, or prompts to discuss the mappings with a partner (Fiorella & Mayer, 2015).

Because perceptual-fluency processes are fundamentally different than sense-making processes, the types of activities that support perceptual fluency are also fundamentally different. Unlike the explicit and verbal instruction that supports sense-making, perceptual-fluency supports are implicit and nonverbal forms of instruction. To support perceptual fluency, instruction should expose students to numerous example visuals that are sequenced in ways that contrast relevant features while prompting students to solve the visual tasks quickly without explaining them (Kellman & Massey, 2013). For example, activities may prompt students to categorize systematically varied examples (Rau, Michaelis, & Fay, 2015) or rapidly construct disciplinary visual representations (Eastwood, 2013). Further, feedback should be given on the accuracy of their responses but should not provide explanatory feedback that may engage students' verbal processes (Rau et al, 2021).

Prior research shows that combining these two types of instructional support for sense-making and perceptual-fluency competencies enhances students' learning of disciplinary knowledge from structured learning environments (Rau, 2017). Further, sense-making competencies should be supported prior to perceptual-fluency competencies so students learn which visual features are conceptually relevant before engaging in pattern recognition across varied examples (Rau, 2018).

3. Research question

Our brief review shows that prior research on visual representations in educational video games and structured learning environments reveals parallel educational goals and obstacles. However, to our knowledge, interventions that overcome these obstacles by supporting students' representational competencies are purely based on research on structured learning environments. Therefore, it is unknown whether the representational-competency supports that are effective in structured learning environments also enhance learning with visual representations in educational video games. To close this gap, we address the following research question: Do representational-competency supports enhance students' learning from an astronomy educational video game? We addressed this question with a 2 (sense-making support: yes v no) x 2 (perceptual-fluency support: yes v no) lab study design.

4. Methods

4.1. Video game

We chose a game for our study that has the explicit goal to enable students to make sense of connections among multiple visual representations of astronomical phenomena (Gear Learning, 2019): At Play in the Cosmos. In the game, students become contractors for a corporation interested in resource mining in space. Through guided missions, students explore various galaxies and acquire needed resources to meet contracts for the corporation. One major goal of the game is for students to become familiar with how and why astronomers use tools (e.g., line emission spectra, see Figure 1) to understand the universe and its evolution. The visuals in the game allow students to gather information about celestial objects (Gear Learning, 2019). Consistent with introductory astronomy courses, this design is meant to enable students to focus on learning concepts related to measuring celestial objects such as luminosity without having to compute mathematical formulas (e.g. Radial Velocity Tool, see Figure 2). Further, the game aims at helping students connect visuals to equations that describe the same concepts.

4.1.1. Visual representations. A critical tool within astronomy is the electromagnetic spectrum. The spectrum represents the radiation given off by objects in space (Franknoi, Morrison, & Wolff, 2017). Astronomers use spectra to identify critical properties of celestial bodies (Barder, Prather, Breecher, & Slater, 2005). Two tools within the game, in particular, engage students in this disciplinary visual—the Spectrum Analyzer (Figure 3) and the Radial Velocity Tool (Figure 2). Students use the Spectrum Analyzer to match observed spectra to laboratory spectra to determine the properties of celestial objects. For instance, students travel to Supernova 1987A to determine if sodium gas is present in its ejecta (Bary, 2017). Students interact with this visual by clicking through multiple labeled spectra from a database until they find the one that matches the observed spectra. If students choose the incorrect spectrum, they receive simple feedback that the spectra do not match and are encouraged to try again. If students choose the correct spectrum, they move forward in the mission and the narrative.

Within the game, students use the Radial Velocity Tool to determine the presence of planets orbiting stars. For instance, students use this tool to identify a habitable planet within the Milky Way galaxy. While using the tool, students are prompted to complete a walkthrough of the process. First, they click "measure," and the tool provides the calculation of the difference between the actual and measured wavelengths. Then, students drag the resulting value to the position in the equation that matches the color of the value. Next, the tool calculates the rest of the values in the equation and provides a final output of the mass of the planet and moves them forward in the narrative. The first three times players use a tool, they are provided this type of step-by-step walkthrough.

Both the Spectrum Analyzer and the Radial Velocity Tool described here as well as the other tools within the game seem to align with perceptual-fluency supports in Section 2.2. This design seems to prompt players to rely on their intuitions, provides simple feedback on accuracy, and exposes the player to numerous examples using these tools throughout the missions. Because of these features, it seems like the game supports the implicit, nonverbal learning processes of perceptual fluency rather than explicit, verbal learning processes of sense-making in the interactions with the visuals in the game.

4.2. Participants

We recruited 142 undergraduates from a large United States Midwestern university using email and flyers for monetary compensation or extra credit. Recruitment focused on students who had not previously taken an introductory astronomy course at the undergraduate level. This minimum requirement aligned the participants with those students who would typically play the game. We also did not include students currently taking an introductory course to focus participants' learning gains on the game and support conditions rather than the combination of the game and supports with additional pedagogical elements within a classroom context. Sessions were conducted individually in a private room on campus. Twenty-two participants were excluded from the results due to not finishing all required components of the study. This resulted in a final participant count of $N = 120$.

4.3. Experimental design

We used a 2 (sense-making prompts: yes v no) x 2 (perceptual-fluency prompts: yes v no) experimental design that created four conditions. Participants were randomly assigned to one of four conditions: (a) sense-making, (b) perceptual fluency, (c) combined sense-making and perceptual fluency, and (d) control. The control group received no support for representational competencies while playing the game and instead received information related to general or technical aspects of the game. The other conditions received support for sense-making, perceptual fluency, or both representational competencies while playing the game.

Participants received supports as videos and verbal prompts. Prior to beginning and at intervals during gameplay at each session, participants viewed videos modelling interactions with the game related to their condition. Participants in the control condition viewed videos that introduced features of the game, discussed the benefits of educational video games, and provided step-by-step technical processes for interacting with tools within the game. For support conditions, participants viewed videos that introduced them to key visuals in the game and provided step-by-step processes for interacting with the visuals. Each video was approximately two minutes long.

Participants also received verbal prompts phrased as reminders about the information from the videos one additional time per mission when they began using the first tool. Verbal prompts used language similar to the videos and were meant to remind participants to use the processes outlined in the videos. Control prompts were meant to control for any potential effects of the reminders to the participants' gameplay experience. Table 1 provides example verbal prompts for each condition for Mission 1.

Table 1. Example Prompts for Mission 1

Condition	Verbal Prompt
Control	I just wanted to remind you that you are currently using the spectrum analyzer tool. You are using this tool to find sodium in Supernova 1987A. Follow the instructions that CORI provides to interact with the tool.
Sense-Making	I just wanted to remind you to take your time as you're interacting with the tools. For this one, interpret each spectrum, compare each pair of spectra, and then interpret the comparison carefully before selecting the correct answer.
Perceptual Fluency	Remember to focus on your intuitions as you interact with the tool. Quickly click through the spectra and confirm match selection as soon as you "see" a match. It's ok if you don't get it right the first time.
Combined	Same as Sense-Making

The videos and verbal prompts were designed based on the prior research about instructional designs that support representational competencies described in Section 2.2. Specifically, sense-making support instructed students to engage with the visual representations in a three-step process. Students were asked to first interpret each visual, then compare pairs of visuals, and finally, explain the comparison in reference to astronomy concepts. For example, students were asked to interpret what a line emission spectrum showed (see Figure 1), compare similarities and differences to another spectrum, and then explain what the comparison indicates about the presence of a substance in a star.

Perceptual-fluency support instructed students to train their ability to use the visuals quickly to make decisions within the game. To this end, students were asked not to overthink the visuals, to focus on speed, rely on their intuitions about a match, and to accept mistakes. Because prior research showed that sense-making support should be provided before perceptual-fluency support (Rau, 2018), participants in the combined condition received sense-making support the first time they used a tool and perceptual-fluency support for subsequent uses of the same tool. For example, in session 1, participants first received sense-making support for the spectrum analyzer and halfway through the session they received perceptual-fluency support related to the same tool.

4.4. Measures

We assessed students' learning of astronomy content, sense-making competencies, and perceptual fluency with three isomorphic versions of a test for a pre-test and two post-tests. We counterbalanced the order of the test versions across test times.

The sense-making test assessed students' ability to relate visual features of a representation to the discipline-specific concepts they show and to explain connections between multiple visuals. This test included four items with four separate parts. First, students were presented with two images of electromagnetic spectra—one labeled with an element and one unlabeled (similar to Figure 3) and asked if they matched. Next, students were asked how they knew the spectra did or did not match. Then, students were asked what they could infer about the unlabeled spectra given the relationship between the two visuals. Finally, students were asked how they determined whether the spectra matched or not. Each question part was worth 1 point for a total of 16 possible points. We computed the sum of the correct items for a sense-making outcome score for each student for each test time.

The perceptual-fluency test assessed students' ability to quickly match multiple visuals. This test included six items. In each item, students were presented with an image of the electromagnetic spectrum and four choices to select the matching image. Each correct question was worth 1 point for a total of 6 possible points. For each student for each test time, we computed a time efficiency score by dividing the total correct items by the sum of the duration of time the participant took to complete the items (Van Gog & Paas, 2008).

The content test focused on the use of specific visuals within the game and the underlying astronomy concepts. These questions addressed key visuals and their uses within astronomy including the electromagnetic spectrum and radial velocity. This test included 16 items with four multiple choice items and 12 open-ended questions. We computed the sum of the correct items for a content outcome score for each student for each test time.

Participants also completed the Vandenberg and Kuse *Mental Rotation Test (MRT)* (Peters et al, 1995) to measure their spatial ability prior to playing the game. We chose this test because it has been used in prior research with visual representations in chemistry (Stieff, 2007; Stull, Hegarty, Dixon, & Stieff, 2012) as well as shown to correlate with astronomy abilities (Heyer, Slater, & Slater, 2013).

After completing each mission, participants answered two questions related to their perceived cognitive load adapted from the Schmeck, Opferman, van Gog, Pass, and Leutner (2013) *cognitive load measure*. Participants were asked (1) How much mental effort did you invest in this mission? and (2) How difficult did you perceive this mission to be? Because the test was given verbally, we changed the scale of the questions from seven points to ten points to align with participants' previous experiences of verbal scales such as during doctor visits.

4.5. Procedure

The study involved two sessions approximately 1-5 days apart. During Session 1, participants completed the pre-test and a Mental Rotation Test (MRT), watched a video, played Missions 1-3, watched another video, played Missions 4-5, and took post-test 1. In Session 2, students watched a video, played Missions 6-7, watched another video, played Mission 8, watched the final video, played Missions 12-13, took post-test 2, completed a short interview, and took a survey. While they played, participants also received verbal reminders related to their condition during each mission except for Mission 13. After each mission, participants answered the two questions related to their perceived cognitive load outlined in Section 4.4.

5. Results

We excluded 5 participants from the analysis because their scores on our main outcome variable—the content outcome scores—for the pre-test, post-test 1, or post-test 2 were statistical outliers. This resulted in a final sample of $N = 115$. In the following analyses, we report d for effect sizes. According to Cohen (1988), an effect size d of .20 corresponds to a small effect, .50 to a medium effect, and .80 to a large effect. With 115 participants, pre-test and Mental Rotation Test (MRT) covariates, $\alpha = .05$ and $\beta = .20$ power of .80, and four groups, our study was sensitive to effect sizes of at least $d = 0.264$. Table 2 shows the means and standard deviations for each outcome score—sense-making, perceptual fluency, and content—by condition.

Table 2. Means (standard deviations) for the each outcome score by condition and test time.

	Control Condition	*Sense-Making Condition*	*Perceptual-Fluency Condition*	*Combined Condition*
Sense-Making Outcome Scores				
Pretest	8.85 (2.755)	7.76 (3.280)	8.50 (2.789)	7.45 (2.971)
Post-Test 1	10.00 (2.094)	9.10 (2.858)	8.53 (2.874)	8.97 (2.542)
Post-Test 2	10.85 (1.634)	9.31 (2.892)	9.33 (2.820)	9.17 (2.687)
Perceptual-Fluency Outcome Scores				
Pretest	0.00 (1.033)	-0.21 (1.171)	0.28 (1.049)	-0.23 (1.396)
Post-Test 1	-0.05 (0.808)	-0.15 (0.899)	0.26 (0.707)	0.08 (0.801)
Post-Test 2	0.11 (0.664)	0.21 (0.465)	0.32 (0.532)	0.26 (0.620)
Content Outcome Scores				
Pretest	2.81 (1.178)	2.90 (1.496)	2.77 (1.278)	2.69 (1.466)
Post-Test 1	5.85 (1.791)	5.45 (1.617)	5.33 (1.826)	5.21 (1.449)
Post-Test 2	7.41 (1.803)	7.21 (2.007)	6.57 (2.315)	6.31 (2.661)

5.1. Manipulation checks

First, we checked for differences between conditions on the pre-tests and the mental rotation test (MRT). A MANOVA showed no significant differences between conditions on the content pre-test, sense-making pre-test, perceptual-fluency pre-test, nor the MRT, ($F < 1$). The content pre-test and the MRT correlated significantly with participants' scores on the content post-tests ($r = .373$, $p < .001$ for pretest with post-test 1, $r = .455$, $p < .001$ for pretest with post-test 2, $r = .333$, $p < .001$ for MRT with post-test 1, $r = .460$, $p < .001$ for MRT with post-test 2). Therefore, both the content pre-test and MRT were included as covariates.

Second, we checked for learning gains using repeated measures ANOVAs with test scores as dependent measures and test-time (pretest, post-test 1, and post-test 2) as the repeated, within-subjects factor. We found significant gains on the content outcome scores, $F(2, 113) = 282.552$, $p < .001$, $d = 1.576$ and sense-making outcome scores, $F(2, 113) = 20.097$, $p < .001$, $d = 0.420$. However, we found no significant learning gains on the perceptual-fluency outcome scores, $F(2,113) = 2.874$, $p = .059$.

Third, we checked that sense-making supports enhanced participants' sense-making competencies. We used a repeated measures ANCOVA with scores on the sense-making post-tests as dependent measures, sense-making as the between-subjects factor, test-time (post-test 1 and post-test 2) as within-subjects factor, and sense-making pre-test score as the covariate. The perceptual-fluency pre-test was a significant predicator, so we added it as a covariate in the model. Results showed no main effect of sense-making supports on the sense-making post-tests, ($F < 1$).

Finally, we checked that perceptual-fluency supports enhanced participants' perceptual fluency. We used a repeated measures ANCOVA with scores on the perceptual-fluency post-tests as dependent measures, perceptual-fluency as the between-subjects factor, test-time (post-test 1 and post-test 2) as the within-subjects factor, and the perceptual-fluency pre-test score as the covariate. The sense-making pretest and the sense-making factor were significant predictors, so we added them as covariates to the model. Results showed a significant positive effect of the perceptual-fluency factor on perceptual-fluency post-tests, $F(1, 114) = 5.873$, $p = .017$, $d = 0.234$.

5.2. Effects of representational-competency support on astronomy learning

To test for the effects of the representational-competency supports on participants' astronomy content learning, we used a repeated measures ANCOVA with scores on content post-tests as the dependent measures, test-time (post-test 1 and post-test 2) as the repeated, within-subjects factor, sense-making and perceptual fluency as between-subjects factors, and content pre-test and MRT scores as the covariates.

To construct the ANOVA model, we used the following stepwise approach. First, we tested the combined effects of the representational-competency supports with an interaction of the sense-making and perceptual-fluency factors. Next, we tested the effects of prior representational competencies with interactions of the sense-making and perceptual-fluency pre-tests with the sense-making and perceptual-fluency factors. Then, we tested the effects of prior spatial skills with interactions of the sense-making and perceptual-fluency supports with the mental rotation test (MRT). Then, we tested the effects of cognitive load with interactions of the sense-making and perceptual-fluency factors with the overall cognitive load measure. Finally, we tested the effects of prior astronomy knowledge with interactions of the sense-making and perceptual-fluency factors with the content pre-test scores. None of these interactions were significant ($F < 1$) except for the interaction of the perceptual-fluency factor with content pre-test scores, so we only included this interaction in the final ANCOVA model. Content pre-test scores, sense-making pre-test scores, and overall cognitive load were significant predictors, so they were included in the final ANCOVA model.

With respect to our research question, do representational-competency supports enhance students' learning from an astronomy educational video game, results showed no significant main effect of the sense-making factor, ($F < 1$). However, results showed a significant main effect of the perceptual-fluency factor, $F(1, 114) = 8.814$, $p = .004$, $d = .289$. The main-effect of the perceptual-fluency factor was qualified by a significant interaction between the perceptual-fluency factor and the content pretest scores, $F(1,114) = 6.693$, $p = .011$, $d = .250$. To examine this interaction, we used post-hoc comparisons that showed that participants with low prior content knowledge performed better on the content post-test 2 when perceptual-fluency supports were *not* present, $F(1,114) = 12.833$, $p = .001$, $d = .348$. Further, participants with high prior content knowledge performed better on the content post-test 2 when perceptual-fluency supports *were* present, $F(1,114) = 3.935$, $p = .050$, $d = .193$.

6. Discussion

Building on prior research on learning with visuals in structured learning environments, we investigated whether representational-competency supports would enhance players' astronomy learning from the visuals in an educational video game. To this end, we compared players of an educational video game with and without sense-making and perceptual-fluency supports in 2 (sense-making support: yes v no) x 2 (perceptual-fluency support: yes v no) factor experiment. Results showed that sense-making supports had no significant effect on players' content post-test scores. We found evidence, however, of a significant main effect of perceptual-fluency support on players' content post-test scores. This effect was moderated by participants' prior astronomy knowledge. Specifically, players with lower prior astronomy knowledge performed better *without* perceptual-fluency support while players with higher prior astronomy knowledge performed better *with* perceptual-fluency support.

Prior research has shown that sense-making supports positively impacted students' content learning in structured learning environments (e.g., Bodemer, Ploetzner, Bruchmüller, & Häcker, 2005; Rau, 2017), so why might those same supports not work within an educational video game? Because our manipulation checks showed that players' sense-making competencies improved over time, we can rule out that the game and the support conditions did not effect players' sense-making competencies. Thus, we see multiple possible reasons for this result. First, one possibility is that the game already supports sense-making competencies. As mentioned previously, the design of the game seems more aligned with perceptual-fluency supports with a focus on corrective rather than explanatory feedback and the use of numerous examples throughout the missions. However, one possible reason for this result is that the design itself prompts players to consciously examine the visual representations. For instance, the first three times players use a tool, the game provides a step-by-step walkthrough to interact with the tool. Although the walkthrough is focused on where to click, it is possible that this scaffolding also prompts players to think more deeply about the connections between multiple representations provided in the tool. This explanation would be in line with prior research in structured learning environments that shows that establishing connections between visual representations encourages students' conceptual understanding of disciplinary content (Gilbert, 2008; Rau, 2017). This built-in support could have improved players' sense-making competency across all conditions, thus resulting in a null main effect of the sense-making support.

Second, it is possible that the control condition with supports related to the educational nature of the game and the step-by-step instructions for using the tools in the game could have prompted sense-making. By reminding players of the educational nature of the game, they could have paid more attention, in general. Because visuals mediate interactions in the game, this general increased attention could mean players paid more attention to the visuals specifically. The focus of the videos on the tools could also have encouraged players to pay more attention to the multiple representations present in these tools. This potential effect could explain why we saw overall learning gains on the measure, but no main effect of the sense-making supports across conditions because the control supports also prompted sense-making.

Third, another explanation is that our version of the sense-making supports was incompatible with the game design. It is possible that when the sense-making supports prompted players to think more deeply about the visual representations, the game did not provide the requisite content to make those connections. For instance, the game did not include information about how the tools work or the conceptual connections between the multiple representations related to astronomy content. Thus, when we asked players to reflect on the visuals, there was no effect beyond what the game may already support. This explanation in in line with prior research that shows that sense-making requires retrieval of relevant disciplinary knowledge to be effective (Ainsworth, 2006).

In contrast, results showed that perceptual-fluency supports had a significant main effect on astronomy content learning. Further, the main effect of perceptual-fluency support was moderated by players' prior astronomy learning such that only those players with high prior astronomy knowledge benefited from the supports. Thus, players needed prior astronomy knowledge to induce the patterns of disciplinary content present in the visual representations when using perceptual fluency processes. This finding is in line with prior research on perceptual fluency, suggesting that perceptual-fluency supports are less effective for students with low prior knowledge (Rau & Herder, Rau et al., 2021).

The effectiveness of the perceptual-fluency support suggests that our version of the perceptual-fluency supports was compatible with the game, as opposed to our version of the sense-making supports. This compatibility could from the game design being more aligned with perceptual-fluency processes than with sense-making processes. Thus, when we asked players to move quickly through the game without overthinking it, they were able to do so easily because the game already encouraged intuitive interactions. At the same time, our results suggest that perceptual-fluency supports enhance students' learning of content above and beyond the game itself. This suggests that the intuitive interactions encouraged by the game were not sufficient in helping students fluently process the visuals, so that taken by itself, the game was not maximally effective for students with high prior knowledge.

Overall, these results show that our implementation of perceptual-fluency support only supported those players with high prior astronomy content knowledge. Further, our implementation of sense-making support did not enhance players' sense-making competence nor their content learning outcomes when paired with an educational video game. Because visuals are ubiquitous in video games and this game as well as many other educational video games focus on novice students, future research is critical for ensuring students' learning with visual representations is supported within educational video games.

7. Limitations and future directions

Our results must be viewed in light of the following limitations. First, our results are based on a single experiment that focused on one educational video game related to astronomy content. We chose *At Play in the Cosmos* because one of the goals of the game is to enable players to make connections between multiple representations of astronomy phenomena. It also uses visuals in multiple ways that are authentic to the discipline and support students' learning about introductory astronomy concepts. Although this game provides a valuable examination of visual representations in educational video games, the design incorporates visuals from a specific discipline in specific ways to support players' gameplay and learning. Thus, it is unclear if the results from this study generalize to other ways of using visual representations, other disciplines, and other educational video games. Future studies should test if our findings generalize beyond the focus of our study.

Second, our lab-based experiment did not provide the context in which educational video games are typically implemented. The methodological choice enabled us to maximize internal validity by controlling for time on task, ensuring participants completed all activities, and providing larger doses of the intervention through prompts during gameplay. However, lab experiments, in general, have lower external validity. Further, prior educational video game research showed that teachers, in particular, play an important role in supporting learning within an educational video game (Clark, Tanner-Smith, & Killingsworth, 2016). Additionally, At Play in the Cosmos was designed as a series of homework assignments for introductory astronomy courses. Future studies should triangulate results between lab settings and classrooms to provide a more holistic understanding of how representational competency supports work within the context of astronomy classrooms and as homework assignments.

Third, our combined condition sequenced representational-competency supports based on prior research in structured learning environments (Rau, 2018). Because our results suggest that principles from structured learning environments are not necessarily applicable to educational video games, it is possible that representational-competency supports should be sequenced differently. Future research should test sequencing effects of representational competency supports in educational video games to test this possibility empirically.

Fourth, our intervention provided prompts during gameplay that may have interrupted participants. Prior studies have examined the impact of flow state for supporting learning from gameplay (Tsai et al, 2016). Such interruption could have reduced an effective support mechanism in the game that may impact participants' use of visuals for learning. This limitation would not compromise the internal validity of the study, however, because all conditions, including the control condition, received these prompts. Future research could examine the role of flow in learning with visual representations by creating alternative versions of representational-competency supports that do not interrupt players and keep this potential support mechanism intact.

8. Conclusion

In sum, our research begins to fill a gap in empirical research that investigates the role of representational competencies for students' learning with visuals in educational video games. Our results show that support for representational competencies that were successful in structured learning environments do not seem to work the same way in the context of educational video games, especially those supports designed to encourage sense-making processes. Thus, our research demonstrates a need to investigate which game designs and supplemental supports enable students' representational competencies and learning with visual representations. If educators want to leverage the power of video games to engage students in authentic STEM practices with visual representations, then more work is needed to understand the prerequisite representational competencies and support students need to be successful in these environments.

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