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Representational-competency supports in the context of an educational video game for undergraduate astronomy

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A R T I C L E I N F O

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A B S T R A C T

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. Research demonstrates, however, that learning from multiple visuals is complex. Prior research in structured environments has demonstrated that providing supports for representational competencies in terms of sense-making competencies and perceptual fluency can support learners, but such research has not been conducted in game environments. To address this gap, we investigated whether supports for representational competencies enhanced students' learning with an astronomy video game. We conducted an experiment with 115 students to investigate the effects of sense-making support (yes vs. no) and perceptual-fluency support (yes vs. no) within an astronomy game. Results showed that sense-making supports did not enhance students' content learning. Further, perceptual-fluency supports enhanced students' content learning outcomes only when they had high content pre-test scores. Hence, interventions that support representational competencies in non-game environments may work differently in the context of educational video games. This suggests that designers may need to develop new strategies to support students' learning with disciplinary visuals in educational games.

1. Introduction

Educational video games are multi-representational learning environments (Virk et al., 2015) that can engage students in authentic practices of STEM disciplines (Clark et al., 2009). These practices often include the use of visual representations for problem solving and communication (Airey & Linder, 2009). While disciplinary visuals play a key role for learning, prior research shows that these visuals 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 the ability to fluently perceive disciplinary-relevant information in them (Rau, 2017). Further, research provides instructional strategies for representational-competency supports to enable students to effectively interact with visuals (Rau & Wu, 2018).

However, prior research on representational competencies and providing relevant supports focused on highly structured learning environments that are qualitatively different from educational video games. While structured environments are designed to purposefully engage students with visuals in ways that encourage reflection, many video games aim to intuitively engage students with

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visuals without necessarily requiring reflection (Virk et al., 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 et al., 2015). Due to these differences, it is unclear whether the effectiveness of instructional supports for representational competencies generalizes to educational video games.

To address this gap, we investigate the following question: Do representational-competency supports enhance students' learning from an astronomy educational video game? We conducted a lab experiment that tested whether instructional supports designed based on research on structured learning environments enhance students' learning of representational competencies and content knowledge from an educational video game. Our findings yield novel insights into how representational competencies affect learning in games and have implications for teaching with and designing educational video games.

In the following, we review the literature that motivates our research question. After presenting the methods and results of our experiment, we discuss our findings with respect to theories of learning with visual representations and recommendations for teaching with and design of educational video games.

2. Theoretical background

Extensive prior research has investigated questions about learning with visual representations in non-game, structured settings. For instance, as detailed below, studies have investigated the competencies involved when students use visuals to understand content (Mayer, 2009; Rau, 2017) and difficulties learning with visual representations (Ainsworth, 2006; Kozma & Russell, 2005; Rau, 2017). Further, a large body of other research has established the effectiveness of video games for learning (Clark et al., 2016; Yu et al., 2021). However, despite the ubiquity of visual representations within video games, few articles address the intersection between these two lines of inquiry. In the following, we briefly review prior research on visual representations in educational video games and in 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; Tahir & Wang, 2020). For our study, we define *games* as interactive experiences that model disciplinary phenomena, 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 specifically designed to achieve learning goals, as opposed to recreational games designed for entertainment (Zhonggen, 2019).

By definition, video games are highly visual, and a strength is their ability to engage students in disciplinary practices that involve interactions with visuals (Clark & Sengupta, 2020). Many STEM disciplinary practices centrally involve the ability to use visual representations to solve problems (Airey & Linder, 2009; Rau, 2017). Indeed, scientists across disciplines use visuals to make abstract concepts visible and explain scientific phenomena (Gilbert, 2008; Kozma & Russell, 2005). For example, astronomers use visual representations such as line emission spectra (Fig. 1) as tools for determining compounds present in celestial bodies. Hence, an important goal of educational video games is to immerse students in disciplinary practices with visuals (Virk & Clark, 2019). The present study focuses on visuals within games that serve as disciplinary tools (e.g., line emission spectra), as opposed to visuals that engage students with the game environment (e.g., a spaceship).

While little prior research has focused on the role of visuals in educational video games, our review of the literature identified several ways in which visuals may enhance students' learning within games. First, visuals may provide a meaningful context for a game within which students interact (e.g., Annetta & Cook, 2007; Garnli et al., 2021). This use of visuals supports learning in games by situating meaning (Mayo, 2009; Nikolopoulou, 2022), creating space for problem solving (Chen, 2018), or providing an immersive environment (Sherin et al., 2016). Second, by supporting meaningful interactions with characters (e.g., Tuzun et al., 2019) and objects (e.g., Mayfield et al., 2019), visuals provide feedback related to students' interactions within a game (e.g., Muehrer et al., 2012). This feedback enables students to iteratively refine conceptual understanding (e.g., Sengupta et al., 2015). Third, through interactions with visuals, students manipulate disciplinary phenomena that are not directly observable. These interactions support learning by allowing students to see and interact with abstract concepts within the discipline (e.g., electrical currents; Kortemeyer et al., 2019). Further, this supports students' deep conceptual understanding and development of flexible mental models related to disciplinary phenomena (e.g., DNA encoding; Corredor et al., 2020).

Our review also identified obstacles that could reduce students' benefit from visuals within games. First, prior research suggests that providing numerous visuals may make it difficult for students to distinguish between visuals relevant to disciplinary learning and visuals that purely support gameplay (e.g., Lim et al., 2006). Second, 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 has been shown to be less effective than disciplinary visuals that students actively manipulate (e.g., Anderson & Barnett, 2013). Third, some games require students to learn

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

gameplay conventions and navigation in a manner that impedes their ability to invest cognitive effort into making sense of disciplinary visuals (e.g., Wang et al., 2022).

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. Specifically, research on structured learning environments shows that visuals 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; Kozma, 2020). For instance, in astronomy, students use visuals to understand the structure and characteristics of celestial objects such as the Orion nebula (Eriksson, 2019) or the Sun and Earth in our solar system (Ampartzaki & Kalogiannakis, 2016).

Further, this prior research identified obstacles that could impede students' learning with visuals, which also parallel our review of research on video games. Specifically, making sense of visuals is cognitively demanding, especially when students must connect multiple visuals (Ainsworth et al., 2002; Rau, 2017). For instance, students have difficulties translating visual features into the disciplinary concepts they illustrate (Change et al., 2021). Further, students have difficulties distinguishing relevant visual features from irrelevant ones (Goldstone & Son, 2005). Specifically, students may focus on surface features of visuals rather than the underlying concepts they represent (Gkitzia et al., 2020). Finally, students tend not to make sense of visuals unless they actively manipulate them (Bodemer et al., 2004). This interaction with visuals enables students to establish the relationships among multiple visual representations (Rau et al, 2021).

Several studies show that a lack of learning from visuals is, to a large part, caused by a lack of representational competencies (Ainsworth, 2006; Rau, 2017). Specifically, students need sense-making competencies and perceptual fluency (Kellman & Massey, 2013; Rau, 2017).

Sense-making competencies describe students' ability to relate visual features to the discipline-specific concepts the visual shows and to explain connections between multiple visuals based on such conceptual mappings (Seufert, 2003). For example, when learning about radial velocity in astronomy, students must understand the concepts underlying each visual and connect multiple visuals as illustrated in Fig. 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 et al., 2017).

Students acquire sense-making competencies through verbally mediated processes (Rau, 2017), which are involved when students actively explain relationships between visuals and relevant disciplinary concepts (Chi et al., 1989; Koedinger et al., 2012). To support sense-making competencies, instruction should encourage students to actively construct mappings between visuals and the concepts they show while explaining these connections (Bodemer et al., 2004). For example, interventions designed to prompt students' connection making lead to more detailed mental models of content (Schnotz et al., 2022). This support can be accomplished through self-explanation prompts or prompts to discuss the mappings with a partner (Fiorella & Mayer, 2016). For example, students may be prompted to explain relationships among concepts while manipulating multiple visuals (Joo et al., 2020).

In contrast, perceptual fluency describes students' ability to quickly extract relevant information from visuals and to fluently translate among different visuals (Kellman & Massey, 2013). For instance, in astronomy, students must become efficient at matching spectra to determine critical properties of celestial bodies, as illustrated in Fig. 3. Perceptual fluency is critical because it enables students to automatically process visuals and frees up cognitive resources for more complex thinking processes such as problem solving (Goldstone & Barsalou, 1998) and enhance disciplinary learning (Taber, 2014).

Students acquire perceptual fluency through non-verbal, perceptual-induction processes that rely on pattern recognition (Rau, 2017), which are fundamentally different from sense-making processes. Specifically, the verbal explanations that characterize sense-making processes may disrupt perceptual-induction processes (Schooler et al., 1997). Instead, students engage in perceptual-induction processes when they attempt to quickly and efficiently classify disciplinary content shown in visual representations (Kellman & Garrigan, 2009). For example, as students experience contrasting examples, they may induce relevant scientific principles (Chase et al., 2019).

Instructional supports for perceptual fluency are fundamentally different from sense-making supports because of the nonverbal

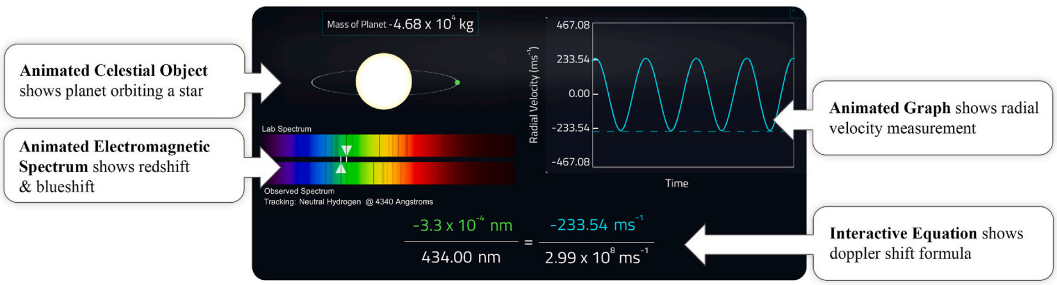

Fig. 2. Multiple representations showing radial velocity.

Fig. 3. Spectra Visual Representations: 1) Students view a spectrum observed from a celestial body with multiple elements. 2) Because each element has a unique signature, they select a lab spectrum that matches the observed spectrum to 3) identify an element present. In this case, the match indicates there is Xenon present in the Crab Nebula.

nature of perceptual-fluency processes. Specifically, perceptual-fluency supports focus on nonverbal forms of instruction by exposing students to numerous example visuals sequenced in ways that contrast relevant visual features (Kellman & Massey, 2013). Throughout, students are prompted to solve visual tasks quickly without explaining them (Kellman & Massey, 2013). For example, perceptual-fluency support may prompt students to categorize examples (Rau et al., 2015) or to rapidly construct visuals (Eastwood, 2013). Further, feedback should be given on the accuracy of their responses but should not provide explanations that could engage students' verbal processes (Rau et al., 2021).

Prior research shows that combining sense-making support and perceptual-fluency support enhances students' learning of content knowledge from structured learning environments (Rau & Wu, 2018). Further, sense-making support should be provided prior to perceptual-fluency support Rau, 2018.

2.3. Research question

Our brief review shows that students have difficulties in learning with visuals both in educational video games and structured learning environments that may create barriers to students' learning success. Research on structured learning environments suggests that adding instructional supports for sense-making competencies and perceptual fluency offer a solution. However, to our knowledge, design recommendations for representational-competency supports are purely based on research on structured learning environments. Therefore, it is unknown whether these representational-competency supports are also effective in the context of 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?

Addressing this question yields new theoretical insights into the generalizability of representational-competency supports to unstructured types of learning environments. It yields practical recommendations about how to enhance students' learning with visuals in educational video games. To this end, we conducted a lab experiment with an educational video game for undergraduate astronomy learning.

3. Methods

All components of this study were approved by our Institutional Review Board for Human Subjects Research and we upheld to rigorous ethical standards during the implementation of our study, as described by Petousi and Sifaki (2020).

Fig. 4. At Play in the Cosmos Star Chart. Students use the Star Chart to explore the universe and select celestial objects to examine using their tools.

3.1. Video game

We chose a game with the explicit goal of enabling students to make connections among multiple visuals of astronomical phenomena: At Play in the Cosmos (Squire, 2021). In the game, students work for a corporation that mines resources in space. Through guided missions, students explore galaxies and acquire resources to meet contracts for the corporation (Fig. 4). A major feature of the game is a set of tools that include visuals that portray basic astronomy concepts taught in introductory courses. Students interact with these visuals to understand how astronomers gather data about celestial objects to learn more about the universe and its evolution (e.g., line emission spectra, Fig. 1). Interactions with these visuals are meant to enable students to focus on learning concepts related to measuring celestial objects, such as the mass of exoplanets, without having to compute mathematical formulas (e.g., radial velocity, Fig. 2).

3.1.1. Game walkthroughs. Each time a student encounters a new tool featuring a new visual, the game provides a walkthrough. For example, in Mission 13, students use the Radial Velocity Tool (Fig. 5) for the first time when they are asked to identify a habitable planet. First, students click "measure", and the tool calculates the difference between the actual and measured wavelengths of the celestial object. 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, provides the mass of the orbiting planet, and moves students forward in the narrative. Calculating the mass relies on advanced computations that are not readily apparent within the game due to the complexity of the underlying formula.

3.1.2. Visual representations. The tools provided by the game incorporate multiple visuals that enable astronomers to make sense of the universe. For example, a commonly used visual in astronomy is the electromagnetic spectrum. The spectrum represents the radiation given off by objects in space (Franknoi et al., 2017). Astronomers use spectra to identify important properties of celestial bodies (Bardar et al., 2005). Students engage with the electromagnetic spectrum many times throughout the game. Specifically, the electromagnetic spectrum is integrated in the Spectrum Analyzer Tool (Fig. 3), the Blackbody Analyzer Tool, and the Radial Velocity Tool (Fig. 2).

To illustrate students' use of the electromagnetic spectrum, consider the Spectrum Analyzer Tool, which allows students to match observed spectra to laboratory spectra to determine key characteristics of celestial objects. For instance, students travel to Supernova 1987A in Mission 1 to determine if sodium gas is present in its ejecta (Bary, 2017). To use the Spectrum Analyzer Tool, students click through labeled spectra from a database until they find one that matches the spectrum emitted by Supernova 1987A. If students choose incorrectly, they receive feedback that the spectra do not match and are encouraged to try again. If students choose correctly, they move forward in the mission.

The tools within the game share features with the perceptual-fluency supports described above. Specifically, these tools foster intuitive rather than analytical processing of visual information, provide feedback on accuracy only, and expose students to numerous examples.

3.2. Participants

We recruited 142 undergraduates from a large United States Midwestern university for monetary compensation or extra course credit. Recruitment focused on students without prior undergraduate astronomy courses. This requirement aligned participants with those students who would typically play the game. We also did not include students currently taking an introductory astronomy 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. Prior to participating, students signed a written consent form that detailed the purpose of the research, requirements for participating, risks and benefits, compensation, and how confidentiality would be protected. Participants were informed that they could end their participation at any time during the study without penalty.

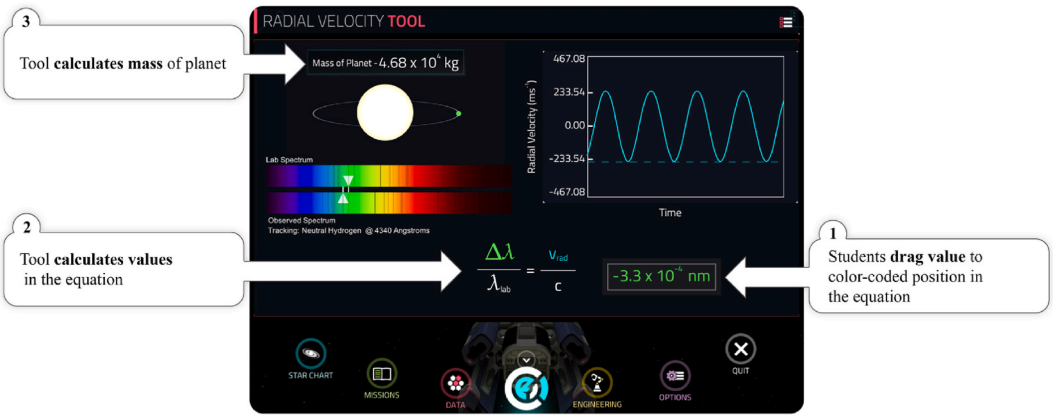

Fig. 5. Example game walkthrough.

3.3. Experimental design

We used a 2 (sense-making support: yes vs no) x 2 (perceptual-fluency support: yes vs no) experimental design that yielded four conditions. Students were randomly assigned to: (1) sense-making support, (2) perceptual-fluency support, (3) combined sense-making and perceptual fluency support, or (4) control. The control condition 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 competencies, perceptual fluency, or both representational competencies while playing the game.

The representational-competency supports were given in the form of prompts, delivered via videos and verbally. Prior to and at intervals during gameplay, students viewed videos that modelled interactions with the game related to their condition, detailed below. Students in the control condition viewed videos that introduced features of the game, discussed benefits of educational video games, and provided step-by-step technical processes for interacting with the game. Students in the support conditions 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 2 min long.

Additionally, students received verbal prompts phrased as reminders about the information from the videos once per mission when they first interacted with a visual. Verbal prompts used language similar to the videos to remind students to use the processes outlined in the videos. Control prompts were meant to control for any potential effects of the reminders to the students' gameplay experience. Table 1 provides example verbal prompts for each condition for two example missions.

These forms of representational-competency supports (i.e., videos and verbal prompts) were designed based on the prior research described above. Specifically, videos and prompts that served as sense-making supports instructed students to engage with visuals in a three-step process: they were asked (1) to interpret each visual, (2) to compare pairs of visuals, and (3) to explain the comparison in reference to astronomy concepts. For example, students were asked to interpret what a line emission spectrum showed (see Fig. 1), compare similarities and differences to another spectrum, and then explain what the comparison indicates about the presence of a substance in a star.

Videos and prompts that served as perceptual-fluency supports 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, and to accept mistakes. Because prior research showed that sense-making support should be provided before perceptual-fluency support (Rau, 2017), students in the combined condition received sense-making support the first time they used a visual and perceptual-fluency support for subsequent uses of the visual. For example, in Session 1, students first received sense-making support for the spectrum analyzer and halfway through the session they received perceptual-fluency support related to the same visual.

3.4. Measures

We assessed students' learning of content knowledge, sense-making competencies, and perceptual fluency with three isomorphic versions of a test for a pre-test and two post-tests. A pre-test was included because, even though we recruited students without prior astronomy courses at the undergraduate level, we cannot rule out that they encountered some astronomy concepts within prior science courses or outside of formal schooling. We counterbalanced the order of the test versions across test times.

The *sense-making test* assessed students' ability to relate features of a visual to the discipline-specific concepts they show and to explain connections between multiple visuals. This test included three questions with four separate parts each, yielding 12 items, nine of which were open-response items. For each question, students were first presented with two images of electromagnetic spectra—one labeled with an element and one unlabeled (similar to Fig. 3) and asked if they matched. Second, students were asked how they knew the spectra did or did not match. Third, students were asked what they could infer about the unlabeled spectra given the relationship between the two visuals. Fourth, students were asked how they determined whether the spectra matched or not. Open-response items

Table 1
Prompts for two example missions.

Condition	Verbal Prompt
Mission 1	
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 Support	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 Support	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 Support	Same verbal prompt as Sense-Making condition
Mission 4	
Control	Here you'll encounter the spectrum analyzer again. You will use this tool, in particular, many times throughout the game. Right now, you're trying to find xenon gas to refuel your thrusters.
Sense-Making Support	Remember: As you interact with the tool, reflect on the visuals. Follow the steps from the video: Interpret each spectrum, compare each pair of spectra, and then interpret the comparison carefully before selecting the correct answer.
Perceptual-Fluency Support	Remember to follow the advice from the video. Click through each spectra until you think you have a match. Focus on your intuitions like an astronomer would. Just try again if you get it wrong.
Combined Support	Same verbal prompt as Perceptual Fluency condition

were graded based on a codebook that described the sense-making competencies assessed by each item and captured multiple ways of describing how the given visual depicts astronomy concepts. Inter-rater reliability was established by two independent raters on 20% percent of the data and revealed a kappa of .700. Internal reliability analysis showed that the test was reliable with Cronbach's Alpha = .800. We computed sense-making scores as the average of the correct items for each student for each test time.

The *perceptual-fluency test* assessed students' ability to quickly match multiple visuals. This test included six items, all of which were multiple choice. In each item, students were presented with an electromagnetic spectrum visual and four choices to select the matching visual. Since perceptual fluency describes the ability to quickly and efficiently extract information from visuals, we computed an efficiency score based on the efficiency metric by Van Gog and Paas (2008):

$$\text{Perceptual fluency} = \frac{Z(\textit{average correct answers}) - Z(\textit{average response time per test item})}{\sqrt{2}}$$

Because this calculation involves Z standardization, a negative score was possible. For example, a negative perceptual-fluency score might indicate that a student's average of correct answers was at the median while the average response times were longer than the median.

The *content test* assessed students' understanding of how specific visuals describe astronomy concepts, such as the electromagnetic spectrum and radial velocity. This test included 13 items, 11 of which were open-response items. Open-response items were graded based on a codebook that described the conceptual knowledge assessed by each item and captured multiple ways of describing the targeted concept. Inter-rater reliability was established by two independent raters on 20% percent of the data and revealed a kappa of .700. Internal reliability analysis showed that the test was reliable with Cronbach's Alpha = .717. We computed content scores as the average of correct items for each student for each test time.

Students also completed the *Vandenberg and Kuse Mental Rotation Test (MRT)* (Peters, 2005), which assessed 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 (Stull et al., 2012) as well as shown to correlate with astronomy abilities (Heyer et al., 2013).

We assessed students' *cognitive load* after each mission. Students answered two questions adapted from Schmeck and colleagues (2015) cognitive load measure. Students were asked (1) how much mental effort they invested and (2) how difficult they perceived a mission to be. Because students answered verbally, we changed the scale of the questions from seven points to ten points to align with common practice in many daily life situations (e.g., rating scales about pain levels at U.S. doctor visits).

Students also completed a *survey* with demographics questions about how often they play video games, their previous astronomy experience, how often they use visuals in their learning, and their majors.

3.5. Procedure

The study involved two sessions approximately 1–5 days apart (Fig. 6). During Session 1, students completed the pre-test and 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 an interview, and took a survey. While they played, students also received verbal reminders related to their condition during each mission except for Mission 13. After each mission, students answered the two questions related to their perceived cognitive load.

3.6. Analysis

A first set of analyses served as prior checks. First, to determine if there were differences between conditions prior to the experimental manipulation, we conducted a MANOVA with the three pre-test scores and MRT scores as dependent measures, sense-making and perceptual-fluency factors as independent measures, and an interaction between the sense-making and perceptual-fluency factors.

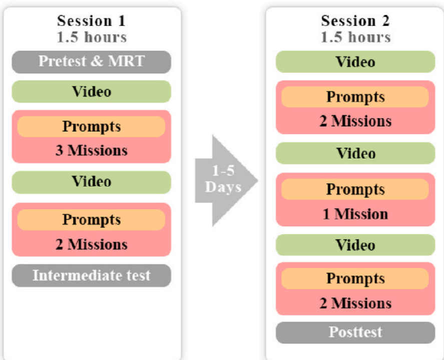

Fig. 6. Procedure: tests (gray) and missions (pink) were the same for all conditions; videos (green) and prompts (orange) differed between conditions. MRT = Mental Rotation Test. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

We chose a MANOVA over separate ANOVAs to reduce the Type 1 error rate by including all dependent measures in one analysis (Field, 2018). Second, we checked for correlations among the outcome scores and additional variables described above. The content pre-test and the MRT correlated significantly with students' scores on the content post-tests ($r = 0.373$, $p < .001$ for pre-test with post-test 1, $r = 0.455$, $p < .001$ for pre-test with post-test 2, $r = 0.333$, $p < .001$ for MRT with post-test 1, $r = 0.460$, $p < .001$ for MRT with post-test 2). Therefore, both the content pre-test and MRT were included as covariates in our analyses of the effects of representational-competency supports. Third, we checked for learning gains using repeated measures ANOVAs with test scores as dependent measures and test-time (pre-test, post-test 1, and post-test 2) as the repeated, within-subjects factor. Fourth, we ran a manipulation check testing whether sense-making supports enhance students' sense-making competencies. We used a repeated measures ANCOVA with scores on the sense-making post-tests as dependent measures, sense-making support 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. We also tested each variable described in the Measures section to determine if it was a significant predictor. The perceptual-fluency pre-test was a significant predictor, so we added it as a covariate in the model. Fifth, we ran a manipulation check testing whether perceptual-fluency supports enhance students' perceptual fluency. We used a repeated measures ANCOVA with scores on the perceptual-fluency post-tests as dependent measures, perceptual-fluency support 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. We also tested each variable described in the Measures section to determine if it was a significant predictor. The sense-making pre-test and sense-making support were significant predictors, so we included them in the model.

Finally, to address our research question, we tested for the effects of representational-competency supports on students' astronomy content learning. To this end, we constructed a repeated measures ANCOVA model using the following stepwise approach. First, we tested the combined effects of the representational-competency supports for an interaction of sense-making support and perceptual-fluency support. Second, we tested the effects of prior representational competencies (i.e., sense-making and perceptual-fluency pre-tests) as well as interactions of prior representational competencies with sense-making support and perceptual-fluency support. Third, we tested the effects of MRT as well as interactions of MRT with the sense-making support and perceptual-fluency support. Fourth, we tested the effects of cognitive load as well as interactions of cognitive load with sense-making support and perceptual-fluency support. Fifth, we tested the effects of prior content knowledge with interactions of the sense-making support and perceptual-fluency support with the content pre-test scores. We also tested each variable described in the Measures section above to determine if it is a significant predictor. Only the interaction of the content pre-test scores with perceptual-fluency factor was significant, 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. This yielded 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 support and perceptual-fluency support as between-subjects factors, and content pre-test, sense-making pre-test, and overall cognitive load as the covariates with an interaction of content pre-test and perceptual-fluency support.

4. Results

Twenty-two students were excluded from the results due to not finishing all required components of the study. Five students were excluded from the analysis because their scores on the content pre-test or post-tests were statistical outliers (i.e., lower or higher than 1.5 times the interquartile range from the median). We removed these outliers to avoid skewing of the mean data in the ANCOVA analysis. 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 0.20 corresponds to a small effect, 0.50 to a medium effect, and 0.80 to a large effect. With 115 students, pre-test and MRT as covariates, $\alpha = 0.05$ and $\beta = 0.20$ power of .80, and four groups, our study was sensitive to effect sizes of at least $d = 0.264$. Table 2 shows the unadjusted means and standard deviations for each of our measures—sense making, perceptual fluency, and content—for each of our conditions, which are explored in more detail in the sections below outlining our statistical analyses.

Table 2
Means (standard deviations) of averages of outcome scores by condition and test time.

	Control Condition	Sense-Making Condition	Perceptual-Fluency Condition	Combined Condition
Sense-Making Scores				
Pretest	.74 (.23)	.65 (.27)	.71 (.23)	.62 (.25)
Post-Test 1	.83 (.18)	.76 (.24)	.71 (.24)	.75 (.21)
Post-Test 2	.90 (.14)	.78 (.24)	.78 (.24)	.77 (.22)
Perceptual-Fluency Scores				
Pretest	.25 (.62)	−.13 (.70)	.44 (.62)	.13 (.83)
Post-Test 1	.00 (.63)	−.11 (. 77)	.25 (.56)	.11 (.63)
Post-Test 2	−.14 (.89)	.00 (.63)	.13 (.73)	.06 (.83)
Content Scores				
Pretest	.22 (.09)	.22 (.12)	.21 (.98)	.21 (.11)
Post-Test 1	.45 (.14)	.42 (.12)	.41 (.14)	.40 (.11)
Post-Test 2	.57 (.14)	.55 (.15)	.51 (.18)	.49 (.21)

4.1. Demographics

Survey data revealed that the students included in our analysis were split between STEM majors (57 students) and non-STEM majors (58 students). Also, most students were not frequent video gamers with 38 students playing very often or always, 31 students sometimes playing, and 46 students playing rarely or never. Students had a range of prior astronomy experience with 33 students with no experience, 58 students with informal experiences such as social media, and 24 students with prior lessons in a related course such as earth science. No students had a prior astronomy course. Students also varied in their prior use of visual representations when learning. Sixty-four students very often or always used visuals, 39 students sometimes used visuals, and twelve students rarely used visuals. Prior astronomy experience and prior visual representation use did not correlate with any of our tests.

4.2. Prior checks

First, we verified that there were no significant differences between conditions at the pre-test. A MANOVA showed no significant differences between conditions on the content pre-test, sense-making pre-test, perceptual-fluency pre-test, nor the MRT (Fs < 1).

Second, we checked that playing the game was associated with learning gains. We found significant gains on the content outcome scores, $F(2, 113) = 282.552$, $p < .001$, $d = 1.576$, sense-making outcome scores, $F(2, 113) = 20.097$, $p < .001$, $d = 0.420$, and perceptual-fluency outcome scores, $F(2,113) = 4.024$, $p = .021$, $d = 0.266$. This result indicates that regardless of condition, students' content knowledge, sense-making competencies, and perceptual fluency improved over the three test times (pre-test, post-test 1, post-test 2).

Third, we conducted a manipulation check of sense-making support. We found no main effect of sense-making support on the sense-making post-tests, ($F < 1$). This result indicates that the presence of sense-making support did not improve students' sense-making competencies.

Fourth, we conducted a manipulation check of perceptual-fluency support. We found a significant positive effect of perceptual-fluency support on perceptual-fluency post-tests, $F(1, 114) = 5.873$, $p = .017$, $d = 0.234$. This result indicates that the presence of perceptual-fluency support improved students' perceptual fluency.

4.3. Effects of representational-competency support on content knowledge

With respect to our research question (whether representational-competency supports enhance students' learning from an astronomy educational video game), results showed no significant main effect of sense-making supports on students' content knowledge, ($F < 1$). Thus, this result indicates that the presence of sense-making support did not improve content knowledge.

However, results showed a significant main effect of the perceptual-fluency support, $F(1, 114) = 8.814$, $p = .004$, $d = 0.289$. The main-effect of perceptual-fluency support was qualified by a significant interaction between perceptual-fluency support and content pre-test, $F(1,114) = 6.693$, $p = .011$, $d = 0.250$ (Fig. 7). To examine this interaction, we used effect slices, which determine the effect of perceptual-fluency support at a pre-defined cutoff point of content pre-test scores. This allowed us to treat content pre-test scores as a continuous variable. Effect slices showed that students with low content pre-test scores (at the 10th percentile or lower) performed better on the content post-test 2 when perceptual-fluency support was *not* present, $F(1,114) = 12.833$, $p = .001$, $d = 0.348$. Further, students with high content pre-test scores (at the 90th percentile or higher) performed better on the content post-test 2 when perceptual-fluency support *was* present, $F(1,114) = 3.935$, $p = .050$, $d = 0.193$. This result indicates that the presence of perceptual-fluency support improved students' astronomy content knowledge but only for those students with high content pre-test scores.

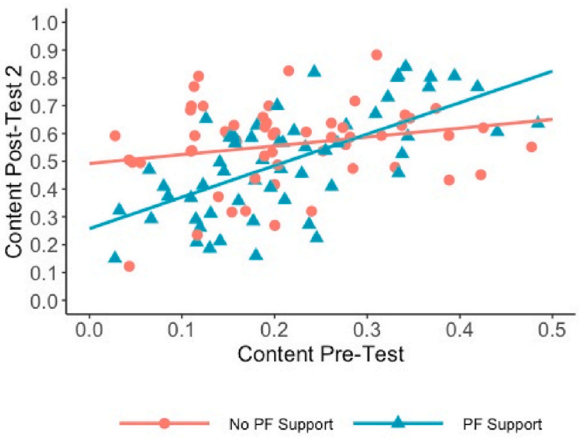

Fig. 7. Plot showing content pre-test to post-test 2 learning gains comparing the presence (teal triangle) or absence (orange circle) of perceptual-fluency (PF) supports.

5. Discussion

The goal of our experiment was to investigate whether representational-competency supports designed in the context of non-game, structured learning environments enhance students' learning from an astronomy educational video game. Results showed that sense-making support had no significant effect on students' learning of content knowledge. We found, however, that perceptual-fluency support affected students' learning of content knowledge, but this effect was moderated by students' pre-test content scores. Specifically, students with lower pre-test content scores had higher learning outcomes if they played the game *without* perceptual-fluency support whereas students with higher pre-test content scores had higher learning outcomes if they played the game *with* perceptual-fluency support.

Prior research has shown that sense-making support positively impacts students' content learning in structured learning environments (e.g., Rau, 2017), so why might those same supports not work within an educational video game? Considering that our manipulation checks showed that students' sense-making competencies improved after playing the game, we see multiple possible explanations. First, it is possible that the game itself supported sense-making competencies, so that additional sense-making support may not have further enhanced students' sense-making competencies. For instance, each time students encountered a new tool, the game provided a walkthrough. This walkthrough may have prompted students to think more deeply about the connections between the visuals provided in the tool. The walkthroughs could have improved students' sense-making competencies across all conditions, thus resulting in a null main effect of the sense-making support despite the sense-making competency gains across conditions. A caveat of this explanation is that the walkthroughs mainly focused on where to click to manipulate a visual or equation and did not offer extensive support for reflection and conceptual reasoning that has proven effective in prior research on sense-making competencies. Thus, there may be further opportunities to support sense-making processes to complement the walkthroughs.

Second, it is possible that the instructions provided for the control condition could have prompted sense-making processes. Recall that the control condition received information related to the educational nature of the game and step-by-step instructions for using the game. Reminding students of the educational nature of the game could have resulted in students paying more attention to the game content in general. Because visuals mediate interactions in the game, such general increased attention could have implied paying more attention to the visuals. This could explain why we saw overall sense-making competency gains, but no main effect of the sense-making supports across conditions. A caveat of this explanation is that it does not address why students in the perceptual-fluency condition, which did not receive this general information also gained sense-making competencies.

Third, it is possible that our version of the sense-making supports was incompatible with the game design. The sense-making supports prompted students to think more deeply about the visuals. However, the game did not provide in-depth information for making those connections. For instance, it did not explain how the visuals depict astronomy concepts. Thus, when students were asked to reflect on the visuals, they may not have had adequate information for doing so. Further, students may have been unwilling to engage in sense-making processes because the game focused on intuitive interactions more than reflective processes necessary for sense-making. For example, the game offered corrective rather than explanatory feedback on students' interactions with visuals, which seems more aligned with perceptual-fluency supports than with sense-making supports.

Given the caveats of the first two explanations, we find the third explanation most likely. Nevertheless, we note that these explanations are not necessarily mutually exclusive. It is possible that all three explanations account for the ineffectiveness of the sense-making supports as designed for our study.

In contrast, results showed that perceptual-fluency supports had a significant main effect on content learning outcomes. We interpret this finding in the context of the design of the game itself. As previously mentioned, the game design aligns with the design recommendations for perceptual-fluency support because it focuses on intuitive processing of visuals, provides feedback on accuracy, and exposes students to multiple examples. Therefore, we argue that the game aligns with support of implicit, nonverbal learning processes that lead to perceptual fluency rather than with explicit, verbal learning processes that lead to sense-making competencies. Indeed, prior research has shown that video games often support more intuitive understanding of disciplinary concepts (Virk et al., 2015). Thus, the effectiveness of the perceptual-fluency supports could be due to its compatibility with the game. When the perceptual-fluency supports asked students to move quickly through the game without overthinking it, they may have been able to do so easily because the game already encouraged intuitive interactions. At the same time, our results suggest that perceptual-fluency supports enhanced 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 perceive information shown by the visuals, so that taken by itself, the game was not maximally beneficial for students' content learning.

However, the main effect of perceptual-fluency support was moderated by students' prior content knowledge, as assessed by their content pre-test scores, such that only those students with high content pre-test scores benefited from the supports. This finding is in line with prior research on perceptual fluency, suggesting that perceptual-fluency supports are less effective for students with low prior content knowledge (Rau et al., 2021).

In sum, in response to our research question on whether representational-competency supports enhance students' learning from an astronomy educational video game, we found that our implementation of perceptual-fluency support only supported those students with high prior content knowledge as assessed by our pre-test. Further, our implementation of sense-making support did not enhance students' sense-making competence nor their content learning from the game. These findings begin to fill a gap in empirical research by investigating the role of representational competencies for students' learning with visuals in educational video games. Representational-competency supports that are successful in structured learning environments do not seem to work the same way in the context of educational video games. In the context of our astronomy game, this was especially true for sense-making supports, potentially because they were incompatible with the design of the game.

This research has significant implications for future research. It presents a starting point for navigating the limitations of instructional supports that were designed based on research in structured learning environments, thereby closing a gap between research on structured learning environments and games. Our findings suggest that alternative designs of supports may be needed to support students' learning with visuals in educational video games. By suggesting that design principles for representational-competency supports are not universal, this expands prior research on learning with representations. Research on learning with visuals should consider educational video games as a platform for future studies. Further, our findings expand prior research on educational video games by suggesting that their effectiveness could be improved by supporting representational competencies, especially perceptual fluency. Thus, this research provides a starting point for optimizing the use of visuals in video games.

This research also has implications for educational practices of using educational video games. Specifically, our results show that perceptual-fluency support, which was delivered through prompts, enhanced students' benefit from the video game. This suggests that teachers may implement instructional supports alongside a game to further enhance outcomes. By simply prompting students to engage in intuitive thinking, teachers may enhance students' learning from the game. Further, our finding that perceptual-fluency support was effective only for students with high content pre-test scores suggests that games that target perceptual fluency may be effective later in a learning sequence. Finally, our finding that sense-making support was ineffective during our game suggests that teachers may use caution when attempting to promote sense making because certain games may not adequately support it.

6. 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. We chose *At Play in the Cosmos* because a goal of the game is to enable students to make connections between multiple representations of astronomy phenomena and because it uses visuals in ways that are authentic to the discipline and support students' learning about introductory astronomy concepts. Although this game provides a valuable examination of visuals in educational video games, the design incorporates visuals from a specific discipline in specific ways to support students' gameplay and learning. Thus, it is unclear if the results from this study generalize to other ways of using visuals, 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. This methodological choice enabled us to maximize internal validity by controlling for time on task, ensuring students 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 play an important role in supporting learning within an educational video game (Clark et al., 2016). 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.

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 students. Prior studies have examined the impact of flow state for supporting learning from gameplay (e.g., Tsai et al., 2016). Such interruption could have reduced an effective support mechanism in the game that may impact students' use of visuals for learning. However, this limitation does not compromise the internal validity of the study because all conditions, including the control condition, received these prompts. Nevertheless, future research should examine the role of flow in learning with visual representations by creating alternative versions of representational-competency supports that do not interrupt students and keep this potential support mechanism intact.

7. Conclusion

In sum, our research empirically tested representational-competency supports shown to be effective in structured learning environments within the context of educational video games. Our results showed that support for perceptual fluency enhanced students' learning of content knowledge within an astronomy educational video game, but only for students who scored high on the content pre-test. Further, our results showed that sense-making support did not improve students' learning. Thus, our research demonstrates a need to investigate how supports for representational competencies should be designed to enhance learning with visual representations within educational video game environments. In future work, we will investigate alternative sense-making supports during gameplay as well as test if off-loading sense-making supports prior to gameplay would prepare students to benefit from the effects of perceptual-fluency supports during gameplay. Further, while this particular game stressed intuitive interactions that are a common focus of video games and align with perceptual-fluency supports, other games may be more aligned with the effortful, reflective processes of sense-making. Future work will broaden this research to clarify design recommendations for representational-competency supports within a range of educational video game designs. If educators want to leverage the power of video games to engage students in authentic STEM practices with visuals, then this research is critical enable students to achieve this goal.

Author statement

Tiffany Herder: Conceptualization; Methodology; Formal analysis; Investigation; Resources; Data curation; Writing; Visualization, **Martina Rau**: Conceptualization; Methodology; Supervision

Data availability

The authors do not have permission to share data.

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References

Ainsworth, S. E. (2006). DeFT: A conceptual framework for considering learning with multiple representations. *Learning and Instruction, 16*(3), 183–198.

Ainsworth, S., Bibby, P., & Wood, D. (2002). Examining the effects of different multiple representational systems in learning primary mathematics. *The Journal of the Learning Sciences, 11*(1), 25–61.

Airey, J., & Linder, C. (2009). A disciplinary discourse perspective on university science learning: Achieving fluency in a critical constellation of modes. *Journal of Research in Science Teaching, 46*(1), 27–49.

Ampartzaki, M., & Kalogiannakis, M. (2016). Astronomy in early childhood education: A concept-based approach. *Early Childhood Education Journal, 44*(2), 169–179.

Anderson, J. L., & Barnett, M. (2013). Learning physics with digital game simulations in middle school science. *Journal of Science Education and Technology, 22*(6), 914–926.

Annetta, L. A., & Cook, M. (2007). Video games: A vehicle for problem-based learning. *E-JIST, 10*(1), 1–12.

Bardar, E. M., Prather, E. E., Brecher, K., & Slater, T. F. (2005). The need for a Light and Spectroscopy Concept Inventory for assessing innovations in introductory astronomy survey courses. *Astronomy Education Review, 4*(2), 20–27.

Bary, J. (2017). *Instructor's manual for at play in the cosmos: The videogame*. New York, New York: WW Norton & Company.

Bodemer, D., Ploetzner, R., Feuerlein, I., & Spada, H. (2004). The active integration of information during learning with dynamic and interactive visualisations. *Learning and Instruction, 14*(3), 325–341. https://doi.org/10.1016/j.learninstruc.2004.06.006

Change, J. Y., Meng-Fei, C., Lin, S. Y., & Lin, J. L. (2021). Exploring students' translation performance and use of intermediary representations among multiple representations: Example from torque and rotation. *Teaching and Teacher Education, 97*, 1–12.

Chase, C. C., Malkiewich, L., & Kumar, A. S. (2019). Learning to notice science concepts in engineering activities and transfer situations. *Science Education, 103*, 440–471.

Chen, C. H. (2018). The impacts of peer competition-based science gameplay on conceptual knowledge, intrinsic motivation, and learning behavioral patterns. *Educational Technology Research & Development, 67*, 179–198.

Chi, M. T., Bassok, M., Lewis, M. W., Reimann, P., & Glaser, R. (1989). Self-explanations: How students study and use examples in learning to solve problems. *Cognitive Science, 13*(2), 145–182.

Clark, D. B., Nelson, B., Sengupta, P., & Angelo, C. D. (2009). Rethinking science learning through digital games and simulations: Genres, examples, and evidence. In *Learning science: Computer games, simulations, and education workshop sponsored by the National Academy of Sciences*. Washington, DC.

Clark, D. B., & Sengupta, P. (2020). Reconceptualizing games for integrating computational thinking and science as practice: Collaborative agent-based disciplinarily-integrated games. *Interactive Learning Environments, 3*, 1–19.

Clark, D. B., Tanner-Smith, E. E., & Killingsworth, S. S. (2016). Digital games, design, and learning: A systematic review and meta-analysis. *Review of Educational Research, 86*(1), 79–122.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2 Ed.). Lawrence Erlbaum Associates.

Corredor, J., Sanchez-Mora, J., & Bustamante-Barreto, A. (2020). Situated conversations during video game play and the understanding of viral replication. *E-learning and Digital Media, 18*(4), 325–343.

De Freitas, S., & Oliver, M. (2006). How can exploratory learning with games and simulations within the curriculum be most effectively evaluated? *Computers & Education, 46*(3), 249–264.

Eastwood, M. L. (2013). Fastest fingers: A molecule-building game for teaching organic chemistry. *Journal of Chemical Education, 90*(8), 1038–1041.

Eriksson, U. (2019). Disciplinary discernment: Reading the sky in astronomy education. *Physical Review Physics Education Research, 15*, 10133-1-10133-19.

Field, A. (2018). *Discovering statistics using IBM SPSS statistics* (*5th* ed.). London: Sage Publications.

Fiorella, L., & Mayer, R. E. (2016). Eight ways to promote generative learning. *Educational Psychology Review, 28*(4), 717–741.

Franknoi, A., Morrison, D., & Wolff, S. C. (2017). *Astronomy*. Houston, Texas: OpenStax.

Garnli, V., Patiniotis, K., & Chorianopoulos, K. (2021). Designing multiplayer serious games with science content. *Multimodal Technology Interaction, 5*(8), 1–17.

Gee, J. P. (2003). *What video games have to teach us about learning and literacy*. Palgrave MacMillan.

Gilbert, J. K. (2008). Visualization: An emergent field of practice and inquiry in science education. In J. K. Gilbert, M. Reiner, & M. B. Nakhleh (Eds.)*, Vol. 3. Visualization: Theory and practice in science education* (pp. 3–24). Dordrecht, Netherlands: Springer.

Gkitzia, V., Salta, K., & Tzougraki, C. (2020). *Students' competence in translating between different types of chemical representations* (Vol. 21). Royal Society of Chemistry.

Goldstone, R. L., & Barsalou, L. W. (1998). Reuniting perception and conception. *Cognition, 65*, 231–262.

Goldstone, R. L., & Son, J. Y. (2005). The transfer of scientific principles using concrete and idealized simulations. *The Journal of the Learning Sciences, 14*(1), 69–110.

Heyer, I., Slater, S. J., & Slater, T. (2013). Establishing the empirical relationship between non-science majoring undergraduate learners'spatial thinking skills and their conceptual astronomy knowledge. *Revista Latino-Americana de Educação em Astronomia*, (16), 45–61.

Joo, H., Park, J., & Kim, D. (2020). Visual representation fidelity and self-explanation prompts in multi-representational adaptive learning. *Journal of Computer Assisted Learning, 37*, 1091–1106.

Kellman, P. J., & Garrigan, P. (2009). Perceptual learning and human expertise. *Physics of Life Reviews, 6*(2), 53–84.

Kellman, P. J., & Massey, C. M. (2013). Perceptual learning, cognition, and expertise. In B. H. Ross (Ed.)*, Vol. 558. The psychology of learning and motivation* (pp. 117–165). Elsevier Academic Press.

Koedinger, K. R., Corbett, A. T., & Perfetti, C. (2012). The knowledge-learning-instruction framework: Bridging the science-practice chasm to enhance robust student learning. *Cognitive Science, 36*(5), 757–798.

Kortemeyer, G., Anderson, D., Desrochers, A. M., Hackbardt, A., Hoekstra, K., Holt, A., Iftekhar, A., Kabaker, T., Keller, N., Korzecke, Z., Gogonis, A., Manson, Q., McNeill, G., Mookerjee, D., Nguyen, S., Person, B., Stafford, M., Takamoribraganca, L., Yu, Z., Zeng, F., & Ratan, R. (2019). Using a computer game to teach circuit concepts. *European Journal of Physcis, 40*(5), 1–15.

Kozma, R. B. (2020). Use of multiple representations by experts and novices. In P. Van Meter, A. List, D. Lombardi, & Kendeou (Eds.), *Handbook of learning from multiple representations and perspectives*. New York, NY: Routledge.

Kozma, R., & Russell, J. (2005). Students becoming chemists: Developing representationl competence. In J. Gilbert (Ed.), *Visualization in science education* (pp. 121–145). Dordrecht, Netherlands: Springer.
Lim, C. P., Nonis, D., & Hedberg, J. (2006). Gaming in a 3D multiuser virtual environment: Engaging students in science lessons. *British Journal of Educational Technology, 37*(2), 211–231.
Mayer, R. E. (2009). Cognitive theory of multimedia learning. In R. E. Mayer (Ed.), *The cambridge Handbook of multimedia learning* (pp. 31–48). New York, New York: Cambridge University Press.
Mayfield, K., Cline, S., Lewis, A., Brookover, J., Day, E., Kelley, W., & Sparks, S. (2019). Designing a molecular biology serious educational game. *ACMSE 2019 - Proceedings of the 2019 ACM Southeast Conference*, 210–213.
Mayo, M. J. (2009). Video games: A route to large-scale STEM education? *Science, 323*(5910), 79–82. https://doi.org/10.1126/science.1166900
Muehrer, R., Jenson, J., Friedberg, J., & Husain, N. (2012). Challenges and opportunities: Using a science-based video game in secondary school settings. *Cultural Studies of Science Education, 7*(4), 783–805.
Nikolopoulou, K. (2022). Digital technology in early STEM education: Exploring its supportive role. In S. Papdakis, & M. Klogiannakis (Eds.), *STEM, robotics, mobile apps in early childhood and primary education: Technology to promote teaching and learning*. Singapore: Springer Nature.
Peters, M. (2005). Sex differences and the factor of time in solving Vandenberg and Kuse mental rotation problems. *Brain and Cognition, 57*(2), 176–184.
Petousi, V., & Sifaki, E. (2020). Contextualising harm in the framework of research misconduct. Findings from discourse analysis of scientific publications. *International Journal of Sustainable Development, 23*(3–4), 149–174.
Rau, M. A. (2017). Conditions for the effectiveness of multiple visual representations in enhancing STEM learning. *Educational Psychology Review, 29*(4), 717–761.
Rau, M. A. (2018). Sequencing sense-making support and fluency-building support for connection making among multiple visual representations. *Journal of Educational Psychology, 110*(6), 811–833.
Rau, M. A., Michaelis, J. E., & Fay, N. (2015). Connection making between multiple graphical representations: A multi-methods approach for domain-specific grounding of an intelligent tutoring system for chemistry. *Computers and Education, 82*, 460–485.
Rau, M. A., & Wu, S. P. W. (2018). Combining instructional activities for sense-making processes and perceptual-induction processes involved in connection-making among multiple visual representations. *Cognition and Instruction, 36*(4), 361–395.
Rau, M. A., Zahn, M., Misback, E., Herder, T., & Burstyn, J. (2021). Adaptive support for representational competencies during technology-based problem solving in chemistry. *Journal of the Learning Sciences, 30*(2), 163–203.
Schmeck, A., Opfermann, M., van Gog, T., Paas, F., & Leutner, D. (2015). Measuring cognitive load with subjective rating scales during problem solving: Differences between immediate and delayed ratings. *Instructional Science, 43*, 93–114.
Schnotz, W., Hauck, G., & Schwartz, N. H. (2022). Multiple mental representations in picture processing. *Psychological Research, 86*, 903–918.
Schooler, J. W., Fiore, S. M., & Brandimonte, M. A. (1997). *At a loss from words: Verbal overshadowing of perceptual memories*. Academic Press.
Sengupta, P., Krinks, K. D., & Clark, D. B. (2015). Learning to deflect: Conceptual change in physics during digital game play. *The Journal of the Learning Sciences, 24*(4), 638–674.
Seufert, T. (2003). Supporting coherence formation in learning from multiple representations. *Learning and Instruction, 13*(2), 227–237.
Sherin, Z. W., Cheu, R., Tan, P., & Kortemeyer, G. (2016). Visualizing relativity: The OpenRelativity project. *American Journal of Physics, 84*(5), 369–374.
Squire, K. D. (2021). At play in the cosmos. *International Journal of Designs for Learning, 12*(1), 1–15.
Stull, A. T., Hegarty, M., Dixon, B., & Stieff, M. (2012). Representational translation with concrete models in organic chemistry. *Cognition and Instruction, 30*(4), 404–434.
Taber, K. S. (2014). The significance of implicit knowledge for learning and teaching chemistry. *Chemistry Education: Research and Practice, 15*, 447–461.
Tahir, R., & Wang, A. I. (2020). Codifying game-based learning: Development and application of LEAGUE framework for learning games. *Electronic Journal of E-Learning, 18*(1), 69–87.
Tsai, M. J., Huang, L. J., Hou, H. T., Hsu, C. Y., & Chiou, G. L. (2016). Visual behavior, flow and achievement in game-based learning. *Computers & Education, 98*, 115–129.
Tuzun, H., Barab, S. A., & Thomas, M. K. (2019). Reconsidering the motivation of learners in educational computer game contexts. *Turkish Journal of Education, 8*(2), 129–159.
Van Gog, T., & Paas, F. (2008). Instructional efficiency: Revisiting the original construct in educational research. *Educational Psychologist, 43*(1), 16–26.
Virk, S. S., & Clark, D. B. (2019). Signaling in disciplinarily-integrated games: Challenges in integrating proven cognitive scaffolds within game mechanics to promote representational competence. In O. O. Adesope, & A. G. Rud (Eds.), *Contemporary technologies in education: Maximizing student engagement, motivation, and learning* (pp. 67–95). Palgrave Macmillian.
Virk, S., Clark, D., & Sengupta, P. (2015). Digital games as multirepresentational environments for science learning: Implications for theory, research, and design. *Educational Psychologist, 50*(4), 284–312.
Wang, J., Stebbins, A., & Ferdig, R. E. (2022). Examining the effects of students' self-efficacy and prior knowledge on learning and visual behavior in a physics game. *Computers & Education, 178*, 1–13.
Yu, Z., Gao, M., & Wang, L. (2021). The effect of educational games on learning outcomes, student motivation, engagement and satisfaction. *Journal of Educational Computing Research, 59*(3), 522–546.
Zhonggen, Y. (2019). A meta-analysis of use of serious games in education over a decade. *International Journal of Computer Games Technology*, 1–8, 2019.