Research in Science Education (2021) 51:235–275
https://doi.org/10.1007/s11165-018-9794-8

# Conceptual Blending as an Interpretive Lens for Student Engagement with Technology: Exploring Celestial Motion on an Interactive Whiteboard

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## Abstract

We present and analyze video data of upper secondary school students' engagement with a computer-supported collaborative learning environment that enables them to explore astronomical phenomena (Keplerian motion). The students' activities have an immersive and exploratory character, as students engage in open-ended inquiry and interact physically with the virtual environment displayed on an interactive whiteboard. The interplay of students' playful exploration through physical engagement with the simulation environment, their attention to physics concepts and laws, and knowledge about the real planets orbiting the Sun presents an analytical challenge for the researcher and instructor encountering such complex learning environments. We argue that the framework of conceptual blending is particularly apt for dealing with the learning environment at hand, because it allows us to take into account the many diverse mental inputs that seem to shape the student activities described in the paper. We show how conceptual blending can be brought together with theoretical ideas concerned with embodied cognition and epistemology of physics, in order to provide researchers and instructors with a powerful lens for looking critically at immersive technology-supported learning environments.

**Keywords** Conceptual blending · Physics · Computers · Interactive whiteboard · Embodied cognition · Computer-supported collaborative learning

## Introduction

In this paper, we deal with a technology-supported learning activity in physics. We study two small groups of upper secondary students as they engaged with an interactive whiteboard

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(IWB) to explore the mechanics of orbital motion and analyze their engagement through the theoretical lens of conceptual blending (Fauconnier and Turner 2002).

The students used the IWB in combination with Algodoo—a 2-D simulation software that can serve as a *Newtonian sandbox*, allowing the user to draw objects in a virtual 2-D world; set their material properties, such as mass and *bounciness*; and construct virtual scenarios using these objects. The created objects can also be manipulated via the IWB's touch-sensitive screen. For example, one can grab an object, drag it around, and throw it.

At the beginning of the activity that we study here, students were introduced to a virtual scenario in the form of a scaled-down model of a massive body interacting with other bodies via gravity. The Algodoo scene contained a large central object, which attracted other (typically smaller) objects that students could create themselves. It became clear very early that students interpreted the virtual scene as representing astronomical phenomena. The instructor present in the room gave each group of three students brief instructions: explore how smaller bodies move in the vicinity of a massive central body (quickly interpreted by students to represent the Sun). Excitingly, students almost immediately took advantage of the setup's affordances for open-ended inquiry and started exploring the environment by interacting with the IWB. In this paper, we attend to two groups of students engaging in exploration on the IWB.

The two groups of students differed somewhat in their approaches to exploration within the IWB-based environment. While group 1 took what resembled a hands-on, experimentalist approach, group 2 explored the orbital motion phenomena from a more theory-driven perspective, continuously relating their findings to their existing knowledge of physics and astronomy.

We propose that the framework of conceptual blending[1] (Fauconnier and Turner 2002) provides a useful lens and language through which the studied complex and multifaceted student activities can be interpreted. We show how conceptual blending has the potential to account for context-specific features of student interaction and engagement that emerge in the observed learning activities, as well as for the variation in the two groups' approaches to inquiry. Finally, we show that conceptual blending as a framework, paired with other theoretical inputs, can serve as a tool for investigating students' epistemologies at the crossroads of real and digital worlds.

Conceptual blending (Fauconnier and Turner 2002) is particularly apt for interpreting the activities at hand for two main reasons. First, it deals with in-the-moment and on-the-spot thinking and meaning-making, which depend on the context in which they occur. Second, it provides an explanatory mechanism for how people can mentally bring together (blend) seemingly disparate *mental spaces* to gain new insights from the resulting *blended spaces*.

We propose a model, which, in conceptual blending terms, consists of a set of five conceptual input spaces that students recruit in diverse ways when they engage in collaborative and creative exploration in the IWB-based learning environment. We have arrived at these particular input spaces by informing the blending analysis with theoretical considerations about the epistemology of science, as discussed by Hestenes (1992) and diSessa (1988), and insights from embodied and distributed cognition (Barsalou 2008; Hutchins 1995a, 2005; Lakoff and Johnson 1980).

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[1] Conceptual blending as a cognitive theory should not be confused with "blended learning," the approach of combining, or blending, teaching through digital interactive technology with physical face-to-face lectures.

The central goal of the paper is to show how the relatively broad theory of conceptual blending can be used as a frame, which can accommodate other more narrowly focused theoretical constructs to provide us with a better understanding of different facets of technology-supported learning environments. In particular, the examples and their treatment provided in this paper give insights into students' creative exploration of a topic that is typically unavailable for exploration at the human scale. Furthermore, the proposed way of conceptualizing student activities provides researchers and students with an interpretive lens, which can guide them in exploring and even addressing students' epistemologies of computer simulations, as they relate to the discipline of physics.

## Emergence of "Planet-Throwing"

Before we describe the framework of conceptual blending in more detail, we wish to give the reader a flavor of the students' spontaneous and immersive engagement with the IWB-based learning environment. We thus start by presenting examples 1–3 of student interaction.

These examples illustrate how one of the groups (group 1) spontaneously interpreted the learning environment as relating to astronomical phenomena (example 1), recognized the environment's affordance for physical engagement—"throwing of planets" (example 2), and in a matter of minutes began to investigate the motion of planets by "throwing" them into orbits around the "Sun" (example 3). In other words, from the point of view of conceptual blending, they engaged in "running a blend" of everyday and astronomical conceptual spaces.

**Example 1: Interpreting the Central Object as the Sun** A group of three students was presented with a learning environment that consisted of an interactive whiteboard running a piece of software that simulated a massive star. The star was represented as a yellow circle on a dark background. However, the students were not explicitly told that this virtual object is supposed to represent a star, when the following interaction occurred:

> The instructor (the first author, BG) opens up the Algodoo scene and points to the yellow circular object in the middle.
> In a matter of seconds, S2 says: "The Sun."

As can be seen in the very brief excerpt above, one student almost immediately interpreted the yellow central object on the screen to be the Sun. While the scene was designed with the purpose of invoking such associations, it was not clear before the student activity began that the students would spontaneously and in such a short time make connections to an astronomy context. It became clear from the first seconds of the activity that it was going to be about astronomical phenomena.

**Example 2: Coming up with the Idea of Throwing Objects in the Digital Environment** As students started to engage with the IWB, they drew multiple objects on the screen. The software simulated the created objects as massive bodies that were attracted by the "Sun." The objects fell onto the Sun's surface (the Sun is modeled as a solid object and smaller objects typically bounce and tumble for a few seconds before they come to a rest on its surface). The instructor encouraged the students to explore the scene further:

I: What else could you do now with these objects that you have there?
S2: Can we throw them around? [looks at the instructor]

After being encouraged by the instructor's question to consider new ways of interacting with the on-screen content, one of the students came up with the idea of manipulating ("throwing", in his own words) the created objects in the virtual environment projected onto the IWB. Shortly after S2 came up with this idea, the students began to create additional objects and "throw" them into orbits around "the Sun." The act of throwing was performed using a stylus, as is described in Fig. 1.

**Example 3: "Throwing Planets into Orbit"** Just minutes after the idea of throwing objects on the IWB emerged, the students were already actively attempting to throw objects that they created into closed orbits (orbits that repeat themselves periodically). The objective of achieving closed orbits was set by the students themselves—it seemed to have been perceived as a compelling outcome of a throw.

We should point out that while the idea of throwing planets is extraordinary and detached from the ways in which we as human beings relate to the world of celestial objects, the involved students recognized the affordance of the learning environment astoundingly quickly and engaged in planet-throwing immediately thereafter. As we will further elaborate in this paper, the students were able to recruit the seemingly disparate conceptual input spaces of celestial phenomena and throwing, because they share an underlying generic structure—a generic conceptual space common to the seemingly disparate input spaces.

The particular throw (one of many performed throughout the activity) presented in Fig. 1 was not considered particularly successful by the students, since the planet left the field of vision (the virtual space visible on the screen). This outcome initiated a debate about whether the planet would return back after sufficient time had passed. Eventually, the planet did return, orbiting in an eccentric, but closed orbit, which could be seen upon zooming out within the simulation environment. Zooming out was suggested by S3 shortly after S2 performed the throw.

## Variation in the Two Groups' Creative Exploration Strategies

In addition to proposing and arguing for conceptual blending as a framework to study student engagement, this paper will use the framework of conceptual blending to interpret some of the

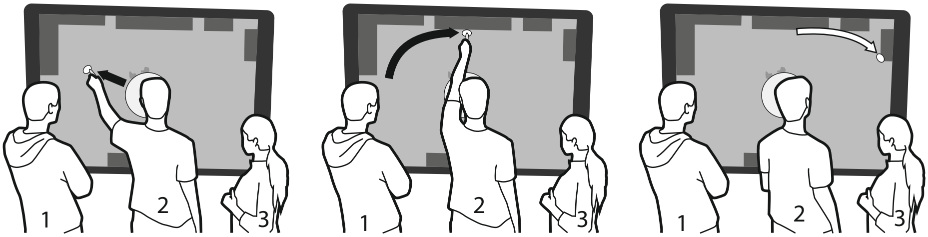

**Fig. 1** A student (S2) performing a typical "planet throw." He (a) picks up a planet (using a stylus) which is resting on the "Sun's" surface, and carries it away from the Sun (to the left); (b) moves his hand across the screen, releases the planet (releases the contact of the stylus and the IWB, while still moving the hand), retracts the stylus away from the IWB surface; and (c) observes the planet continue on its trajectory after the release. The other two students attentively follow his actions. The black arrows illustrate the path of the student's hand as he dragged the planet, and the white arrow represents the path of the planet itself, continuing also after the release in (b)

differences (procedural and epistemological) in explorative approaches that the two studied groups of students exhibited.

To better understand the approach to inquiry employed by this first group, we are interested in how students can quickly go along with the idea of being able to "throw planets into orbits around the Sun." In particular, group 1 engaged in exploration using their bodies via manipulation of on-screen content. In the section "Immersion and Emergence," we look at how notions stemming from embodied cognition can feed into conceptual blending theory to provide insights into students' spontaneous physical engagement in the studied learning environment.

In contrast to group 1, the second group of students, group 2, took a more analytical and theoretical approach to exploring the virtual environment on the IWB. Group 2 more explicitly addressed conceptual questions in the topic of celestial mechanics by referring to formal physics concepts and by making connections between their knowledge of Newtonian mechanics and the observable universe as it was made known to them through sources other than the learning environment at hand (school, the internet, books, documentaries, etc.). Furthermore, group 2 also compared the output of the used simulation to known observations of real-world celestial phenomena—questioning and testing its range and fidelity. We will demonstrate the second group's more critical approach to the learning environment through more detailed examples later in the paper (see section "Disambiguation and Unpacking").

Instead of seeing the two groups' differing strategies for engagement with the IWB-based environment as two fundamentally different approaches to inquiry, we propose that both groups exhibited some elements of the immersed and embodied, as well as analytical and theory-driven engagement. Looking at student engagement through our proposed interpretive lens can give researchers and hopefully also instructors a more nuanced perspective on students' creative activities. It can help explain variation in students' approaches to inquiry especially in multifaceted learning environments like ours. Furthermore, it allows us to uncover the processes that may lead to students' different epistemological appreciation of the activities at hand. In this way, the framework we propose can serve as an instructor's road map, helping them to locate students in the conceptual and epistemological landscape. By doing this, the instructor can help students navigate the conceptual landscape, and help them in developing appropriate disciplinary epistemological perspectives.

## Research Questions

In light of the introduction above, the research questions that guided our study were as follows:

1. How do students recruit their embodied experience when engaging in collaborative inquiry about orbital motion in an interactive computer-supported learning environment?
2. What differences are there in two studied groups' approaches to creative exploration of the environment, and how can we account for them using conceptual blending as an interpretive framework?
3. What limitations of immersive engagement with the studied learning environment are there with regard to the development of expert-like epistemological views of physics?

## Theoretical Framework

### Embodied Cognition and Learning

Embodied and distributed perspectives on cognition and learning (e.g., Barsalou 2008; Hutchins 1995b; Lakoff and Johnson 1980; Wilson 2002) have developed with the insight that we cannot study cognition as a phenomenon that is isolated in individual human minds. Instead, cognition has to be regarded as interaction between body and mind and between individuals and their material and social environments. Such perspectives seem to provide useful insight into student participation in learning environments that combine computer-generated worlds, student immersion, and students' physical engagement. Gallagher and Lindgren (2015) have used the term *enactive metaphor* in their analysis of students' enactment of asteroid motion, among others, to refer to physical movements as expressions of conceptual metaphors, drawing on the theory of Lakoff and Johnson (1980), as well as other theoretical frameworks, including Fauconnier and Turner's (2002) conceptual blending.

Lakoff (1987) and Johnson (1987) argue that our cognition and language are grounded in embodied experiences, which form basic conceptual structures termed *image schemas*. As an example, through our interactions in physical space, we develop a container image schema, a basic structure through which we can conceptualize objects being in or outside of a confined volume. Such schemas can be expressed in language, for example in the utterance "John is in the kitchen." Furthermore, image schemas also structure the manner in which we conceptualize abstract domains, such as states or emotions, by means of metaphorical projection from more concrete domains through *conceptual metaphor* (Lakoff and Johnson 1980, 1999). For example, by stating that "John is in danger," an abstract state is conceptualized as if it were a physical location. Lakoff and Núñez (2000) have even shown how mathematics—one of the most abstract areas of human thought—is grounded in embodied experiences. For instance, the idea of an equation draws on a shared balancing image schema.

Lakoff and Johnson's (1980, 1999) theories have received interest in educational research, in arguing that students can draw on their embodied experiences in learning abstract concepts in mathematics education (e.g., Hall and Nemirovsky 2012) and science education (Amin 2009; Amin et al. 2015; Andersson 1986; Jeppsson et al. 2013; Niebert et al. 2012; Roth and Lawless 2002). For example, Amin (2009) shows how energy, a highly abstract concept, often is construed as a concrete substance-like entity in physics textbooks. By means of conceptual metaphor, the container image schema is projected onto the energy domain, so that we can talk about energy in an object at a certain state, and processes of energy moving in and out of the object.

For the purpose of our study of student interaction with a digital learning environment, we found conceptual blending (Fauconnier and Turner 2002) particularly apt, as it allows analysis of how the students came to draw on a wide diversity of previous experiences when realizing that they suddenly had the ability to throw planets into orbit. In spite of apparent dissimilarity, we argue that the experiences they draw upon share a similar structure, which allows for congruence across these experiences (Johnson-Glenberg et al. 2014).

In our observations, we have seen students bringing together ideas from diverse conceptual domains and combine them to produce new meaning. The emergence of novel ideas during students' engagement is thus not necessarily a result of unidirectional projection of ingrained patterns of thought and language from embodied experiences to more abstract phenomena, as in the case of conceptual metaphor (Lakoff and Johnson 1980). Using conceptual blending as the theoretical lens for our analysis allows us to account for the emergence of new ideas as a result of students bringing together diverse and multifaceted experiences, explicit and implicit knowledge and skill sets.

In the following section, we describe conceptual blending, how it has been used in previous educational research, and how we have adopted it in the present study.

## Conceptual Blending

Fauconnier and Turner (1998, 2002) have developed the theory of *conceptual blending*, also known as conceptual integration, within the academic field of cognitive linguistics. With the rather grand title of their book, "The way we think," Fauconnier and Turner (2002) set out to describe conceptual blending as a type of cognitive operation, with detailed descriptions of the underlying mechanisms of thought, illustrated with a wide range of examples from language, literature, images, human interaction, etc.

As an illustration of conceptual blending, consider the example of "the Regatta" (Fauconnier and Turner 1998). A catamaran sailed from San Francisco to Boston in 1993 in an attempt to break the record established by a clipper in 1853. At some stage after the journey began, a sailing magazine reported that the catamaran was "barely maintaining a 4.5 day lead" over the clipper (cited in Fauconnier and Turner 1998, p. 155). What could "maintaining a lead" mean here? Fauconnier and Turner suggest that the phrase refers to a blend, a fictitious race where the ships are sailing from San Francisco to Boston at the same time—regardless of the separation of 140 years between the actual events.

Conceptual blending makes use of *mental spaces* (Fauconnier 1994), distinct conceptual domains that have internal structure with elements and relations between those elements, representing events, causality, etc. As a starting point for the overall process of conceptual blending, there are two or more *input spaces*. In the case of the ship race, the journey of the clipper and the journey of the catamaran constitute the two involved input spaces, with elements such as the clipper and the catamaran, respectively, a starting point, an end point, the position of the ships at different points in time, etc. The two spaces share many characteristics and can be argued to draw from and be instantiations of a *generic space*, consisting of a (nonspecified) ship, the same starting and end points, and the sequence of days on a journey between them.

In this case, due to the similarity of the input spaces, they can easily be related to one another through the process of *cross-space mapping*, where corresponding elements and relations are identified across the two input spaces. Now, selected features from the two input spaces are projected to a new space, a *blended space*. Some of the features are unaltered, such as the starting and end points of the journeys, others correspond to each other (e.g., the first day of the journeys), or are ignored. Crucially, however, in this process of *composition* of the blended space, novel characteristics emerge in the blended space that do not exist in any of the input spaces. In this case, *both* the clipper and the catamaran are projected to the blended space and can be put in relation to one another. Through the process of *completion* of the blended space, we can now draw on our previous familiarity with races in construing the scenario of a ship race. Situations like one of the ships maintaining a lead unfold through imaginative mental simulation, *running the blend*, in the process of *elaboration* of the blend. Finally, having run the blend before our mind's eye, we can draw inferences with regard to the original input spaces, a type of backward projection from the blend (Fauconnier and Turner 1998, 2002). For instance, we can conclude that the catamaran has traveled faster on average than the clipper did. Ultimately, the blend can be *unpacked* and thereby reveal the nature of the network of spaces that fed into it (Fig. 2) (Fauconnier and Turner 2002).

The Regatta is a quite simple example of conceptual blending, with two similar input spaces that feed into the blending process. Similarly, analogy and conceptual metaphor may be considered as cases of *single-scope networks* of spaces, where the blended space inherits the structure entirely from one of the input spaces, the source domain. Here, the structure of the source domain is projected onto the target domain, and new structure features do not emerge during the elaboration. Insight is rather gained from interpreting the target domain in a novel way.

Fauconnier and Turner (1998, 2002) also describe a range of more complex types of blending that involve several input spaces that differ strongly in character. As an example, Fauconnier and Turner (1998) describe how the development of the computer desktop environment relied on a blend of the structure from two very dissimilar spaces: the physical desktop, with its working space, chests of drawers, etc., and computer operation systems in a very productive manner. The computer desktop environment is an example of a *double-scope network*, where different structural elements are brought from two input spaces into the blended space and novel features emerge in the elaboration. Even more complex *multiple blends* can be generated by drawing on more than one input space in forming a blend, or a sequence of blends, where blended spaces serve the function of input spaces for yet another blended space (Fauconnier and Turner 2002).

With regard to challenges to running a blend, Fauconnier and Turner (2002) suggest that we are helped by different governing principles, with the overarching goal being to “achieve human scale,” in the form of blends that “typically have very few participants, direct intentionality and immediate bodily effect, and are immediately apprehended as coherent”

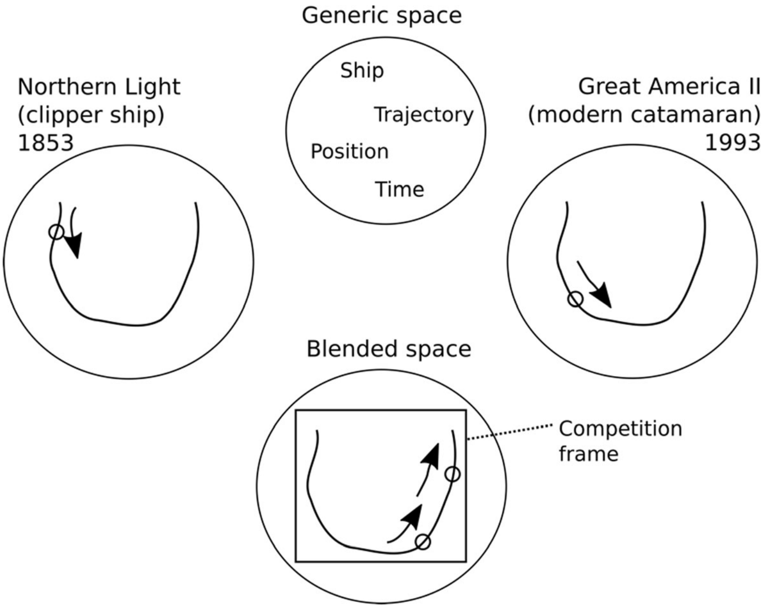

**Fig. 2** The figure represents two input spaces (left and right), a generic space (top) and a blended space (bottom). In this case, two ship voyages separated in time by more than a century are brought into a common frame (competition), resulting in a blended space, where the two ships race each other from San Francisco to Boston

(p. 312). One central way to achieve human scale when forming blends is *compression* of different kinds. Taking an example from science learning, in understanding evolution of species, we readily compress entire populations of animals into individual specimens as representatives for their periods and compress hundreds of thousands of years down to a matter of years or even minutes, which is manageable at the human scale. The mechanism is powerful, but therefore also possibly deceptive. In our view, as analysts and science teachers, this may help us understand the immediate attraction among students of Lamarck's theory of evolution in terms of inheritance of acquired traits from one individual to its offspring, without considering Darwin's recognition of the role of random variation in a population and the process of natural selection.

Then again, Fauconnier and Turner (1998) also suggest that conceptual blending has served academic development in more productive ways, and propose the case of complex numbers as a blend of two input spaces representing the real numbers and geometrical points in 2-D space. Much of the creative power of blending lies in the possibility to generate *counterfactuals* by combining characteristics of disparate spaces in double-scope blending (Fauconnier and Turner 2002). Counterfactuals can be used in everyday settings, such as the example of the Regatta—the ships are actually not engaged in a race—but also in formal, scientific reasoning, such as the method of *reductio in absurdum*. Fauconnier and Turner (2002) describe this method as falsification of a hypothesis by blending it with unquestionable premises and experimental results and showing the unreasonable consequences. In our view, the tradition of thought experiments in science (e.g., Gilbert and Reiner 2000) can also be regarded as relying on counterfactual scenarios generated through blending. Examples include Einstein imagining what it would be like to chase or ride on a ray of light, or "Newton's cannon," in which Newton foresaw that a cannon ball, if launched horizontally with sufficient velocity, would orbit the Earth and hit the gunner in the back (Velentzas and Halkia 2013).

## Material Anchors of Conceptual Blends

Based on the case of the complex cognitive task of navigation of a large marine vessel, Hutchins (1995a) contributed to the development of the theory of distributed cognition, according to which cognition is not confined to manipulation of symbols in an individual's mind. Cognition is rather seen to be materially anchored in our physical surroundings, through the use of our senses, perception, technological tools, etc., and socially dependent on shared culture and communication. In relation to conceptual blending, Hutchins (2005) points to the general problem of achieving conceptual stability, in terms of knowing what elements and relations can change and which need to remain unaltered, in particular when combining inputs of very disparate nature. Hutchins argues that material structure—including but not restricted to technical artifacts—may contribute to conceptual stability, by acting as *material anchors* for the blends. Hutchins provides a queue as an example, where the physical location and orientation of its participants contribute to the experience of linearity and order. Rather than using mental representations of the involved people as the input space for the blended space of the queue, with material anchors, Hutchins sees the people themselves, as physical objects, as the input to the blending process. In this way, our perception of the material world provides structure to the blend, through a kind of cognitive offloading.

## Conceptual Blending in Educational Research

In the last decade, conceptual blending has attracted increasing interest as an analytical approach in educational research, in particular within the physics education research community. The interest was sparked off with Bing and Redish's (2007) suggestion that mathematical machinery and students' understanding of the physical world can be interpreted as input spaces which students draw on in forming a blend of physically meaningful calculation in problem solving. Such connections between physics and mathematics in terms of conceptual blending were investigated in more detail by Hu and Rebello (2013), as they analyzed physics students' productive and unproductive approaches to setting up integrals in physics problem-solving exercises.

Students' understanding of wave phenomena is another area of research where conceptual blending has been seen as a fruitful analytical perspective. Podolefsky and Finkelstein (2007) analyze how increasingly abstract phenomena have been interpreted in terms of waves (from water waves, through sound and electromagnetism, to quantum phenomena) from the perspective of conceptual blending. Knowledge of visible mechanical waves and sound are input spaces in generating the blend of sound-as-wave, which, in turn, serves as an input space in theorizing electromagnetic radiation in terms of waves, forming a sequence or kind of cascade of blends.

In parallel with the example of natural selection above, Wittmann (2010) uses the blending theory to explain that it is tempting, although misleading, for students to use their experience of throwing balls when identifying factors that impact the speed of propagation of a wave on a suspended string. Similarly, Hrepic et al. (2010) studied students' understanding of sound propagation and found students to combine a scientifically sanctioned view of sound as longitudinal waves with ideas involving sound as a self-standing entity, different from the medium through which it propagates. As a result, students formed different conceptual models of the phenomenon, drawing on the constituent, scientific models but in inconsistent ways and with features that did not exist in any of them, which is interpreted as cases of conceptual blending. In their analysis, Hrepic et al. further relate such blended models to the notions of "synthetic models" (Vosniadou 1994) and "hybrid models" (Justi and Gilbert 1999) from research on students' challenges with science learning.

In a special issue on the theme of "Conceptual metaphor and embodied cognition in science learning" in the *International Journal of Science Education*, two of the contributions comprise conceptual blending analyses. Close and Scherr (2015) show how in-service science teachers' engagement in Energy Theater—an activity where individual participants represent units of energy and enact physical scenarios involving energy transfer and transformations—may be interpreted as a blend of a literal learning space of the involved people and equipment and a physical scenario space of the enacted phenomenon. In addition, Dreyfus et al. (2015) analyze a lecturer's and a student's coordination of different metaphorical construals of energy in terms of conceptual blending. In particular, they give examples where spoken language of energy as a substance is used in conjunction with gestures indicating energy as a vertical location. The resulting blend shows how different ontological views on the nature of energy can be applied concurrently in an adequate, flexible way in science communication. Recently, Dreyfus et al. (2016) have identified similar blending of energy as a vertical scale and energy as a substance also in students' group discussions when trying to understand the mechanism for atomic emission spectra.

Enyedy et al. (2015) draw on individual students' conceptual blending, material anchors (Hutchins 2005), and socially distributed cognition, in analyzing how groups of elementary students interact with an augmented reality learning environment relating to mechanics. In bringing together the multiple theoretical perspectives, they developed a new framework termed *liminal blends*, a blend in its own right. They studied how students enacted with their bodies the effects of different types of surfaces on a rolling ball, and could compare their own enactment to the outcome in a simulation environment. Enyedy et al. used liminal blends to account for the complex emerging dynamics in a setting where the simulation, physical, and students' social spaces were tightly intertwined. Similarly, Hoehn and Finkelstein (2018) employ conceptual blending in conjunction with distributed cognition (Hutchins 1995a) and sociocultural perspectives on learning (e.g., Lave and Wenger 1991) in their analysis of university physics students' small group dialog on modern physics, and students have been found to make use of collectively constructed blends as they reasoned about quantum phenomena and negotiated their understanding of what different quantum entities, such as electrons and photons, actually are (Fredriksson and Pelger 2018).

## Intuitive Engagement with Digital Environments

Astonishingly, the human capacity for intuitive problem solving in combination with fine-tuned motoric skills in interaction with computer-game-like environments has been shown to be a viable resource for solving computationally difficult problems in science, including quantum mechanics—Quantum Moves (Sørensen et al. 2016) and chemistry—Fold it! (Cooper et al. 2010). The intuition, even that of nonscientists, appears to have the potential to become a credible partner of other more "rigorous" approaches in contemporary science, by means of interactive media.

From an educational perspective, these findings are of great interest in two ways. First, they reinforce the idea that developing intuitive conceptual understanding is worthwhile (Clement 2008). If we only convey formal, algebraic problem-solving skills to our students, we miss out on powerful resources for doing science. Second, they showcase how topics that are otherwise far from experiential reach can be brought to the human spatial and temporal scales by means of modern technology. This can help learners develop understanding of topics that have traditionally only been accessible to those with good mastery of higher mathematics, as in the case of Quantum Moves.

The increasing availability of technologies, such as virtual reality goggles, technologies that allow superposition of digital elements on real-world objects (the so-called augmented reality), large touch-responsive interfaces (e.g., the IWB), or more common handheld gadgets (tablets and smartphones), so ubiquitous in our lives, allow for ever-increasing levels of immersive experiences. At a general level, immersion means deep involvement in something. In the context of computer environments, Dede (2009) defines immersion as "the subjective impression that one is participating in a comprehensive, realistic experience" and further elaborates that "interactive media now enable various degrees of digital immersion. The more a virtual immersive experience is based on design strategies that combine actional, symbolic, and sensory factors, the greater the participant's suspension of disbelief that she or he is 'inside' a digitally enhanced setting" (p. 66). Johnson-Glenberg et al. (2014) have proposed a taxonomy for digital learning environments based on their immersiveness (i.e., user-perceived immersiveness) and the degree and type of sensorimotor engagement they afford. Intuitively, it seems that experiences from a first-person perspective in a 3-D space in which the user can move and act in ways that closely resemble their everyday interactions with the environment invoke a stronger sense of immersion. Still, the sense of immersiveness is subjective and depends both on the content being displayed, as well as the users—their motivation, willingness, and tendency to suspend disbelief.[2]

Yet, as exciting and engaging the digital environments can be, their use in education should be accompanied with a degree of skepticism. Will learners develop a proper epistemological attitude toward physics, if they learn important lessons completely immersed in carefully engineered digital environments? How refined will be their understanding of the distinction between the real world and the models we use to describe it? In the next three subsections, we will briefly introduce epistemological considerations that shape physics as a scientific field. We will use conceptual blending together with these ideas to frame some of the intricacies of the interplay between the *real* and the *modeled* worlds.

## A Conceptual Blending Look at the *Model–Reality* Relationship

The creation and testing of models is arguably the central activity of the physics enterprise (Hestenes 1992). An expert physicist-like epistemology of the field therefore entails an understanding of the relationships between models and the physical phenomena they represent. Infusing the conceptual blending framework with the modeling theory proposed by Hestenes gives it the potential to become useful for educational purposes in physics, as a research tool, as well as an instructor's aid, by providing a language for discussing epistemological issues involving physics instruction in technology-rich learning environments.

In portraying modeling as the core activity of physics, Hestenes (1992) assumes a constructivist epistemology of science. In the constructivist view, the laws of physics (e.g., Newton's laws) are considered a construct of the human mind, not to be confused with physical reality. In this paradigm, there is a clear distinction between a model and a phenomenon that is represented by the model. Models in physics are built using formal rules that can form complete conceptual domains (e.g., Newtonian mechanics, Maxwell's electrodynamics).

Even though there is a clear distinction between the physical world and models of it, formal concepts and models derived from them in important ways shape our perception of the world. "Seeing physics" in everyday phenomena—such as focusing on the uniform acceleration of a falling object rather than avoiding being hit by it—exemplifies the process of understanding the world in terms of models, though this process may often remain unconscious not only for physics students, but also for physicists.[3] Furthermore, the formal concepts and theories determine the reach of scientific observation, measurement and discovery: "One cannot discover what one cannot conceive" (Hestenes 1992, p. 733).

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[2] Assessing the degree of immersiveness opens up an interesting issue. It is not clear how one can draw the line between immersion as a process in which a person temporarily suspends disbelief, on one hand, as suggested by Dede (2009), and immersion as pretense, on the other. Pretense means the person merely *acts* as if the situation was real, or acts by simply imitating another person performing certain actions, without necessarily submitting to their "realness."

[3] Yet, many everyday experiences, while often perceived by physicists as being "cases of physics," are also available for those, who have never heard about Newton's laws.

## Students’ Blends of Formalism and the Physical World

Students do not necessarily make explicit distinctions between physics formalisms (e.g., the Newtonian world) and the real, physical world (Hestenes 1992). Hestenes suggests that students often have a hard time realizing that the Newtonian world is an ideal world, built on clear definitions and axioms, in contrast to the physical world, which we experience through our senses and measuring equipment. In the language of conceptual blending, students can form their personal blends of *formal model* and *physical reality* conceptual spaces, without necessarily realizing the distinct nature of these input spaces, which is characteristic of a constructivist epistemology of science. This means that students might not think of concepts such as forces or energy purely as human constructs, but also as physical entities.

For the time being, we will therefore not assume that all students in our study make clear and conscious distinctions between the formal and physical worlds, although certain examples that we present suggest that some of them are able to do so.

## Computer Simulations in Relation to Physics Modeling

Computer simulations seem to fit quite well with the formal side of the model/modeled duality and can be viewed as digital instantiations of formal models. As in any modeling activity, one has to choose which aspects of a phenomenon are to be incorporated into a simulation. In the case of mechanics, one can choose to account for inelastic collisions or extended body gravitational interactions or go for perfectly elastic collisions and point mass gravitational interactions, for example. However, a more fundamental characteristic is that simulations, in contrast to traditional analytical mathematical modeling, operate numerically through algorithms. Choosing a particular integration time step in the algorithms that constitute the simulation may cause the computer model to deviate not only from the physical phenomena it attempts to model, but also from the underlying formalisms that serve as their base.

Assuming a learner’s point of view provides us with another perspective on this matter, one that does not fit nicely into either of the two poles of the model/modeled duality. Simulations can help a learner who is not well versed in operating within formal domains make more intuitive sense of formalisms. As visualization tools, simulations can serve as a perceptual bridge between the physical and formal domains. Furthermore, simulations can be manipulated to get quick, often instant feedback on the behavior of a digitally instantiated model. In many cases, they lend themselves to inquiry-style learning activities, similar to physical experiments, but also allowing counterfactual scenarios. DiSessa (1988, p. 64) introduced the term *semiformalisms* for “manipulable systems that can serve as general and precise formalisms, but which retain for students a sense of familiarity and evident controllability.”

In this sense, Algodoo fits very well with diSessa’s formulation of semiformalisms (Euler and Gregorcic 2018). On one hand, it makes possible the use of traditional representations, such as force and momentum vector arrows, and allows the user to change the modeled objects’ parameters (mass, “bounciness,” etc.). On the other hand, it allows students to play around in the digital environment, observe consequences of their actions, and develop a “feel” for the Newtonian world (or at least its digital instantiation) through exploration. With its intuitive graphical interface, especially when combined with the touch-screen capability of the IWB, Algodoo speaks to those who feel at home in the digital world and allows them to spontaneously engage with the simulated environment.

From the point of view of modeling as central in the physics enterprise, Hestenes (1992) points out that confusion about the “trueness” of models is common among students, who often misinterpret formal descriptions as one-to-one mappings of reality. If physics is presented to students as consisting primarily of formal descriptions, which are in turn demonstrated by experiments (“demos”), this should come as no surprise. Furthermore, if this is done in an authoritative way, the students may see “doubting physics” as undesirable, despite the cultivation of skepticism toward models and theories being crucial to the physics (or any science, for that matter) enterprise.

Simulations in physics appear to invite more direct scrutiny than traditional mathematical models. This seems to be due to the simulations’ tendency to inhabit a different epistemological category than “pure” mathematical models. This has also been pointed out by Greca et al. (2014), who, in reference to Johnson and Lenhard (2011), suggest that simulations, by merely *imitating* phenomena, are clearly not their “true” representations. This contrasts to mathematical models of physical phenomena that can more easily be perceived as being “true” representations of the workings of the world—thus the expression “laws of nature.” We speculate that this epistemological distinction, though not necessarily expressed in such explicit terms, is a key factor in shaping students’ critical attitude toward simulations.

## The Case of Orbital Motion

Astronomy is an example of a domain with which students typically have few, if any, experiences. Astronomical observations—beyond seeing the stars in the night sky—often require a great amount of time and are rarely simple to interpret. It does not come as a surprise that astronomy relies on representations such as drawings and simulations, both in research and education (Eriksson 2014). Thought experiments, such as Newton’s cannon, is another potential teaching approach (Velentzas and Halkia 2013).

The topic two-body orbital dynamics (e.g., Keplerian motion of a star and an orbiting planet) is an example of a topic that lends itself to representations in computer simulations, not least because it is relatively simple to model. Examples include educational simulations (LASP n.d.; PhET Interactive Simulations n.d.; Test Tube Games n.d.; The Nebraska Astronomy Applet Project n.d.) and various computer games. However, although widespread, many of these computer games are often not easily usable for educational purposes. For example, a version of the well-known game Angry Birds (Angry Birds Space 2016) models the motion of objects in space in a way that does not correspond to simple Keplerian motion,[4] in contrast to its flat-earth version, which models the flying trajectories as parabolas and has been shown to be useful in physics instruction (Rodrigues and Carvalho 2013). The game Kerbal Space Program[5] offers a well-simulated Keplerian experience but requires a significant investment of time and effort on the part of the student, so its use in the classroom can be a challenge.

Lindgren and colleagues (Lindgren and Moshell 2011; Lindgren et al. 2016) have developed and studied a so-called mixed reality learning environment where students act out the orbital motion of asteroids by walking across a floor with computer-generated images of stellar objects projected on the floor from above. They show that mixed reality learning environments can benefit learning by engaging students in physical motion, and thereby taking advantage of the principles of embodied learning (Lindgren et al. 2016). Related research shows that in

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[4] See Allain (2012) for a more detailed reverse engineering of the model behind Angry Bird Space.

[5] For an educational version of the game, see http://kerbaledu.com/.

order to best leverage students' embodied inputs for the purpose of conceptual learning, their physical actions need to be *congruent* (Johnson-Glenberg et al. 2014) with the concepts to-be-learned. For example, when learning about the movement of asteroids, the students' physical actions should relate to the movement of the asteroids. By enacting the motion of asteroids, students can thus develop intuitions about celestial kinematics.

The increasing availability of virtual reality technology and the development of accompanying software make it a natural choice for engaging with otherwise hard-to-reach phenomena. An excellent example of an extremely immersive 3-D environment that allows the exploration and manipulation of astronomical phenomena in intuitive ways is the Universe Sandbox (http://universesandbox.com). However, its educational potential is yet to be explored.

## Methods

### Instructional Design

The learning materials that we used in this study (Gregorcic 2015) have been developed as a part of a larger research project on the educational potential of interactive whiteboards in high-school physics. The rationale behind these instructional materials was to allow students to engage with the content (orbital motion) in a way that productively brings together students' motoric engagement and the relevant physics concepts. The initial goal of our learning environment has been to get students to explore Keplerian motion of objects in a simplified two-body system—both bodies behave gravitationally as point masses, they interact with each other via Newtonian gravity, and one body's mass is significantly larger than the other's. A more specific goal was to get students to explore the role of the initial velocity of an object in such a system, in how it impacts the shape of the orbit. As students "throw a planet into orbit" on the IWB surface, they enact, with their hands and arms, the initial motion of the planet, before they release it. As the initial velocity and position determine the body's motion after its release, the conceptual and embodied aspects of the activity can be seen as highly congruent (Johnson-Glenberg et al. 2014). At the same time, the large touch screen makes the experience relatively immersive for the students, compared to ordinary computer-screen and mouse interfaces or handheld touch-screen devices.[6]

Our learning environment is based on a 2-D physics sandbox software, Algodoo (www.algodoo.com, for examples of its educational potential, see Gregorcic and Bodin 2017). In addition to enabling student-embodied engagement with the simulation through the large touch screen of the IWB, Algodoo offers many different graphical representational possibilities (e.g., tracers, dynamic velocity and force vector arrows, plots) and allows students to engage with the digital environment in creative ways; they can draw planets of custom shapes, sizes, masses, and colors, as well as explore diverse hypothetical scenarios (e.g., the introduction of air resistance in space). One of the practical benefits of the Algodoo–IWB setup, compared to many other technologies used in studies of mixed reality or other technology-enhanced environments, is their accessibility. The IWBs have become relatively widespread in the recent decades (although they are often underused in schools) and Algodoo is freely available to download on Windows and Mac platforms and can be easily used in combination with

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[6] For a more detailed analysis and classification of immersiveness in computer-supported learning environments, see Johnson-Glenberg et al. (2014).

practically all IWB brands. In this way, a great number of schools, who already own an IWB, can use this setup at no additional cost.

## Participants and Setting

The student participants in the study were 15–16-year-old students from the first year of a 4-year upper secondary school in Slovenia. The school prepares students aged approximately 14–19 for university. All students in the school had experienced IWBs as a teaching tool for at least 6 months prior to our study and were familiar with its basic functions and operation. As part of the broader study of the school context (Gregorcic et al. 2018), we found that most students own or use on a regular basis smaller touch-enabled devices, such as tablets and smartphones. The students participating in our study were also part of a culture where touch-screen devices are ubiquitous—not surprising in this day and age (the data collection was done in 2014). All students had previously had 3 years of physics instruction (two 45 min lessons per week), 2 years at compulsory school level, and 1 year at upper secondary level.

On the request of the researcher (the first author of this paper), one of the physics teachers at the school asked, during his regular physics lesson, if any of the students would be interested in taking part in a study on the use of IWBs in physics instruction. The volunteering students (nine altogether) were asked to self-organize into groups of three. Each of the groups was then separately introduced to the Algodoo software a week prior to the recording session. In the presentation given to the students, the researcher demonstrated to the students Algodoo’s basic functionality and allowed them to briefly try it out on the IWB. This included the demonstration of drawing tools (to create virtual objects) and the possibility to play, pause, and undo the simulation. The students were not made aware of the possibility to use Algodoo to simulate celestial motion and had not used it in such a context until the recording session a week later.

In the weeks before the recording session, the students had learned in their regular physics class about the dynamics of circular motion, as well as Newton’s law of universal gravitation. Students in group 2 came from a class with special emphasis on natural sciences and had a stronger background in physics and mathematics than their peers from other classes. Some students already had some prior knowledge about Kepler’s laws, but their familiarity with the topic varied across and within groups.

At the beginning of the recording session, the researcher gave each group of students short instructions. They were asked to “explore how smaller objects behave in the vicinity of the central massive object.” During the recording session, the only person present in the room besides the three students was the researcher, who mostly sat at the back and did not interact with the IWB. However, he facilitated the students’ group activity by assuming a role of a technical advisor, helping students carry through with those ideas that he recognized as manageable and potentially conducive to learning, such as adding a tracer to the objects (see Fig. 7, for an example of tracer use). In addition to that, he steered students away from situations that would lead them too far away from the topic of simple orbital motion. For example, when students wanted to attach rocket engines to planets, the researcher suggested that they first explore their motion without the engines. Furthermore, the researcher also encouraged students to discuss their ideas, as they surfaced throughout the activity, by asking students for clarifications and further elaborations of their ideas. However, the students were given significant freedom to take the activity in their own direction, which, as we will see, resulted in differences among the scenarios that took place in each session.

### Data Collection, Processing, Analysis, and Representation

The recording sessions took place at the school, after the students had finished their classes for the day, and lasted for about 60 min. The student group activities were recorded using a video camera (which also recorded sound) placed on an elevated stand (about 2.5 m above the floor) about 4 m from the IWB, so that it did not disrupt the students' movement in front of the IWB. All students were in the frame of the camera for the whole duration of the session.

We have transcribed the video recordings and translated the transcripts into English.[7] We have used *InqScribe* software to transcribe student utterances. In the transcripts presented here, we have described gestures in square parentheses and underlined speech that coincided with the gestures.

We have repeatedly watched the video recordings and, informed with the theoretical framework of conceptual blending, identified cases of student engagement that indicate different subprocesses of blending taking place. In this article, we present a selection of cases in the form of vignettes that lend themselves to blending analysis and allow us to make a clear case for the usefulness of this approach from a researcher's, as well as a practitioner's perspective. The vignettes that we present in the "Introduction" first led us to consider conceptual blending as a theoretical lens to interpret what was going on in these learning situations.

The data collected offer a rich repertoire of episodes, which could be of great interest for their physics and astronomy conceptual richness, as well as students' resourcefulness in making meaning using means of expression other than spoken language, such as gestures (Gregorcic et al. 2017). However, our analysis here will not focus on the learning of particular concepts (e.g., shapes of orbits, escape velocity, which are kinematic parameters that impact motion), or the unique semiotic ecology that the students recruit. Instead, we will use conceptual blending to explain how students brought together diverse ideas and experiences to generate new ideas and engage creatively in collaborative inquiry. We will also show how the conceptual blending perspective can help instructors gain some insight into student epistemologies regarding computer-based learning environments.

## Analysis and Findings

### The Conceptual Input Spaces of the Learning Activity Blend

To formulate in terms of conceptual blending the complex learning situation at hand requires us to identify the ideas, concepts, and experiences that enter the learning activity as different *input spaces*. The spaces, elements within them, and relations (connections) between these elements within and across spaces form what we call a *learning web* of input spaces.

In building a model of the learning web of input spaces that make up and account for the multiple aspects of the learning materials and ways in which the students engage with them, we turn to (a) theoretical considerations about *modeling* as a core practice of the discipline of physics, to account for the "physics-side" of the learning activity; and (b) *embodied cognition*, to account for the students' physical engagement with the learning environment. While the

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[7] The analysis was based on the original utterances in Slovene, and translated excerpts in English are provided for the readers.

initial and central aim of our model (the learning web) has been to inform the interpretation and analysis of a highly complex learning situation, we propose that the same model can also be used to inform instructional design (see section "Implications for Instruction" at the end of the paper).

To illustrate our choice of the input spaces, we give an example of a student activity and propose five ways of interpreting it, each interpretation corresponding to a different input space. Take the student action of "throwing a planet into orbit" on the IWB screen (see Fig. 1). From a perspective of physics instruction, this can be interpreted as:

1. Launching a physical object (rock, asteroid, planet…) into orbit around a massive star.
2. Setting the initial conditions (size and direction of velocity, initial position) in a formal model (e.g., a Newtonian model) that represents two bodies interacting via gravity.
3. Setting the initial conditions in a computer instantiation, a simulation, of a model of a Keplerian system. This is different from (2), because the computer "runs the model" for us, giving the simulation a different epistemological status (Greca et al. 2014).
4. Throwing a physical object using one's hand.
5. Manipulating the touch-screen interface to perform a "touch-screen throw."

The first three interpretations make up what we call a *physics triad*. They stand for three possible ways in which physicists could be expected to conceive this situation/action. The most important distinction is that between the physical world and the models that represent it. We have further distinguished between physics formalisms (such as Newtonian mechanics) and computer environments in which models, based on those formalisms, are run. The physics triad, as we conceptualize it, thus consists of three spaces:

(a) The real, physical world (in our case, the "universe out there" with physical celestial objects)
(b) Physics formalisms (in our case, formal models of physical phenomena, the world of Newtonian mechanics, or alternatively, Einstein's general relativity, for example)
(c) Computer simulations (in our case, the way in which the formalism of Newtonian mechanics is instantiated in a digital model of a two-body system, and given a graphical interface, which can be observed and interacted with—the Algodoo software environment)

Our decision to conceptualize the physics inputs in terms of these three input spaces (a), (b), and (c) is based on the work of Hestenes (1987, 1992) and diSessa (1988), discussed in the section "Theoretical Framework." In summary, Hestenes proposes that a productive epistemology in physics assumes a distinction between models (based on formalisms, such as Newtonian mechanics, for example) and real, physical phenomena. Furthermore, the simulation environment in our case can be seen as playing a distinct role—one of a *semiformalism* (Euler and Gregorcic 2018), a term introduced by diSessa (1988), building on the ideas of microworlds (Papert 1980). Semiformalisms are tools that can be used to provide learners with intuitive access to the behavior of formal models—something that can be used both as a toy and as a serious model.

The input spaces (d) and (e) have a somewhat different nature from the physics triad of input spaces. They account for a participant's embodied experience of interacting with tangible objects on one hand and with virtual environments through human–computer interfaces on the other. We formulate the two spaces as distinct inputs, because they, although related, correspond to qualitatively different experiences (for instance, on the touch screen, the virtual object's mass cannot be experienced in the same embodied way as in its physical counterpart). The so-called *embodied pair* of inputs therefore consists of two spaces:

(d) The embodied experience of manipulating one's physical surroundings (in our case, the experience of throwing an object with our hand)
(e) The embodied experience of manipulating virtual environments (in our case, the experience of performing a "touch-screen throw")

We argue that the following interpretation of students' engagement in "planet-throwing" is an illustration of the aptness of conceptual blending for the analysis of student engagement in learning environments that combine multiple epistemological aspects, as well as student physical engagement, and which allow for students' immersion in the learning environment and the topic of instruction. For example, conceptual metaphor, which is often considered as an interpretive lens offering similar insights to that of conceptual blending, falls short here. In particular, as conceptual metaphor theory only assumes a source and target concept, it is not able to account for the multiplicity of conceptual inputs and their interplay, nor for the in-the-moment emergent character of the students' actions, i.e., the extraordinary case of "planet-throwing."

**Example 4: Student Referring to His Previous Action with Words and Gestures** In the next vignette, the students had successfully sent two planets into orbits of noticeably different eccentricity. A discussion ensued about what is causing the different shapes of orbits. One of the students (S2) suggested that the way they throw the planet influences the shape of its orbit (namely, the eccentricity). The below excerpt shows S2 using a gesture, accompanied by the word "throw," to explain to the other two students how he envisaged a throw that would produce a different outcome than the orbits that are currently visible on the screen.

He refers to the "touch-screen throw" using hand gestures and speech. The "touch-screen throw" emerged as a context-specific action (throwing by swiping across a surface), which is distinct from regular throwing (grabbing and releasing with one's hand). This suggests that the two proposed input spaces (physical object manipulation and touch-screen manipulation) were recruited simultaneously as students engaged with the activity at hand:

> S2: I threw it from *here* somewhere, like this…[an extended finger gesture from left to right, representing a touch-screen throw].

In summary, each of the five input spaces brings into the central blend a key component for interpreting the students' engagement. Although each vignette that we present may explicitly reveal only a part of the blending process (as in the case of Fig. 3), the observed student interactions indicate that students have, as a group, during the approximately hour-long session, and often within much shorter sequences, drawn on all five input spaces.

In the section "Immersion and Emergence" below, we focus on the projection of the input spaces, with a focus on the bottom two spaces in Fig. 4 (the embodied pair), onto a shared blended space. We also propose a model of the internal structure of the five initial input spaces—a generic structure (a generic space) shared by all five input spaces. The proposed shared generic structure of the input spaces enables one to perform cross-space projections, which are the basis for the multiscope blending that takes place in the studied learning setting.

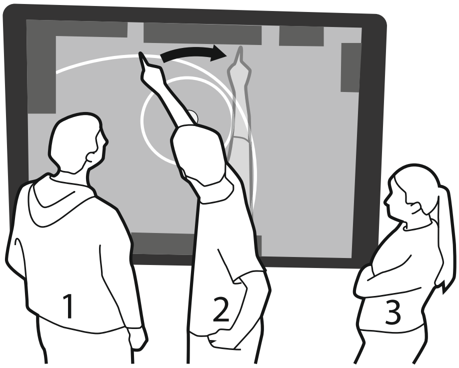

**Fig. 3** In this excerpt, the student talks about "throwing" and performs a gesture that mimics a touch-screen manipulation action. This indicates that he was drawing on the embodied pair of input spaces. The word "throw" indicates the projection from the physical object manipulation input space (throwing), and the gesture indicating a projection from the touch-screen manipulation input space (touch-screen "throwing")

In the subsequent section "Variation in Students' Approaches to Exploration: Diverse Recruitment of Input Spaces," we look at how the proposed framework can be used to make sense of the ways in which different groups of students engage in creative exploration within the studied learning environment.

Following that, in "Disambiguation and Unpacking," we analyze how the students scrutinize the way input spaces of the physics triad relate to one another. This opens up room for the discussion and criticism of the possible effects of immersive learning environments on shaping students' epistemology of physics.

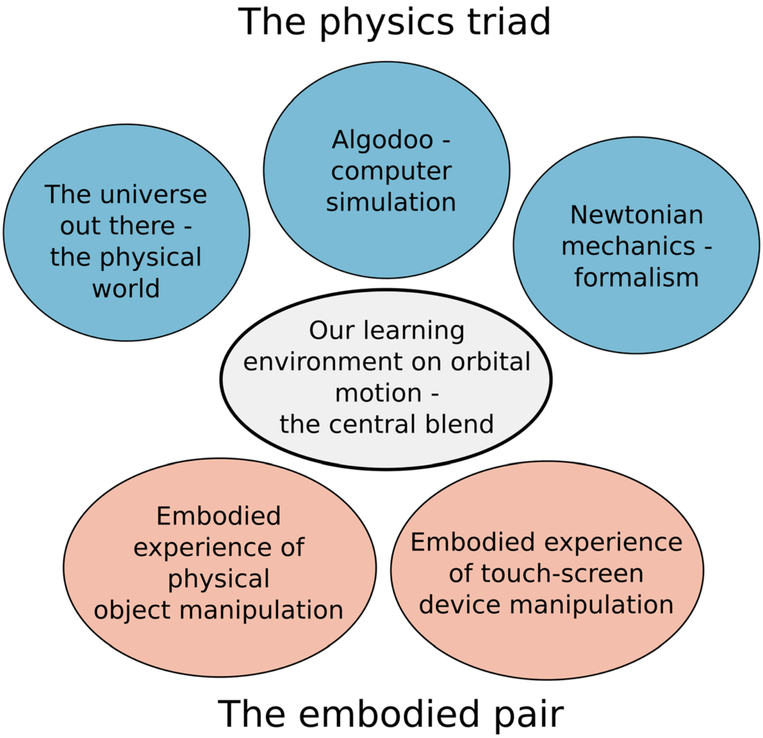

**Fig. 4** The scheme of the five input spaces, three constituting the *physics triad* and two constituting the *embodied pair*

## Immersion and Emergence

For the purpose of the first part of our analysis, we will consider immersion as a process of spontaneous and mostly nonreflective and unconscious integration of different mental input spaces, particularly those reflecting everyday experience of interactions with physical and digital environments and those reflecting students' ideas about the universe and the relevant physics. We propose that conceptual blending as an analytical lens allows us to account for immersion in the given IWB-based learning environment and helps us better understand the potential of immersion for instruction. However, the analysis also sets the stage for a critical assessment of the role of such nonreflective immersion in physics instruction.

### The Generic Space

When students engage in planet-throwing and refer to it as a physical, embodied activity that is performed with one's hand, they effectively bring celestial phenomena down to the human scale. In the conceptual blending framework, this is an example of the process of compression. We propose that compression on a spatial and temporal scale is necessary for student immersion to become feasible in the studied context. However, the mechanism of compression depends on cross-space mappings, which themselves depend on the underlying commonalities of the input spaces that are involved in the blending process. To account for the blending process with the mechanism of compressions, we must identify a generic space—one that shares its internal structure with the input spaces that enter the blending process. In our case, we propose a generic space that underlies all five input spaces.

The generic space (Fig. 5) consists of three elements and an internal relation that connects them. The elements are (1) *input*, (2) *object* (of the input), and (3) *output* (or outcome). The three elements are connected through (4) *a causation mechanism*. A physical, virtual, imagined, or formal (e.g., stone, planet, point mass, simulated body) *object* is at the center of our attention. This *object* is affected by some kind of *input*, which has an impact on its motion in terms of the *output*. The *causation mechanism* provides an explanation for how the three elements are connected.

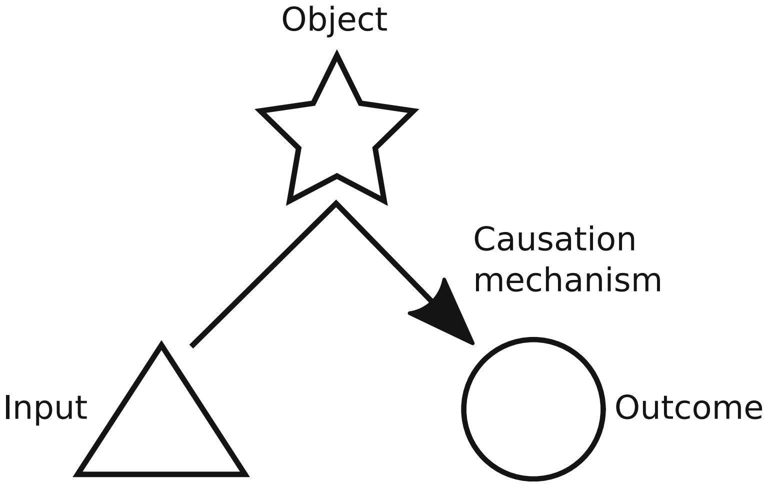

**Fig. 5** The generic space, underlying each of the five input spaces that enter the blending process

Below, we explain how the generic space can be interpreted in each of the five proposed input spaces.

In Newtonian formalism, the dynamics of a system are governed by Newton's laws of motion. In particular, Newton's second law, $F = ma$ or equivalently $a = F/m$, states that an object's acceleration (which can be interpreted as the output) is equal to the net force exerted on the object (the input) divided by its mass (a property of the object). The causation mechanisms are thus explicit, when perceived through the lens of formalism, such as Newtonian mechanics. Clearly conceptualized objects, their properties, and state variables, as well as causation mechanisms, also lie behind computer simulations.

It is perhaps less clear how the proposed generic space applies to the real world, "the universe out there" input space. Indeed, it is hard to speak about astronomical phenomena without referring to Newtonian conceptualization of gravity, mass, etc.[8] However, we can take Johannes Kepler's discussions of the motion of planets as an example of a description and attempt of explanation that does not conceptualize planets and the Sun in a Newtonian way, but nevertheless contain what resembles the elements of objects, their behavior, and causal mechanisms. In fact, Kepler assumed incorrect causal mechanisms (by today's standards of physics), in explaining the movement of planets around the Sun, which led him to propose correct descriptions of planetary motion (today known as Kepler's laws). Kepler assumed that the Sun was pushing a planet "forward" in a tangential direction and that the planet's speed reduced with the distance from the Sun due to the Sun's tangentially directed "force" being "spread" over a longer distance—the length of the orbit (Holton and Brush 2001).

We can conceive of a conceptual space where orbital motion of objects (planets, man-made probes, etc.) happens, and can even be initiated (humans are capable of sending probes into orbits around planets and the Sun). In a conceptual space of real-world astronomical phenomena, the causation mechanisms are not expected to be as explicit and formalized as in Newtonian mechanics but can nevertheless be referred to, for example, as the "workings of the universe." In fact, depending on the problem at hand, scientists and engineers may choose to use Newtonian or relativistic approaches in the production of explanatory models of astronomical observations.

On the other hand, from the perspective of embodied cognition, in everyday life, the idea of causation emerges first from our experience of interacting with the world. Lakoff and Johnson (1980) propose that causation is a gestalt—an implicit mental construct that is grounded in everyday sensorimotor experience (e.g., the experience of throwing objects) that links our actions to outcomes, a view that Andersson (1986) adopted in a science education context. In the *experiential gestalt of causation*, a sentient agent provides input to an object in order to achieve an intended output by means of physical touch.

One can extend this idea of the experiential gestalt of causation to digital environments. The main difference compared to the physical world is that the experiential gestalt of causation in computer environments is shaped by the users' experiences in manipulating digital worlds, which can be to a large degree engineered by human–computer interface designers and

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[8] This suggests that the distinct input spaces are not sharply separated and independent of each other, but in fact form blends even before they are recruited in novel contexts such as our learning activity. While blending, for example, formalisms and the real world is a natural and often productive way of thinking, it carries some risks. For example, Hestenes (1992) points out that students' conflation of the physical and Newtonian worlds can lead to learning difficulties.

software developers. The virtual world can function in ways that differ from or are unfamiliar in the physical world (e.g., Quantum Moves). However, human–computer interfaces can take advantage of users' experience with manipulating real objects and build in sensorimotoric congruencies that connect the real and the virtual worlds. Our case of throwing objects on a touch screen is one such example; the objects respond in a way that is similar to real-world objects, but with certain differences. First, they do not provide any haptic feedback related to the mass of the object being thrown or the force that the "central massive object" exerts on other objects (users cannot feel the pull of the Sun as they hold a planet still). Second, the movement of the object when released differs from what can be experienced in everyday life. The object can be thrown so that it "never falls down," or "falls past the central massive object" indefinitely. The output of a student's action is therefore critically conditioned by the digital environment.

Whether experiences in digital environments lead to a gestalt that is separate from the one that involves experience with physical objects remains an unanswered question. Actions of users of touch-screen devices can be interpreted both as drawing on the experiential gestalt of causation when engaging with digital environments or drawing on a separate gestalt that reflects the particularities of the touch-screen environment. Because the experience of throwing on a touch screen involves somewhat distinct hand and finger movements (dragging an object similarly to moving a flat piece of material on a smooth flat surface), we regard it, for the purpose of our analysis, as a separate causation mechanism, though it is not completely disconnected from experiences involving physical objects (thus, it can still be referred to as "throwing"). Further blending analysis could give additional insights into how the experience of throwing in the physical and touch-screen environments is related; however, it is not our main interest to further probe into this direction in the present paper.

## Section Discussion—Immersion and Emergence

In summary, the proposed generic space, that allows the blending to happen across the five input spaces, consists of the elements of (1) *input*, (2) *object*, (3) *output*, and finally (4) *causation mechanism*, which connects the first three elements. We can map the elements in each of the five input spaces onto these four generic elements (Fig. 6).

The structural similarities between the five input spaces can explain how students can draw from them, rapidly and simultaneously, in forming a blended space as they engage with the IWB-based learning environment.

A crucial feature of a blend is that novel features emerge during the process of completion, features that do not exist in the original input spaces. In this case, what primarily emerges in the blended space is the capacity or ability to manipulate planets, by throwing them into orbit around a star. This provides a new causation mechanism to the motion of planets. Students clearly do not have such capacity in any of the input spaces, but through immersion in the computer-supported learning environment, they accept it in the context of the blended space and start to investigate the outcomes of their manipulations.

Despite being exciting, intuitive, and attractive for students, however, playful immersion is rarely sufficient for the development of conceptual understanding. Students need to, in addition to playing around and getting a feel for orbital mechanics, relate to their previous knowledge of physics and astronomy.

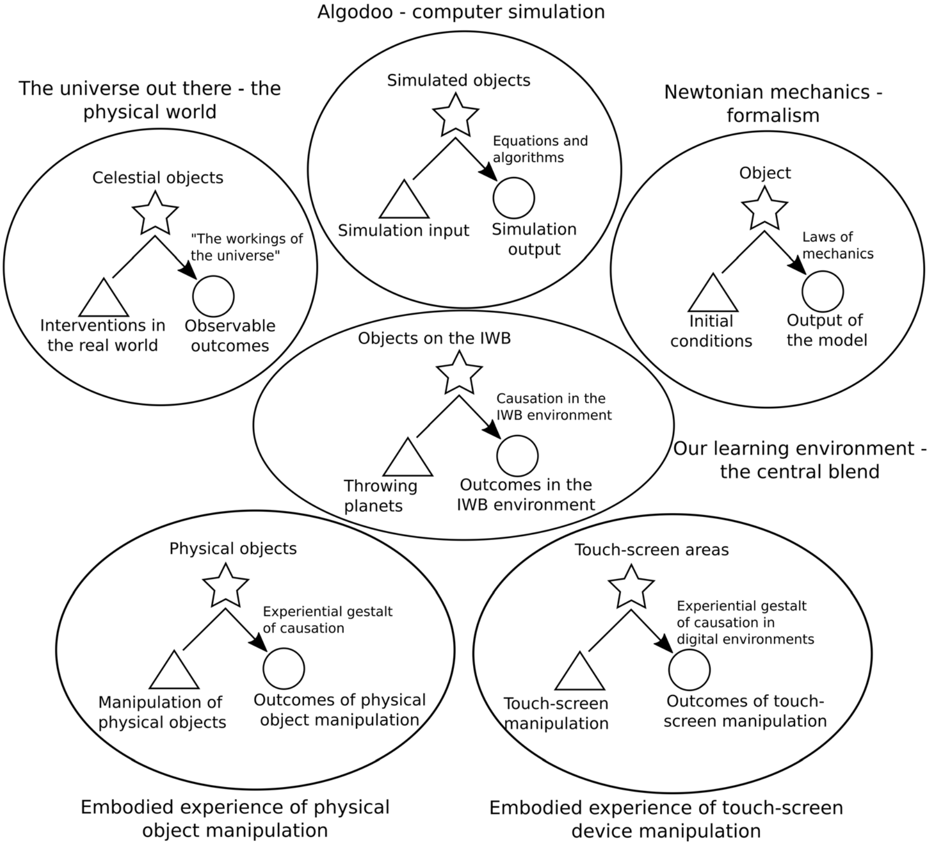

**Fig. 6** The learning web of input spaces and the central blend, into which they feed. The elements inside each space are represented in terms of the generic space that allows the cross-space mappings and compressions to happen in the blending process. In each space, the generic elements take on different roles, as described next to each element

## Variation in Students' Approaches to Exploration: Diverse Recruitment of Input Spaces

In this section, we use conceptual blending, which has been argued by its creators to be particularly suitable for explaining both creative and on-the-spot thinking, to bring to the fore processes that underlie student exploration and explain some of the variation in students' strategies of inquiry. First, we present excerpts that illustrate some of the approaches to exploration and inquiry that the two observed groups of students took. We analyze in terms of conceptual blending each episode as we present it.

The following excerpt (example 5) illustrates how the studied learning environment and the blended space associated with it allowed students to discuss counterfactual scenarios and produce predictions, which can then be put to the test in the digital environment (continued in example 6).

**Example 5: Counterfactual Scenario—"What If There Was Air in Space?"** Students in group 1 noticed that one of the planets that they had thrown always follows the same path (it has a closed orbit, meaning that the planet follows its own path repeatedly). S3 suggested this is due to the lack of any resistance (similar to air resistance in everyday life) to the planet's movement. This suggestion was followed by an instructor-facilitated discussion, in which the participants elaborated on a counterfactual scenario—that assumes the presence of air in interplanetary space. In physics, such scenarios are traditionally called *thought experiments* (Gilbert and Reiner 2000). For the students, resistance seemed to imply that the planets would gradually slow down. This should not come as a surprise, given that most everyday experiences with resistance and friction are connected to the dying-out of motion. The students elaborated on what they believed would happen if air was introduced into interplanetary space, using the IWB as their reference for gestures and speech:

> S2: Yes, it would fall down. If we completely stopped it (the planet), it would fall directly.
> S1: (nods in agreement)
> S2: But if we added air drag just now...
> S1: Then its ellipse would get smaller [gestures a spiral-like shape with his hand, starting from the existing ellipse drawn on the IWB by a tracer, and spiraling inwards].
> S2: Its ellipse would slowly get smaller.
> S3: It would keep getting closer and closer [points towards the Sun with a spiral-like gesture].

The above example illustrates how our learning environment allowed the students to bring together their everyday experiences (everyday ideas about resistance and motion) and experiences gained in the environment itself (the role of the planet's velocity on the shape of its orbit). The combined experience of the influence of resistance on objects and the orbital motion of celestial objects allowed students to form a blended counterfactual space in which there was air in interplanetary space and *run the blend* to produce predictions.

Furthermore, as is seen in example 6, the learning environment allowed students to actually follow up on the thought experiment with a computer simulation. This way, the learning environment made it possible for the participants to bring to life some of the counterfactual scenarios, which spontaneously emerged in discussions accompanying their inquiry. In effect, Algodoo enabled the participants to go from counterfactual (purely imagined) scenarios to computer models representing such scenarios, in a quick and intuitive way. The value of this possibility is demonstrated especially (but perhaps not only) in scenarios that are very difficult or impossible to translate into physical experiments, such as celestial motion.

**Example 6: Modeling the Counterfactual Scenario and Explaining the Outcome of the Simulation** The students in group 1, after predicting the outcomes of their thought experiment, created and observed the simulation on the IWB as they turned on air resistance (which is very easy to toggle on and off in Algodoo using a dedicated button). As the scenario unfolded, the students attempted to make sense of their observation and began to explain it in a piece-wise manner. The planet on the IWB followed an inward-spiraling trajectory (see Fig. 7), just as predicted by the students. The students commented on the observed pattern:

> S1: The drag keeps slowing it down, and so...
> S3: And so it (the Sun) can attract it more, I mean...
> S1: Well, the attraction is always the same.

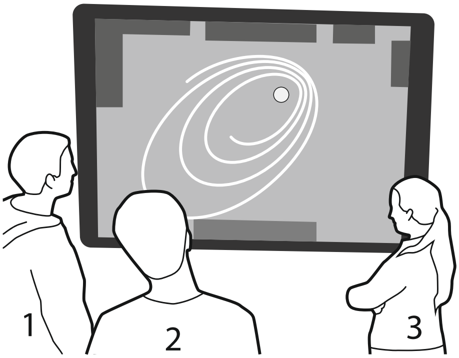

**Fig. 7** Students observing the motion of a simulated object (planet), after air resistance has been turned on in the simulation environment

In example 6, the students were beginning to formulate an explanation for the observed outcome of the experiment on the IWB. While their intuition for the system, arguably acquired in the learning environment at hand (the blend), allowed them to correctly predict the outcomes, the explanation for such outcomes was at this point not yet clearly articulated in physics terms. It appears that the students at this point in the activity started to look for more formal concepts—drawing on the input space of physics formalisms. In this case, the students began to discuss the causal mechanism behind "spiraling-in" in terms of the interplay of the kinematic (the object's velocity) and the dynamic (attractive force of the Sun) parameters, though not (yet) expressed in formal physics terminology. At this point, they appeared glad that the outcome matched their prediction.

The following example shows a student in group 2, the other studied group, making more explicit references to formal physics concepts, when trying to explain the periodically changing speed of an orbiting planet. In fact, group 2's ability to draw on formal physics concepts (a more fluid recruitment of one of the input spaces) seems to have played a role in shaping their exploration strategy.

As we have mentioned already, there was considerable variation in the two groups' approaches to exploration within the given learning environment. One such difference was the extent to which the students engaged in "throwing." We have observed the first group engage in extensive explorations of orbital motion by "throwing" planets into different orbits and discuss how the throw itself affects their orbital trajectories. The second group, in contrast, while being creative and innovative in their exploration, did not engage to the same degree in the same type of embodied interaction with the IWB. They only performed one "touch-screen" throw and only after the instructor prompted them to do it. However, the throw that one of the students performed was successful in the sense that it produced a closed orbit.

**Example 7: Extending the Tracer to See What the Orbit Looks Like (Group 2)** S4 suggested that they send a body into orbit around the Sun. The instructor suggested that they can, instead of setting its velocity using a slider, or by typing in a value using a keyboard (an idea that the students proposed), simply grab it and throw it. S4 then proceeded to throw the planet into orbit and succeeded in the first try. After they observed the orbiting planet complete its orbit, S4 suggested that they attach a tracer to it. The instructor helped him to do so. Shortly after, S4 started to gradually extend the tracer's duration using a dedicated slider on the IWB. While he was extending it, the other two students (S5 and S6) suggested that he should extend it further. The argument for extending the tracer was spontaneously elaborated on by S5; he wanted to see how the planet moves over longer periods of time in order to compare it to a known orbit of a real planet.

> S6: More, more, more... (referring to the tracer duration)
> S5: Maybe a bit longer, so it comes around, so we can see if it's a spiral. It's probably a spiral.
> I: What do you mean by spiral?
> S5: Like Mars is circling… It goes like this [gesture of a precessing perihelion – the elliptical orbit shifts its orientation with time, see Fig. 8].

The manner in which these students discussed and engaged with the learning environment and each other differed somewhat from that of group 1, and it can be interpreted as a different pattern of recruitment of inputs that feed into the central blend. The students had first thrown an object into orbit (drawing on the embodied pair of input spaces). However, unlike group 1, the students in group 2 did not spontaneously grab and throw planets into orbit but had to be prompted to do so. Nevertheless, when the instructor introduced this idea, S4 had no problems performing the throw and actually managed to get a planet into an elliptical orbit on the first try. The embodied action of throwing and experience related to it therefore played a part in the second group's activity as well, although it was far less central to their exploration strategy.

Group 2 then proceeded to explore the characteristics of the orbit's shape with the help of the available software tools. They suggested themselves the use of the tracer (a persistent representation of the orbit; Fredlund et al. 2012), which indicates that they had a good overview of Algodoo and its affordances. They were leveraging their familiarity with the software to support their exploration. The use of a tracer and expressed interest in the shape of the orbits was also shared by both groups.

However, in contrast to group 1, in the last part of example 7 (see Fig. 8), S5 spontaneously drew connections between the orbital patterns on the IWB and the behavior of a particular (real) planet (belonging to the "universe out there" input space). Even though he did not use a completely appropriate word (spiral), he was able to express a complex idea, the precessing perihelion of an orbit, by using hand gestures. This shows that group 2 was more geared toward drawing on elements of the "universe-out-there" input space, looking for connections and examining relationships between what happens on the IWB and what is known about the solar system. In addition, as we will argue in the next subsection, example 7 indicates a process that goes beyond mere projections from inputs into the blend. It suggests that a reverse process is also taking place, where students project findings from the blend back into the input spaces.

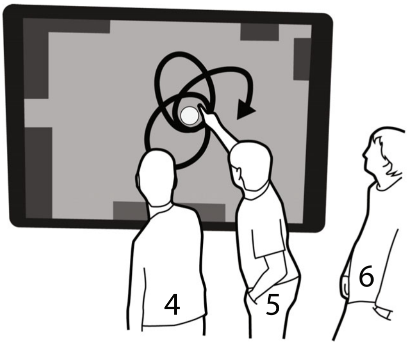

**Fig. 8** A student performs a gesture, representing a precessing perihelion of a planet's orbit

Furthermore, group 2 (in contrast to group 1) often discussed ideas using well-articulated formal physics concepts, as they investigated the patterns of orbital motion. During this process, the students appeared to collaboratively co-construct shared blended spaces (Hoehn and Finkelstein 2018).

**Example 8: Orbital Motion and Energy Transformations** The following example shows two students in group 2 engaging in what resembles a collaborative construction of a shared blend, with each student providing his input to the common blend—one student from the physics formalisms input space and one from the "universe-out-there" input space. The topic they are discussing is the periodically changing speed of the orbiting planet. Students are proposing explanations for this pattern of orbital motion (also described by Kepler's second law):

> S5: The sum of the potential and kinetic energy is always the same. We can look at the potential as the distance from the Sun. So it has a bigger potential [gestures, moving his hands apart from each other] and smaller kinetic. And then it comes closer and it has larger kinetic [bringing his hands back together] and smaller potential energy.
> S4: Yes, exactly.
> S5: So the common energy is always the same. Nothing changes its energy.
> I: Aha, and what could change its energy? So if this is the system...
> S4: So for example if we had an atmosphere here [steps to the board and points to the part of the orbit, where it passes near the Sun] so that it would enter the atmosphere when it came near, and so the air drag would slow it down and the orbit would become smaller.

Here, in example 8, S5 referred to formal physics concepts (energy) when discussing the reasons for the changing speed of a planet in an elliptic orbit around the Sun. We interpret this as him drawing on the physics formalism input space. In contrast to the explanations proposed by students in group 1, S5 articulated his explanation using physics vocabulary much more clearly as he referred to formal concepts, such as energy, to support his argument (Fig. 9).

After S5 explained his understanding of the energy transformations during orbiting, concluding that the sum of potential and kinetic energy remains constant over time, the interviewer asked the students to think of a scenario where this would not be the case (where the sum of the potential and kinetic energy is not constant). To this, S4 replied with an imagined scenario, very similar to that of group 1 in example 5. He proposed that the introduction of an atmosphere (in this case localized to the vicinity

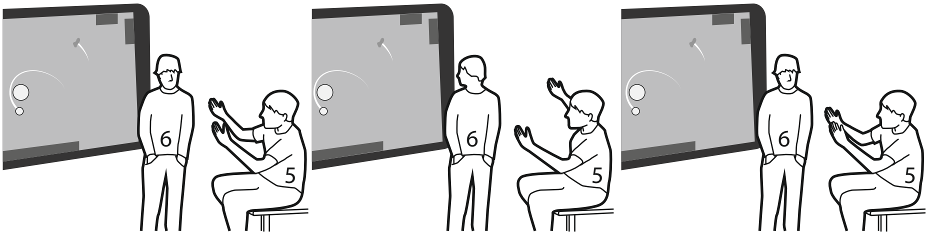

**Fig. 9** A student performs a gesture illustrating the changing distance of the planet from the "Sun"

of the Sun) would change the sum of the planet's kinetic and potential energy.[9] This is an example of S4 building on S5's blended space and further projecting into it new elements. Once again, one can interpret this kind of argument construction as student engagement in collaborative and collective blending (Hoehn and Finkelstein 2018), each projecting some elements into an emerging shared blended space.

The examples above show that group 2's discussions and explorations had a somewhat different character from those of group 1. This can be attributed to more active and fluent recruitment of the physics formalism and the universe-out-there input spaces and a less pronounced recruitment of the embodied pair of input spaces. Group 1 had a more hands-on and experiential approach to the exploration, while group 2 more explicitly drew on known information about our solar system and theoretical constructs of physics.

### Backward Projections

Group 2 focused, much more than group 1, on exploring how the virtual phenomena of the simulation environment relate to their existing knowledge about astronomical phenomena and their knowledge of physics formalisms. For example, S5's attempt to draw comparisons between what is happening on the IWB to astronomical phenomena (the precession of Mars's perihelion—example 7) suggests that discovery of and inquiry into new phenomena through "hands-on" exploration is not the only process that is taking place. In fact, his conscious posing of a question that brought up the relationship between what happens on the IWB and the world of physical celestial objects can be considered as being a part of a process that goes beyond merely projecting inputs into a central blend. In a similar way to how we draw inferences about the catamaran journey from running the Regatta blend (Fauconnier and Turner 1998, 2002), the students here are engaged in backward projections—from the generated blended space back to the original input spaces.

This sort of backward projection is crucial if students' experiences that are afforded by the blend are to be fully leveraged for the learning of physics—the experiences gained from the blend need to be brought back into the real-world and formal physics contexts.

### Section Discussion—Variation in Students' Approaches to Exploration

In the section "Variation in Students' Approaches to Exploration: Diverse Recruitment of Input Spaces," we have provided examples and accompanying blending analyses that showcase the blending process taking place during the two groups' engagement with the provided learning environment. Students make projections from (and to) the physics triad of input spaces, while they engage in complex discussions and IWB manipulation during their creative inquiry.

In the provided learning environment, the two studied groups took a somewhat different approach to inquiry. A blending analysis of student activities using the proposed learning web of input spaces gave us a better understanding of variation in different groups' approaches to inquiry and provided us with language to express these nuances in students' approaches to creative exploration. Furthermore, examples 9 and 11 (see below) indicate that projection of

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[9] If we are more exact, the sum of kinetic and potential energy of the planet-Sun system decreases as some the energy is converted into internal energy. If fact, Kepler's II. law is a consequence of the conservation of angular momentum of the planet-Sun system and does not require the introduction of energy in order to be explained. Nevertheless, the students' use of formal concepts to provide a mechanistic explanation of the observed patterns is indicative of them drawing on the physics formalisms conceptual space.

features from the inputs into the central blend is not the only process that is taking place. Students, particularly those in group 2, talked about what happened on the IWB and compared and contrasted the observations to their previous knowledge of formal physics concepts and astronomy.

The universe-out-there space, for example, does not only provide language (words such as the "Sun," the "planet," "orbit"), or serve as a visual cue for objects on the IWB, but also is recruited by one student (see example 7—the precession of Mars's orbit) to make comparisons and look for correspondences between what happens on the IWB and what they know about the motion of actual planets. We interpret this process as students making backward projections of emergent features and novel findings within the blend back to original input spaces.

Potentially, such backward projections can allow students to (a) learn about formal physics concepts (projecting back to physics formalism input space), (b) develop a better understanding of observable astronomical phenomena (projecting back to the universe-out-there input space), or (c) learn about the affordances of the Algodoo software and how it works (projecting back to the simulation input space).

Depending on the students' existing previous knowledge, such backward projections can have different starting and ending points. For example, for group 1, the finding from the IWB-based activity that a planet moves faster when it is closer to the Sun on its orbit was novel to them. It can thus be projected back to both the universe-out-there input space—as an empirical finding (corresponding to Kepler's second law), or to the physics formalism input space, where it can help them advance their understanding of the law of conservation of angular momentum, for example.

For group 2, the same finding was less novel, since they already knew about Kepler's laws. Their projection back to the universe-out-there input space was therefore different in that it did not provide new knowledge in the same way as for group 1.

In the following section, we will focus on instances of students beginning to unpack and disambiguate the input spaces of the physics triad. In doing so, students did not only move between the central blend and the inputs, as we have shown so far, but also engaged in deliberate comparison of the different input spaces. Such a process requires students to take sophisticated epistemological positions, as we demonstrate in the next section.

## Disambiguation and Unpacking

We have already shown how students bring together spontaneously a diverse set of conceptual inputs (originating both in their embodied experience and the learning of physics) to form a central blend in which new patterns emerge. In this section, we will use the conceptual blending framework and the web of conceptual spaces proposed in this paper to inquire into students' epistemological orientations toward the learning environment at hand. Students' epistemologies are revealed to us through the processes of *disambiguation and unpacking*.

Disambiguation and unpacking happen when students approach the learning environment by consciously contrasting experienced phenomena within the IWB-based environment where the central blend is formed, with other experiences, be it from the physical world or the formal world. In contrast to the process of immersive engagement, where the creation of connections between inputs is often spontaneous, unpacking is an analytical process that requires a critical approach to the learning environment. It requires students to consciously disambiguate different conceptual spaces that they intuitively bring into a blend.

## Toward Model Scrutiny: Simulation as a “Safe Space”

The observations of student discussions during the orbital motion activities suggest that the studied digital environment provides students with the opportunity to scrutinize the models. In particular, the scrutiny in our case seemed to be directed toward the computer simulation. Interestingly, diSessa also noted that children seem to be able to adopt quite critical positions when interpreting outcomes of computer simulations (DiSessa 1986).

As we show in the following examples, a student tests the simulation to see if its output matches his expectations. It is not always clear whether these expectations arise from the students’ theoretical knowledge of alternative formal models, which could have underlain the simulation, of if the students compare the outcomes to empirical measurements of phenomena that the simulation is designed to represent. Either way, the cases presented in examples 9 and 10 both show a student taking a critical stance toward the simulation by contrasting it to known phenomena (example 9) or by questioning its realism (example 10). Looking back at example 7 reveals a similar process. There, the student argued to extend a tracer’s duration, because it would allow them to see if the planet’s perihelion precesses, a notion that he relates explicitly to Mars’s orbit.

In the following example, the same student scrutinizes the simulation in order to see if it behaves in accordance with general relativity.

**Example 9: Testing for Relativistic Behavior** In this example, S5 comes up with the idea to test whether the simulation accounts for relativistic phenomena (bending of light in the vicinity of massive objects). The episode took place shortly after the beginning of the session, when the students were still exploring how objects fall and how their acceleration changes with the distance from the Sun (in Fig. 10, one can see an array of small objects placed at increasing distances from the Sun).

> S5: I doubt that it will, but… [creates a laser beam and directs it so that it passes close to the Sun] … that it would bend the light.
> S5: [S5 plays the simulation] No, it’s not. It’s not a black hole.

By letting a laser beam pass close to the Sun’s surface, S5 in group 2 tested whether the Sun would bend the light. He found out that it does not and concluded that the Sun is “not a black hole.” Even though it is not necessary for a massive object to be a black hole to bend light and

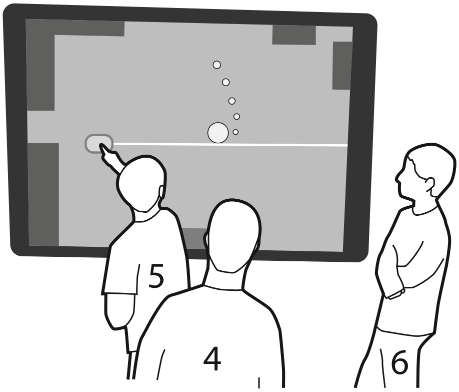

**Fig. 10** One student uses the laser tool to test the simulation for relativistic phenomena (i.e., if the light beam bends when passing close to a massive object)

we cannot be sure of the exact reason he used that term, the student referred to a black hole, probably to invoke an extreme case of light bending. However, it is clear that he referred to phenomena that are consequences of general relativity.

From the given excerpt, we do not know how the student interpreted the outcome. Does this mean that the Sun is not modeled as an object massive enough to bend the light enough to be discerned by the naked eye, or does the model not account for relativistic phenomena at all? Nevertheless, this can be seen as a possible starting point for students' investigation of how the simulation environment relates to both physics formalisms and the observable phenomena.

In the next excerpt, the same student expresses skepticism about the "realism" of the simulation. This is another indicator that scrutiny of the IWB-based learning environment is taking place.

**Example 10: Questioning the Realism of the Simulation** During their exploration, one of the questions that the students were addressing was as follows: What happens if an orbiting object is suddenly slowed down? The following episode shows students as they decide to decrease the speed of an orbiting object slightly, to see how this affects its orbit.

After the objects completes its new orbit for the first time (inner orbit in Fig. 11), S5 turns to the instructor and asks:

> S5: Is this a realistic simulator? I mean, it just goes into such a nice orbit straight away…

The student seems to be surprised that the planet, when its speed is suddenly reduced, begins orbiting on a new elliptical orbit straight away. This outcome in the simulation triggers a skeptic response in S5, as he turned to the instructor and expressed doubt about the realism of the simulation, by implying that the observed outcome is not what he would expect.

This sort of skepticism was also reported by diSessa (1986) in even younger children. In his case, they doubted the outcome of a *dynaturtle* simulation. There, the sideways impulse on a moving object, contrary to students' expectations, did not result in a 90° change in the object's direction of motion. The students' reactions in both cases can be interpreted as indications of conceptual difficulties with the physics concepts to be learned. However, it is even more interesting to consider the students' spontaneous epistemological positioning in both cases. It appears that simulations can invoke in students a critical stance toward digital instantiations of models. The teachers should capitalize on this scrutiny and support students in developing a more nuanced approach to modeling, one that reflects a disciplinary physics epistemology.

**Example 11: Asking About Elasticity of Collisions in the Simulation Environment** The following example is another instance of S5 scrutinizing the simulation. The students observe

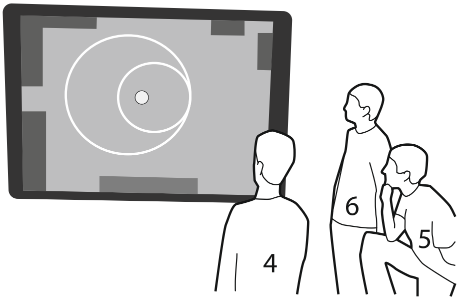

**Fig. 11** Students adjusting (reducing) the speed of a planet near the point where it was closest to the Sun. The planet continues to orbit closer to the Sun (inner ellipse)

a few planets orbiting the Sun simultaneously, when two of the planets collide. After some time, S5 asks the instructor about the elasticity of collisions:

> S5: One question, are there any losses here if two objects collide?
> I: Are you asking if the energy…
> S5: Yes, if it goes into, let's say, heat?

Scrutiny can be seen as a case of the student's unpacking of what is happening on the IWB in the separate input spaces. S5 asks the instructor (who the student supposes knows more about Algodoo) about the elasticity of collisions between objects. In doing so, he unpacks what is happening on the IWB with regard to the space of physics formalism, tracing the observed phenomena into a domain where formal concepts such as energy reside.

While examples 9–11 continue to demonstrate how students are drawing on multiple input spaces, they also show that the students are not just bringing the inputs together uncritically. In fact, in the presented episodes, S5 seems to "disambiguate" and "unpack" the blend in the familiar conceptual spaces. While the process of immersion, as we have conceptualized it, happens quickly, spontaneously, and seemingly without extensive student reflection, the process of disambiguation and unpacking is conscious and deliberate and requires a more reflective student.

However, one can argue that such disambiguation and unpacking can only take place if students have strong prior knowledge of the subject and appropriate epistemological orientations, which allow them to contrast the outcomes from the simulation to their existing ideas about astronomical phenomena, physics, or the inner workings of computer simulations. Seemingly, out of the studied students, only S5 carried out such disambiguation on a regular basis in the exercise. An important question that remains to be answered is how we can use digital learning environments that are similar to ours to help students develop productive scientific epistemologies. One approach could be to take advantage of students' preparedness to be skeptical about simulations.

### Section Discussion—Disambiguation and Unpacking

The development of the presented conceptual blending model leads us to critically reconsider the instructional function of our simulation-based learning environment. The immersiveness of the environment allowed students to naturally engage in "planet-throwing." This further allowed them to approach the topic of orbital motion through "hands-on" experience in a way that resembles experiments. Interacting with a simulation gave the students access to conceptual questions that are hard to address in more traditional instructional setups on the topic, especially at the upper secondary school level.

However, it is hard to say whether the immersive experience alone allowed students to develop or reinforce an appropriate epistemological understanding of physics. What, if any, distinctions did students make between the theoretical foundations on which the simulation is based, and the physical phenomena it is modeling? What potential pitfalls are there of such immersive experiences, and what can instructors do to avoid them, while still leveraging the potential of such learning environments in physics learning?

As already discussed, educational research has found that many students have limited insight into the nature of models and modeling. Students tend to embrace a naive realist epistemology, where models are considered as copies of reality, without considering limitations or the purpose for which they were created (Grosslight et al. 1991). Similarly, according to Hestenes (1992), students often fail to make a clear distinction between conceptual Newtonian models and the real world. This is mainly due to disorganized instructional approaches that do not clearly distinguish between real and formal worlds. As a consequence, students often attempt to memorize information and procedures instead of approaching physics as a modeling activity. Furthermore, because students try to make sense of a convoluted mixture of everyday phenomena and models of these phenomena (with the instructors making explicit distinctions between them only in passing, if at all), few of them come out of such courses with a perspective that aligns with a constructivist view and epistemology of physics.

One of the goals, if not the key goal, of any physics instruction should be to cultivate appropriate epistemological attitudes to the subject. These include the appreciation of the power of models, but also the realization that they are distinct from the real world and are inherently limited in their ability to account for all aspects of real-world phenomena. In this vein, the centrality of model-based reasoning and modeling in science learning has also gained increasing support in science education research (Clement 2000; Gilbert 2004; Lehrer and Schauble 2006). However, as Greca et al. (2014) point out, there has been little attention given to how the use of simulations in education interfaces with students' epistemologies about a given subject.

There is little evidence that the immersive aspect of the studied learning environment prompts the students to explicitly articulate their understanding of the relationship between the simulation and the formal model on which it is based on one hand and the physical world on the other. Even in the utterances of the most advanced students, most prominently S5, it is not clear if they have made a strong distinction between the real and the formal worlds. However, by them starting to question at least the realness of the *simulation*, a window of opportunity opens up, where the instructor could help the students disambiguate these three conceptual spaces (the physics triad) more systematically.

The *simulation* input space therefore appears to play a pivotal role in both immersion and unpacking. In immersion, it provides the interactive potential of a semiformalism (DiSessa 1988), which allows students to get intuitive access to the learning content, especially when combined with an interface such as the IWB, which affords embodied input from the students. In unpacking, the *simulation* input space can provide access (students spontaneously recognize that what is happening on the IWB is not "the real thing") to epistemological questions, by opening up space for distrust and scrutiny. We speculate that the used simulation environment does this by providing students with a sort of a "safe space" for doubt and scrutiny.

However, while simulations like Algodoo may leave more space for spontaneous student scrutiny than pen-and-paper physics models, it is not self-evident that students will actually engage in such scrutiny if not explicitly prompted to do so. In our data, only one student (S5, with very good prior knowledge of physics and astronomy) explicitly questioned the realism of the simulation. This suggests that students may not engage in spontaneous scrutiny if they have no other experience or information against which they can contrast the simulation, or already developed such advanced epistemological views on the subject.

## General Discussion

In this last section, we revisit our research questions in the light of the findings of the study, draw some implications for the instructional practice, and conclude with a discussion about the role and value of the selected theoretical lenses for science and physics education research.

## Answering the Research Questions

**How Do Students Recruit Their Embodied Experience When Engaging in Collaborative Inquiry About Orbital Motion in an Interactive Computer-Supported Learning Environment?** Using our blending model with five input spaces, we conceptualized student recruitment of embodied experiences as drawing on elements of a physics triad and the embodied pair of input spaces. The embodied pair, by sharing a generic structure with the spaces in the physics triad, provides sensorimotor counterparts to the ideas of launching objects into celestial orbits, setting initial conditions in a formal model, or in a simulation. Students appeared to recruit the embodied pair quickly, easily, and intuitively, suggesting that they were to some degree immersed in the environment and acting relatively spontaneously (especially group 1). However, while such immersion is made possible by the underlying generic space, it requires quite radical compressions, some of them more implicit than others. Most notably, while relatively implicit, temporal and spatial compression—from astronomical to human scale—took place almost immediately and without much effort (see example 1).

**What Differences Are There in Two Studied Groups' Approaches to Creative Exploration of the Environment, and How Can We Account for Them Using Conceptual Blending as an Interpretive Framework?** The two groups of students exhibited different patterns of exploration in terms of the direction of their creative and exploratory efforts. While group 1 spent more time engaging in "planet-throwing" and exploring patterns of planet motion, group 2 (including the student with the most advanced lines of reasoning, S5) focused more on contrasting their existing knowledge on the topic with what happened on the IWB. We can interpret the differences in their engagement with the learning environment in terms of differing emphases of the five input spaces and approaches to blending them. Group 1 spent much of their time engaged with throwing, mostly without explicitly referring to real-world contexts, the workings of the simulation, or formal models of the phenomena under study. We thus consider them inhabiting a relatively undifferentiated blended space with pronounced embodied components. In contrast, group 2 engaged with the environment by more explicitly referring to its different aspects, as described by the physics triad (e.g., questioning the realism of the simulation, comparing its outcomes to real-world observations, performing tests to see if it behaves in a relativistic way, asking how it simulates collisions, etc.). This suggests that while the web of five input spaces can help us conceptualize student engagement with the studied learning environment, students can, due to the spaces' shared generic structure, pick-and-mix inputs in creative ways. Furthermore, they can move inwards and outwards, compressing and unpacking. Establishing a web of inputs that feed into the blend is therefore not sufficient if we wish to account for the variation in students' approaches to creative inquiry in such environments. Further investigations need to be done into the way in which students bring together their previous knowledge, experience, and skills, as they engage in blending in computer-supported collaborative learning environments.

**What Limitations of Immersive Engagement with the Studied Learning Environment Are There with Regard to the Development of Expert-like Epistemological Views of Physics?** Immersive engagement, such as that exhibited by group 1, is arguably only a part of the process that we would ideally like to see. In addition to exploring the phenomena via embodied engagement in a largely implicit and undifferentiated blend, students need to engage in scrutiny of the simulation and unpack the blend in order to identify the role of the simulation, how the simulation relates to the physical world it models, and the physics formalism for which it is a semiformal instantiation (such as in the case of group 2). We have shown that the learning environment did not necessarily engage all students in discussions about epistemological questions—namely, only one of the two groups was observed having what we could refer to as an epistemologically sophisticated approach to the learning environment. Perhaps paradoxically, the more realistic a computer-based mixed or augmented reality environment is, the more challenging it may be to snap out of its enticing immersion and sense of reality. We thus speculate that in the future, epistemological questions surrounding the use of digital technologies, such as virtual reality, for example, will become ever more pertinent to the education community.

## Implications for Instruction

When designing the studied learning environment, the central aim was to provide students with activities through which they could learn about orbital motion of planets—Kepler's laws. However, the function of the actual studied learning environment can be seen as twofold. First, it can help students learn about the physics of orbital motion, and second, it can provide students with an opportunity to progress toward a more expert-like epistemology of physics.

In regard to the learning of Kepler's laws, there are two general approaches that a teacher can take, depending on the time limitations, access to equipment and learner group size.

The first approach could be characterized as open-ended inquiry in small groups. We have reported in a separate paper, that small groups of students were able to "discover" qualitative versions of Kepler's laws by investigating planet motion in a collaborative open-ended activity (Gregorcic et al. 2017). This requires the teacher to provide appropriate scaffolding in the form of technical advice on the operation of the software and carefully selected and placed questions in response to student input.

We have, however, also tested a second, more structured approach (for instructional materials, see Gregorcic 2015) in classrooms of around 30 students (Gregorcic et al. 2018). While this version of the activity gave less opportunities to discuss epistemological questions, it actually allowed the teacher to engage students in whole-class exploration and discussion, while they discovered (together with the teacher) all three Kepler's laws also on the quantitative level: the ellipses that planets' tracers draw can be checked by a piece of string held down by two students, the surface areas swept out by a single planet can be measured in Algodoo, and a relationship can be found between the radius and orbital times of different planets orbiting the same star using a distance measuring tool in Algodoo and handheld stopwatches.

In these large classroom activities, conceptual blending can be used as an explanatory mechanism by the researcher studying them, not necessarily informing instruction in any direct way. However, in the case of small group open-ended exploratory activities, the unpacking of the relationship between the real world, the simulation, and the formal descriptions of the problem can be done explicitly either by the students (only group 2 did this spontaneously in our study) or the teacher. We suggest that if the refinement of student epistemologies is one of the goals of instruction, the teacher should take on the task of unpacking the multiple-scope blend characteristic of this learning environment and help students disambiguate it in ways that reflect an expert physics epistemology. We have shown that the learning environment has provided some students with opportunities to ask questions, which touch upon epistemological issues surrounding the interplay of real-world observations, physics formalisms, and computer simulations. It is by asking and trying to answer such questions (see questions asked by students in examples 9, 10, and 11) that students gain opportunities to advance their understanding of the role of physics formalisms and physics computer simulations in relation to the observable physical world. The teacher should thus arguably come forward and ask questions like these, in a way that is responsive to students' own investigations (Robertson et al. 2016), in order to encourage and support students' epistemological growth.

Working in a simulation-based environment may make this job easier for teachers. We have found that some students spontaneously referred to the simulation as a separate entity (see subsection "Toward Model Scrutiny: Simulation as a 'Safe Space'"), which does not necessarily correspond to the physical world and/or physics formalisms (group 2, in particular). Examples of a student questioning the realism of the simulation (example 10) and comparing the simulation outcomes to previous knowledge (e.g., example 7) suggest that critically approaching simulations as tools may be a possible and, for the students, a particularly natural pathway into developing more sophisticated epistemological views of physics. Yet, it remains unclear what initial epistemological commitments different students in our study had. However, it appears that those with a better prior conceptual understanding of orbital mechanics, as assessed formatively from their discussions, also began scrutinizing the simulation more readily.

We can thus speculate that in topics where prior experience is typically scarce (such as astronomy), instruction needs to incorporate other sources of information and explicitly ask students to compare and scrutinize simulations in light of that information. Such contrasting and scrutiny may require explicit prompting and scaffolding by the instructor. This proposal resonates with Greca et al. (2014), who propose that model-based learning can serve as a platform where epistemological questions about the role of simulations in science can be addressed.

Alternatively, providing students only with highly immersive virtual experiences, while offering great potential for developing conceptual understanding, can leave students with a poor understanding of the role of computer simulations in science and with underdeveloped understanding of the epistemological commitments of physics and science more generally.

In conceptual blending terms, physics educators can and arguably should help students develop a more physicist-like web of conceptual spaces, which through its explicitly recognized structure reflects the epistemological commitments of physicists. This means that the spaces that correspond to physics formalisms, computer simulations, and the real world, respectively, retain their distinct roles but also clear connections between each other. We suggest that this be done by deliberately asking questions that require students to disambiguate the *real*, the *simulated*, and the *formal* and discuss with the teacher how these distinctions align with an expert-like epistemology of science and physics. Finally, with a physicist-like web of mental input spaces, the conceptual blends that arise from combining these inputs can be even more potent and creative.

## Conclusion—Reflection on the Theory

The present study has been conducted with conceptual blending—a theory developed within the traditions of cognitive linguistics and embodied cognition—as an interpretive lens. We would like to end the discussion with a reflection on how adopting an embodied cognition perspective and in particular conceptual blending theory may be useful in educational research.

Overall, Vosniadou (2007) suggests that embodied cognition, using Hutchins' (1995a) research as an example, may be a way to bridge the divide that has formed between, on the one hand cognitive approaches to studying students' conceptions, and on the other, research along the lines of a sociocultural tradition. Embodied cognition aspires to retain a focus on the cognition of the individual person, but acknowledges the role of the body and the interaction with the material and social environment. In the present study, the students' thought processes and whatever learning is made possible are clearly influenced by the particularities of the technology to which they are introduced and their social interaction. In addition, from an embodied cognition perspective, Niebert et al. (2012) show the power of providing students with embodied experiences in relation to taught content. In science education, where the content often is of an abstract nature and not directly accessible to the senses, the design of embodied representations that connect to the studied natural phenomena in an indirect, analogical fashion—such as the Algodoo representation of orbital motion—becomes central.

To the degree that science education has adopted theory from embodied cognition and cognitive linguistics, our impression is that it has relied more on conceptual metaphor theory than conceptual blending. Conceptual metaphor theory fits particularly well with the conceptual change tradition in trying to establish typical ways of how students conceptualize natural phenomena and taught content (Amin 2009), as conventionalized patterns of thought and language that are established from embodied experiences are projected onto gradually more abstract domains of thought. However, in our analysis of students' interaction with Algodoo, we found that conceptual metaphor theory did not help us explain how they quickly came to accept that they could throw planets into orbit. They did this by simultaneously drawing from a diverse range of experiences, requiring multiple simultaneous projections from different conceptual domains, producing a new conceptual space with emergent possibilities, where momentary suspension of disbelief was required in order to engage with and learn from the exercise. Here, conceptual blending seemed like a more suitable match. Then again, although conceptual blending can be considered as part of the embodied cognition movement, we did not find the embodied grounding of the input spaces sufficiently emphasized in Fauconnier and Turner's (2002) account for our analysis of how the students drew on their embodied experiences of throwing objects and interacting with touch screens. In this regard, we were much helped by Hutchins' (2005) notion of material anchors. If more conventionalized patterns of thought, which are grounded in embodied experiences, are studied, other analytical approaches than conceptual blending, such as conceptual metaphor theory, may prove more fruitful to pursue.

In conclusion, to leverage from the power of conceptual blending as a theoretical framework, we suggest focusing on such situations where: a domain is formed by drawing elements and structure from more than one input domain, that is, double- or multiple-scope blends, and; the focus is on novel, striking ideas that are generated in the moment, by running the blend, rather than on conventionalized patterns of thought and language. In fact, emergence of novel features that do not exist in the individual input spaces during the completion and elaboration phases is a sine qua non of conceptual blending.

**Acknowledgements** We would like to thank Elias Euler for his help with making the illustrations. In addition, discussions with, among others, Tamer G. Amin and Michael C. Wittmann have been valuable in developing our approach to applying the mechanisms of conceptual blending in an educational context. In particular, Saalih Allie has made us realize the centrality of the emergence of novel features when running the blend. Our thanks also go to Gorazd Planinsic and Eugenia Etkina, for inspiration and instructional philosophy behind the design of the learning activites presented in the paper.

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