Designing Video Games that Encourage Players to Integrate Formal Representations with Informal Play

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Abstract: In this paper we present a case study of a player of the game FormulaT Racing—a prototype racing video game we created to explore design principles that could transform popular games into powerful learning environments—shifting between and ultimately integrating video game and school-based epistemological framings. We show a player shifting from describing acceleration and velocity in a purely game-based narrative during a pre-game interview to descriptions that seamlessly integrated both game and formal representations in a post-game interview. We contend that this change is due to novel interactions with key representations introduced throughout the game and discuss design implications for future games.

Introduction

As technology continues to improve, video games are becoming a preferred way many American children spend their free time. The PEW Internet and American Life Project claims that as many as 97% of all American teens (regardless of gender, age, or socioeconomic status) play video games in some way and 50% play games daily for an hour or more (Lenhart et al., 2008). A more recent report by the Kaiser Family Foundation suggests young "tweens" and Black and Hispanic children (Rideout, Foehr, & Roberts, 2010) spend even more time playing video games daily. With such a time investment by all of our children it is important to not only try to understand the cognitive implications of this common experience, but also to consider ways in which we might enhance this activity that is so central to youth culture.

A number of video games have recently been designed to teach science content in the classroom (Barab, Thomas, Dodge, Carteaux, & Tuzun, 2005; Clark, Nelson, D'Angelo, Slack, & Menekse, 2010; Squire, Barnett, Grant, & Higginbotham, 2004). Like our colleagues, we believe video games are excellent vehicles for experimenting with science phenomena, but rather than design science video games for the classroom, we have chosen to explore design principles that could transform popular commercial video games, games that are typically played outside of school settings, into powerful educational experiences. With this in mind, we have designed a prototype video game, FormulaT Racing (Holbert & Wilensky, 2010a) to be an archetype of the racing genre while providing a platform for experimentation with new representations and interaction mechanisms. Instead of trying to explicitly "teach" players embedded physics concepts, FormulaT Racing (FTR) is designed to tap into children's intuitive notions of motion and to connect these intuitions to formal representations. Consequently, while players may not become experts in kinematics by playing FTR, they should be left with a sense that their experiences in the game are relevant to non-game motion experiences and likewise, that formal definitions and representations of kinematic content are relevant to game experiences.

Many video games designed with educational outcomes in mind have shown moderate success on related assessment measures, however, gains in related but not directly equivalent concepts are often less pronounced (Clark et al., 2010). In this paper we propose this "failure to transfer" may be due to incongruent epistemological framing by players and explore how the design of FTR helps one player overcome this dilemma. In particular, we show Brian, a fourteen year old gamer, shifting from describing acceleration and velocity in a purely game-based narrative during a pre-game interview to descriptions that seamlessly integrated both game and formal representations in a post-game interview. We contend that this epistemological integration is due to interactions with key representational changes introduced throughout the game and discuss design implications for future games.

FormulaT Racing's Design

FormulaT Racing allows players to explore kinematics by putting the player in the shoes of a new driver as they train to join the FormulaT Racing Circuit. The design principles of FTR specifically target relevant phenomenological causal schema (diSessa, 1993) bringing typically intuitive interpretations of in-game motion to the foreground through motion-sensitive and "body-syntonic" controls (Papert 1980) so that they can be explored and manipulated. FTR is designed to look and feel like a traditional commercial racing game though it includes a number of key design changes. One important design feature is the inclusion of intuitive and body-syntonic controls. Using a *Nintendo Wiimote* players manipulate their vehicle's acceleration by rolling the controller forward or backwards for positive and negative acceleration respectively. Track features and level challenges force players to frequently adjust the roll applied to the controller encouraging them to reflect on acceleration as a changing quantity that directly impacts velocity.

Traditionally racing video games have provided kinematic feedback to the player through visual cues such as a passing background, haptic cues such as a controller, and numerical cues such as a speedometer. FormulaT Racing retains the traditional "passing background" visual cue, but adds a new "color-trails" representation. In some of the game's levels, velocity is represented by a color-trail left by the player vehicle that changes with the player car's velocity. The color-trail representation encourages the players to make connections between the motion sensitive controls, changes in acceleration and velocity, and the varying structure and features of the track.

Interviews with children playing popular commercial racing games suggested players rarely attended to provided speedometers (Holbert, 2009). Rather than continue the tradition of providing discrete quantitative indications of the player car's speed, we chose to utilize a velocity versus time graph. This representation serves two important goals. First, as a widely used formal representation, the velocity versus time graph acts as an anchor to formal knowledge within the informal game-space. As we will argue later, we believe this mixing of formal representations and gameplay encourages the player to see her game-knowledge as relevant across contexts. Since the player often identifies as an expert gamer, the application of this game-knowledge to non-game spaces is extremely powerful. Second, rather than a speedometer, which highlights instantaneous speed, a velocity versus time graph foregrounds changing velocity, or acceleration. Though acceleration has been shown to be a challenging concept for children to understand (Tasar, 2010; Trowbridge & McDermott, 1981), we believe that it is a powerful idea that provides an entry point to many other difficult and useful concepts (Papert, 1980).

FTR also includes important construction tools that fundamentally change the way the player causes motion. These designs, inspired by constructionist methods (Papert, 1980; Papert & Harel, 1991) as well as work examining expert and novice embodied interactions with formal graphic representations (diSessa, Hammer, Sherin, & Kolpakowski, 1991; Nemirovsky, Tierney, & Wright, 1998; Roschelle, Kaput, & Stroup, 2000; Sherin, 2000; Wilensky & Reisman, 2006) are intimately connected to previously discussed controls and visual cues but are not explicitly introduced until the third phase of the game. In this phase, rather than drive the car directly, the player constructs personal notions of motion by interacting with the representations of motion rather than the car itself. Specifically this occurs in one of two ways, either by painting the track using the palette presented by the color-trails, or by constructing a velocity versus time graph.

In the "painting" mode of the construction phase the player uses colors corresponding to the previously seen color-trails to paint various parts of the track. Once the player is done painting the entire track, the car begins the race, changing velocity based on the color being driven over. The player can paint the track in any way she prefers, however, because each color corresponds to a particular velocity, and the car's ability to turn is impacted by its current velocity, the choices made in painting the track determine whether or not the car will successfully complete the race. The player may also interact with the car by constructing a velocity versus position graph. In the "graphing" mode, the player constructs a velocity versus position graph using the motion sensitive controller. To construct the graph, the player "accelerates" points added to the graph by rolling the controller forward and backward. Once the graph is constructed, the car "downloads" the data and drives around the track according to the player-constructed graph. In this way the player directly connects the intuitive feeling of acceleration to formal graphic representations and can also explore how varying graphic features, such as sharp drops or plateaus in velocity correspond to particular track features.

Theoretical Framework

While the design of FTR draws upon many important cognitive theories including embodied cognition (Lakoff & Nùñez, 2000; Wilson, 2002) and knowledge-in-pieces (diSessa, 1993; Hammer, 1996; Sherin, 2006), in this paper we draw on two key lines of research to understand how FTR's design impacts player knowledge: restructurations (Wilensky & Papert, 2010) and epistemological framing (Hammer, Eleby, Scherr, & Redish, 2005).

Representations in the world are often created with the intent to store, embody, or alter knowledge and processes. In this way, external representations "become in a very real sense part of our thinking, remembering, and communicating" (diSessa, 2000 p. 6). The term restructuration was proposed by Wilensky and Papert (2006, 2010) to describe the dramatic cognitive shift that can occur due to changes in representational infrastructure. In the same way the processes of multiplication and division—skills only practiced by the priestly few—were democratized after the shift from Roman to Hindu-Arabic numerals, so too do we believe advanced topics such as electricity (Sengupta & Wilensky, 2009), differential equations (Wilkerson-Jerde & Wilensky, 2010), and kinematics (Holbert & Wilensky, 2011a, 2011b) can be taught to younger children.

While we have designed FTR to include important representations for kinematic restructuration, how a player interprets and interacts with these representations in a video game is not always straightforward. In particular, getting players to connect experiences in video games to formal concepts and representations has proved challenging. We believe player epistemological framing might explain much of this difficulty (Hammer et al., 2005). In education research the term "epistemology" is often used to describe an individual's beliefs about the form and type of knowledge in a domain or context. Drawing on the theory of knowledge-in-pieces (diSessa, 1993), which suggests that cognition is emergent from the activation of a large number of fine-grained, highly distributed, context-sensitive primitive elements, Hammer and colleagues (2005) suggests that individual epistemologies change in-the-moment as various cognitive resources are activated. They go on to propose the idea of *epistemological framing* and define it as, "Phenomenologically, a set of expectations an individual has about the situation in which she finds herself that affect what she notices and how she thinks to act" (Hammer et al., 2005 p. 98). In this model, the ability to recall or apply knowledge in a given context then is affected by both the epistemological framing of the learning situation as well as the framing of the recall situation.

Designers interested in creating educationally relevant video games must wrestle with the tradeoff of making the learning goals explicit, versus foregrounding the game narrative and fantasy (Collins, 1995). An overemphasis on learning goals often results in an experience that feels more like interactive flashcards than a game – school work dressed up with animation and sound (Ito, 2007). Here the content remains clearly school-like and as such, likely activates a "knowledge as propagated stuff" epistemology (Hammer & Eleby, 2002). In contrast, by focusing solely on a game narrative, the embedded content that the researcher hopes to share with the player, may become clouded. Here the player sees the game as just that, a game, and not something that is relevant in a traditional school setting (Ito, 2007). The challenge then is trying to find a way to keep players firmly embedded in the game narrative, while making the embedded content flexible enough to be utilized in non-game contexts.

To achieve this delicate balance, we have created FTR to be what Clark et al. (2011) call a "conceptually integrated game" (Habgood and Ainsworth, 2010, discuss a similar idea they refer to as "intrinsic integration"). Such a design ensures the learning outcomes match the game mechanics and are tightly integrated into the game narrative. Furthermore, FTR is "representationally integrated," in that domain relevant representations become highly tied to the player interface and game-mechanics. As we will show in the discussion section, we believe this encourages players to connect formal representations to informal epistemological framings (Hammer et al., 2005) leading to a kinematic restructuration.

Method

To explore the impact of specific design features incorporated into FormulaT Racing we have conducted a number of studies of children playing the prototype game. These studies are conducted exclusively in informal settings to remain consistent with the typical video game playing contexts and employ multiple methodologies. We have written elsewhere about how increasingly complex player strategies in the painting phase match common programming strategies (Holbert & Wilensky, 2011a) and how FTR players learn to construct velocity versus time graphs (2011b, 2011c). For this paper we discuss semi-clinical interviews conducted with participants before and after they play FTR to identify changes in player knowledge about ideas and representations of motion.

In these interviews, participants were asked a series of questions focused on real-world examples of acceleration and velocity using toy cars, adjustable speedometers, and graphing paper. Using methods described by Russ, Lee, & Sherin (in press) we analyzed video data and transcripts of the interviews looking for moments where participant behavior and language indicates a shift in how he frames the interview activity. While we currently have data on 12 participants, in this paper we focus on one participant, Brian, who serves as an exemplar of epistemological integration.

Results

In this paper, the focus of our analysis is on instances of pre- and post-game epistemological shifts. In particular we present a case study of one participant, Brian, shifting from an epistemological stance where game knowledge is separate from formal mathematic and physics knowledge, to a stance that seamlessly integrates the two. While we noticed other interesting shifts, such as players that shifted from a game to a "real world" focused epistemology, we believe the integrated epistemology discussed here highlights the importance of specific design features and offers important lessons for future iterations of FormulaT Racing and other such games.

Brian is a very confident 14 year old boy from a low income neighborhood in a large Midwestern city who prides himself in his ability to not only beat nearly every game he plays, but also to create the "hardest" games. Most of Brian's game building experience has involved personal constructions he's made in *Scratch* at a computer clubhouse he attends near his home. During interviews with the first author, Brian asked many off-the-script questions about the programming environment used to create FTR as well as how he could "hack" the *Nintendo Wiimote* to work with his own Scratch games. There was no doubt that Brian considers himself an expert gamer.

Pre-game interview: Non-fluid epistemological shifting

This sense of himself as an expert gamer impacted how Brian perceived the activity and relevant knowledge for the pre-game interview. Brian approached nearly every question in the pre-game interview from an epistemological frame that privileged video game knowledge – that is, Brian answers all questions about motion as if they are about how motion occurs in the context of a video game – despite the fact that the representations and questions asked in the interview are agnostic about context.

When asked to describe phases of acceleration, or situations involving constant velocity, Brian assumed the appropriate epistemological activity was one of story telling. In particular, Brian answered as if he was describing action occurring in a racing video game. In the exchange below Brian was asked, "Let's imagine this car is at a red light. I want you to sort of show me, by moving the car and also describing with words, what happens when the light turns green." Before speaking, Brian pushes the toy car used in the interview quickly so that it speeds across the table into the interviewer's arm. When asked to describe the motion he states:

> Well I tried, I just kept moving as fast as I could to make sure no one else is coming after me. Maybe I may have used a turbo boost, like a mushroom. And then I bumped into the obstacle, which was your arm. And then I got hurt, and then the other racers passed me.

Brian's description of motion here directly invokes experiences with the commercial racing video games *Mario Kart* (indicated by his reference to a "mushroom" turbo boost). It's important to note again that the interview questions do not reference video games, and the toy cars used by the participants to answer questions more closely resemble "real" cars than the cartoon-like ones of games like *Mario Kart*. Despite this, Brian sees the activity of answering the questions of the interviewer to be about describing events that might occur in the video game world – what we might call a "game story" framing. In this framing, relevant knowledge comes from video game experiences and is about recalling or creating action-filled stories of game play.

It is not surprising that participants might associate the interviewer with video games. While participants have not yet played our racing game at this point in the study, they have been told that we have designed a game that we want them to test. Because we are interested in studying how kids interact with games in informal environments, associating the interviewer with video games is preferred to an association with the classroom. In addition, such a focus on video games in the pre-game interview, like we saw with Brian, increases our confidence in the external validity of the experience. If we want to explore the possibility of designs in real video games impacting the cognition of players, we want to be sure the games are being tested in real gaming settings by individuals that consider themselves gamers. Furthermore, as we will show later in this section, the video game knowledge that Brian draws from throughout the interview seems to be incompatible with formal mathematics knowledge. Moments where Brian is forced to shift into a different epistemological frame are particularly enlightening for theorizing about game design.

The most apparent epistemological shift occurs when the researcher introduces the graphing task. In this task participants are given a sheet of graphing paper with the x-axis labeled as "time" and the y-axis labeled as "velocity." The interviewer uses a paper speedometer with a movable needle to indicate different actions of a hypothetical car, and the participant is asked to "graph what you think is happening." Brian, who has talked freely and playfully during the interviewer while enacting a "game story" framing, becomes uncomfortable and stumbles a bit. Brian pauses, and for the next ten seconds mumbles, "Uh, wait. I'm trying to think which way to go. Lets see, the faster...the faster it moves, which means time…alright, ok, I'm ready." In this moment Brian's physical demeanor changes, as does his playful attitude. Both his verbal "wait" and visible behavior shift indicates Brian is likely experiencing a frame mismatch between his previous "game story" frame and a "school knowledge" frame he interprets the question to be about. Brian sees this "school knowledge" frame as being about providing a formal representation that involves certain rules and vocabulary. This mismatch means abandoning the previous "game-story" frame in favor of the alternate "school knowledge" frame.

As he discusses his graph with the researcher, Brian doesn't invoke a fictional car as it might act in a video game as he has done throughout the interview when confronted with other non-game representations (such as the speedometer). Instead, Brian describes the action of "plotted points." He states:

> *Brian*: Let's see...so, since the y is the speed velocity, like miles per hour, uh...cars, the car increased as the plot, as the plotted points are moving more up. As long...the steeper the slope is the speed of the car.
> *Interviewer*: The, the steeper the slope is the speed?
> *Brian*: Yep.
> *Interviewer*: Okay.
> *Brian*: The speed rate.

At this point of the interview Brian struggles to think of the correct word and the result is statements that seem initiated to use science vocabulary like "slope" as well as mixed terms such as "speed velocity" and "speed rate." This remarkable shift continues for a few moments until he once again relaxes, and then returns to describing his graph as how it might be formed by a car in a video game — sharp phases of acceleration are described as "getting a mushroom" or "hitting a turbo boost" and sharp phases of negative acceleration are described as "bumping into something." Of interest in this analysis is how his earlier "game story" epistemological framing of the activity shifts to a very different "school knowledge" framing. This "school knowledge" framing assumes knowledge comes from expert sources (books, teachers, etc), requires specialized representations and vocabulary, and is about recitation, rather than knowledge creation. While in this frame Brian does not see his expert gaming knowledge as relevant.

Post-game interview: An integrated epistemological framing

While there is still some residue of his earlier framing in the post-game interview, Brian seems to have engaged a highly flexible epistemological frame that privileges both game and formal knowledge. While segments of the post-game interview show Brian continues to answer some motion questions using video game stories, such as describing phases of acceleration as "boosts" and occasionally giving the interviewer an "instant replay" of his movements with the toy car, when describing the motion of two different toy cars being pushed by the interviewer across the table (one is being pushed with constant velocity, the other constant acceleration), he casually states "Well the other one was just this constant rate, but what you did just now, be where...where the slope would increase." Brian's use of the term "slope," invoking a graph representation, is particularly interesting as no graphs have been used yet at this point in the post-game interview. When pushed by the interviewer to explain what he means by slope, Brian states, "well that's what I learned in algebra." Later, when describing his post-game graph, Brian frequently uses terms like "constant rate," intermingling this formal vocabulary with more informal game-like terms like "boost." Of note is that Brian's use of this formal vocabulary is not marked by visible shifts in behavior or language patterns, as was the case in the pre-game interview. In the post-game interview, Brian freely uses terms like "slope," "constant rate," and "turbo boost" apparently without shifting between epistemological frames.

In the pre-game interview, Brian almost exclusively utilized a "game story" frame when answering motion questions using the toy cars. It was only when given the graphing task that Brian attempted to use formal school-like knowledge after a visible shift from his previous epistemological framing. While further investigation shows Brian's explanation of slope is somewhat faulty, the fact that Brian spontaneously and smoothly integrates this formal knowledge from his algebra class into his discussion of the motion of toy cars indicates he is engaged in a very different epistemological framing, one that draws on both game and formal knowledge and is more about knowledge creation, rather than knowledge regurgitation.

Discussion

In this section, we propose a possible mechanism provided by the design of FTR that might lead to the integrated epistemology enacted by Brian in the post-game interview. We also discuss the implication of this case study for future iterations of FTR and other games intending to take advantage of informal game play.

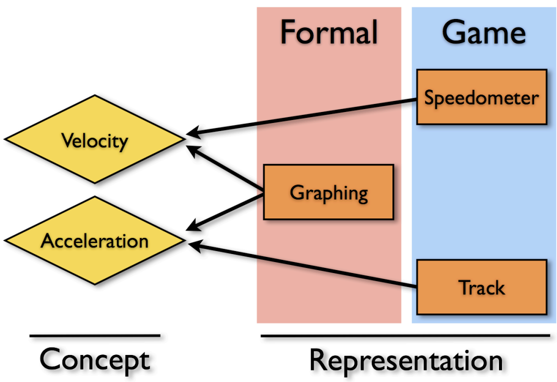

Figure 1. Some representations are better at foregrounding kinematic concepts than others. Before playing the game, video game and formal representations cue different epistemological framings.

In the pre-game interview, Brian's answers to questions and the language used to describe various representations suggest he is framing the epistemological activity as being about drawing on video game experiences. This is particularly true when interview questions utilize a speedometer or toy car and track representations. While it is possible that these representations prompt Brian to engage this gaming epistemological framing, we think it is more likely that the association of the interviewer with games prompted this framing, and since these representations are common in typical commercial racing games, they did not prompt an epistemological shift. Utilizing the toy car and track and speedometer representations, Brian was able to reason about velocity and acceleration with little trouble, though answers to questions typically focused on one concept at a time, with little discussion of how these concepts intertwine (Figure 1).

In contrast, the formal representation of a velocity versus time graph is particularly suited to the integration of velocity and acceleration. While Brian is familiar with this representation, in the interview, the simple introduction of graphing papers causes Brian to shift into a new epistemological framing. Now Brian sees the task as being about formal school-like knowledge. While in this framing Brian ceases to draw on video game knowledge, something he has done throughout the interview, and instead focuses on answering questions using sanctioned science vocabulary. While his explanation is not entirely correct, we see evidence of Brian attempting to use the graphing representation to reason about both speed and acceleration as he not only discusses the height of the "plotted points" but also the steepness of the slope.

During the post-game interview Brian engages a new epistemological framing that allows him to freely use both formal and gaming knowledge. Where did this epistemological framing come from? We propose that specific designs of FormulaT Racing – particularly the intuitive and embodied control interface and the programming phases of the game – encourage players to tie representations that highlight individual concepts of velocity and acceleration to powerful formal representations that integrate the two (Figure 2). Once these formal and informal representations are effectively linked, the player no longer sees the interview task as privileging either game or formal knowledge and instead sees the task as being about constructing new knowledge by drawing on game, "real-world," and formal experiences.

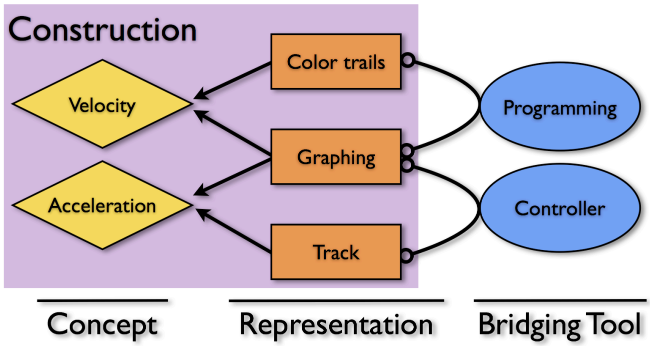

Figure 2. Programming by painting and graphing in the construction phase, and the use of the motion sensitive controller in the racing and construction phases effectively ties the various representations in FTR together. This results in a new epistemological framing for Brian that privileges knowledge construction.

As discussed in the game design section of this paper, FTR includes a number of important representations meant to foreground various kinematic concepts. Of the new representations, most important to this discussion is the color-trail representation. This representation is particularly good at highlighting the player vehicle's current velocity. Moreover, this representation allows players to visually see how the vehicle velocity relates to various track features. The track itself is a representation that is good at highlighting acceleration. The animation of traditional racing video games, the controlling scheme used, as well as real-world experiences shared by American youth provide the player with enough knowledge to know he should slow down around turns and speed up when the track is straight. Finally, a formal graph, which is included instead of a more traditional speedometer, is very effective at foregrounding both acceleration and velocity. However, like the speedometer in traditional racing video games, players rarely consider this representation during a race.

While the new representations in FTR are important, the construction phase of the game effectively ties these representations together in a new way, encouraging players to integrate game and formal representations. This happens first by pairing the painting and graphing constructions within the same game "level." While the interactions in the painting and graphing constructions are somewhat different, because they share a common narrative and goal in the game (that of directing other cars as the pit boss) the representations become highly intertwined. Finally, the two phases share the activity of programming in some form. Whether painting or graphing we see evidence of players systematically enacting computational strategies (Holbert & Wilensky, 2010b).

Video evidence suggests players rarely reference the velocity versus time graph during the racing phases, however, the graphing representation utilized in the construction phase becomes tied to specific track features through the accelerometer-based interface. When players drive the car in the racing phases, they do this using a motion-sensitive controller. This interface foregrounds acceleration as it allows players to feel moments of speeding up and slowing down when they approach straightaways and turns. We've adopted this same interface for the graph construction phase. Here, as we've suggested before, players construct a graph that the car will use to drive around the track. Players construct these graphs by "accelerating" points up and down the y-axis in the same way they accelerated their car around the track—though here, instead of dealing with acceleration in the moment, players consider acceleration over the course of an entire race. By tying these two representations, the track features and velocity versus time graph, though embodied controller use, we believe players more easily see the graphs as being highly relevant to specific race action.

As the graph, track, and color-trail representations begin to be tied together by programming in the construction phases and the embodied controller use throughout the game, Brian more easily integrates previously incongruent epistemological frames. While we did see epistemological shifts with many participants, Brian's merger of game and formal epistemologies was unique. We believe this might be due to Brian's very salient identity as an expert gamer. Furthermore, as our oldest participant (14), Brian likely has more formal experience with the mathematics embedded in FTR. His ability to integrate previously learned knowledge from the classroom with his FTR video game experience gives us hope that younger players might utilize FTR experiences in the classroom.

This case study highlights the importance of both 1) designing new representations that provide infrastructure for complex cognitive tasks and 2) providing mechanisms for connecting representations to alternate contexts and epistemological frames. The very best representation will only be effective if it is seen as relevant in various contexts. As we move forward, we should continue to strive to make connections to more casual gamers as well as those that consider themselves experts. This may mean making certain relevant game features less nuanced. For example, the "forced braking" is only noticed by expert gamers and as such, may be missed entirely by novice gamers. In addition, some features that are large breaks from gaming tradition, such as the painting and graphing phases, may remain unconnected to other commercial racing video games (or even the more traditional phases in FTR) for novice and expert gamers. In this case more care should be taken to gradually introduce these important phases so they can continue to be seen as connected to the rest of the racing genre and typical gaming culture.

Conclusion

Video games permeate the lives of young people in America and continue to be highly relevant in youth culture. Video games are a rich space in which children can experiment with scientific phenomena. Whether we design games for the classroom or beanbag chair, it will be important for designers and researchers to consider player's personal epistemologies both in and out of the gaming context. If neglected, we run the risk of designing isolated experiences that only matter in the moment, rather than providing a rich space for integrating the virtual with the real and the informal with the formal.

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