Representational congruence: Connecting video game experiences to the design and use of formal representations

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Abstract

Video games designed for educational purposes often struggle to effectively connect concepts of interest to gameplay. We propose that to encourage players to mobilize knowledge resources for non-game settings such games must be representationally congruent. Representationally congruent games are construction games where the player builds and/or interacts with the game using primitives relevant to the game world to construct representations that are congruent with those used by domain experts in the real world. Showing data of players constructing velocity v. time graphs before and after playing a representationally congruent racing game, we argue that the shared features of player-constructed and formally accepted representations provide a hook for players to bring knowledge and intuition built in-game to situations and experiences outside of the game context.

Keywords

Video games, representations, physics, graphing, knowledge resources

Introduction

Video games have recently been a popular object of study in the educational community. New research claims video games can serve as powerful spaces to teach critical thinking, spaces for trying on new and refining one's own identity, and can serve as a binding agent for real-world interaction (Gee, 2003; Ito, 2009; Squire, 2006). Furthermore, games are highly motivating and have become a central feature of current youth culture. Recent studies suggest 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). As an activity so central to children's lives, video games are a space ripe with potential. Our research agenda is to strive to make game play, a space that likely contributes much to children's intuitive notions of physical phenomena, a rich experience for deep exploration and meaningful knowledge construction.

Providing a space for knowledge construction doesn't mean we must transform games into something resembling a traditional classroom, nor does it mean games should be played in the classroom. As Papert (1996) noted, "The best learning is learning that is embraced and enjoyed. Children love to learn until they are taught otherwise" (p. 51). While I believe popular, and fun, commercial games do provide opportunities for players to explore and experiment with important mathematical and scientific ideas, these ideas are often backgrounded in favor of gameplay and obscured by visual effects essentially tying the constructed knowledge structures to the game space. The notion of a "play paradox," proposed by Noss & Hoyles (1996) highlights the difficulty in designing playful experiences that provide powerful opportunities for learning. If specific interactions are prescribed to ensure the experience the designer is interested in occurs, it is no longer play. However, if play is held sacred, valuable learning experiences might be passed by.

We, and a handful of our colleagues, believe that carefully designed constructionist video games may provide a solution to the play paradox. Because video games are necessarily constrained to have "quantifiable outcomes" (Juul, 2005; Salen & Zimmerman, 2004) – to have a win condition – certain interactions or pathways through the game are guaranteed. Of course this idea of constraining the possible space of exploration does interfere with how a child interacts with the game somewhat. However, deliberately including opportunities for personal construction within this space harnesses the power of constructionist design, encouraging players to build new ideas and strategies using the rules of the game world even as they pass prescribed goals (for more on the designing constructionist video games see (Holbert, Penney, & Wilensky, 2010; Weintrop, Holbert, Wilensky, & Horn, 2012).

For a game to be truly constructionist we believe the concepts to be explored and the gameplay must be what Kafai (1996; 1998) and Habgood and Ainsworth (2011) call *intrinsically integrated* and Clark and Martinez-Garza (in press) refer to as *conceptually integrated*. Conceptually integrated games directly tie the gameplay to the concepts of interest. So rather than interrupting the "fun" part of the game for mandatory multiple choice questions (a common game design of the *edutainment* industry), conceptually integrated games make the content of interest the mode of interaction. In short, in conceptually integrated games, play is learning.

In this paper we propose a new design principle central to developing constructionist video games. We argue that in addition to being conceptually integrated, video games designed to provide a space for personal construction must also be representationally congruent. Representationally congruent games are construction games where the player builds and/or interacts with the game using primitives relevant to the game world to construct representations that are congruent with those used by domain experts in the real world. In such games the primitives for construction embody the content (as in conceptually integrated games), but by putting them together in personally meaningful ways, the resulting representation has meaning outside of the game.

To further explain the design behind and value of representationally congruent games, we provide examples from our own game *FormulaT Racing* (FTR), a racing game for exploring kinematics. In this paper we will describe important representations included in the construction tools of FTR. We will then present an analysis of a pre- and post-game graphing task completed by FTR players to argue that this important design feature allows players to mobilize knowledge resources gained from playing the game when reasoning about related non-game problems.

Theoretical Framework

The notions of conceptually integrated and representational congruent design can trace their roots back to Papert's (1980) most famous transitional object, the LOGO Turtle. The power of the Turtle is that it embodies not only the users sense of motion and mathematics in the real world, but also the rules and features of formal mathematics – essentially "standing between the concrete/manipulable and the formal/abstract" (Noss & Hoyles, 1996).

The Turtle is often described as "body-syntonic." Papert (1980) suggest "children can *identify* with the Turtle and are thus able to bring their knowledge about their bodies and how they move into the work of learning formal geometry" (p. 56). For example, by "playing turtle" the child can actually feel the appropriate moves necessary to walk out a square. In this way the idea of "squareness" isn't relegated to some abstract formula or set of rules and heuristics. It is instead a very real, and incredibly obvious thing – so obvious in fact that children sometimes have a difficult time using words to explain it! And because the words of the Turtle match the language of the child, creating a square, a triangle, or even a circle, is as simple as telling a friend how to move around in a room.

While playing turtle feels natural, and the language used to command the Turtle match the language a child uses to describe her own motion in the world, the ideas enacted by the Turtle, and representations created by the Turtle, are very much mathematical. Whether constructing a house, a spiral, or a complex animation, the structures created by LOGO users embed highly formal rules and look remarkably like constructions one might find in the formal practices of engineers or computer animators. In this way creating with the Turtle not only allows the user to draw on her own sense of navigation in the world, but also to create artifacts that have value beyond the computer screen they're constructed on.

Conceptual Integration

The term *conceptual integration*, or *intrinsic integration*, was used first by Kafai (1996) to describe a specific categorization of games created by children as part of the instructional design project. Kafai describes these games as those where the "designer integrates the subject matter with the game idea" (p. 82). Kafai likens these games to microworlds (Papert, 1980) but claims that very few students created games that fit this category.

Recently, as video games become an even more popular space for educational design, the idea of intrinsic, or *conceptual*, integration has been utilized by Habgood and Ainsworth's (2011), Clark and Martinez-Garza (in press), as well as our own work in game design. In Habgood and Ainsworth's (2011) *Zombie Division*, the various modes of attack embody the fractions of interest. For example, players using a sword effectively "divide" the zombie in two while punching using a five-fingered glove divides the zombie by five. Clark and colleagues (2011) provide another example of conceptual integration in their game *SURGE*. Here players use impulses and moments of constant, positive, and negative acceleration to navigate a spaceship through a maze. In our own *FormulaT Racing* (Holbert & Wilensky, 2010a), which we will discuss in more detail in this paper, players use motion-sensitive controls to apply positive and negative acceleration to a racecar to complete various challenges.

Unfortunately, conceptually integrated games often fall victim to the play paradox. Clark and Martinez-Garza (in press) argue, "Though playing a conceptually-integrated game engages the player constantly in the targeted relationships, the player may never articulate or even identify those relationships." In an effort to overcome this problem, we propose the principle of representationally congruent design.

Representational Congruence

As mentioned previously, representationally congruent games are construction games where the conceptually integrated building primitives that make sense in the game world are used to construct representations congruent to those used in the real world. In these games the representations created by players should resemble those used in the real world by those that do serious work with the game-embedded content. This isn't to say that the goal of a representationally congruent game is to *teach* players to make these formal constructions. Far from it! Rather, we believe that when constructions created by players in the game share some resemblance to formal representations used outside of the game, players will see the processes used to make these construction as equally relevant in non-game spaces.

Interestingly, while conceptually integrated video games often are not representationally congruent, edutainment games — education games where the content of interest is *not* conceptually integrated to the game action — often go to great lengths to include relevant formal representations of the content. However, because these games lack meaningful construction primitives — primitives that have conceptual meaning — we would argue that these games are *not* representationally congruent. For a game to be representationally congruent, we believe it must involve meaningful construction with primitives that are themselves conceptually integrated, to create representations relevant to expert use of the domain.

While video games designed to be representationally congruent are rare, constructionist software often embrace this design principle. Bamberger's (1996) Impromptu music software is an excellent example of software that includes important new representations to help users come to a better understanding of ideas like rhythm, but final constructions lead to representations and compositions recognizable by any musician. The programming environment Alice (Cooper, Dann, & Pausch, 2000), works especially hard to provide a space where users can experiment with object-oriented programming, quickly creating professional looking animations. However, while Alice is tile-based, "instructions correspond to standard statements in a production oriented programming language, such as Java, C++, and C#".

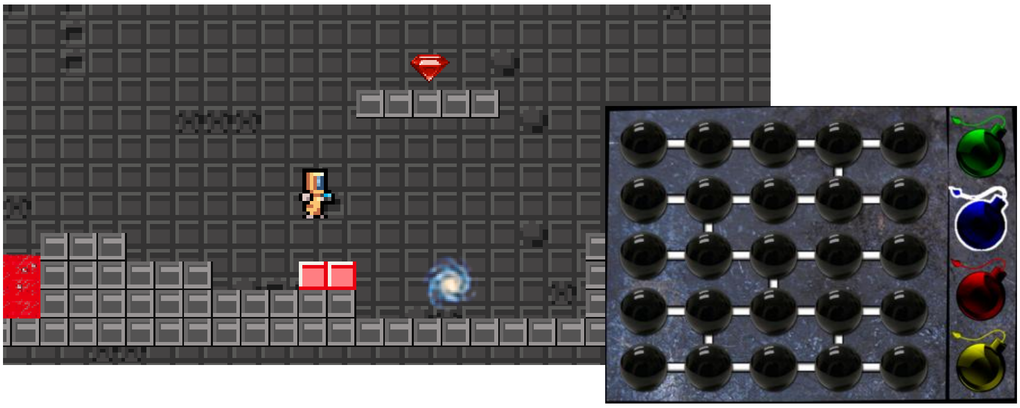

Figure 1. In Particles!, players rearrange bonds between atoms to create blocks in the game world that have physical properties emergent from the molecules constructed. Here the player has created a block with spring by cross-linking chains of atoms.

In our own game design work, representational congruence has been central. In *Particles!*, a platforming game we currently have under development, players organize the "atoms" of all structures and objects in the world (Holbert & Wilensky, 2012). By rearranging the atoms and bonds of a substance in the world the player alters its emergent physical properties (for example creating long cross-linked chains to create "bouncy blocks"), allowing them to develop novel solutions to each level. Here the actual objects that are arranged by the player do not accurately resemble real atoms, but final constructions made share features of traditional molecular models (Figure 1). In *FormulaT Racing* players use motion sensitive controls to accelerate points up and down a y-axis to ultimately construct velocity versus time graphs that the player car will then utilize when driving around the track.

Methods

In the remainder of the paper we present a study of *FormulaT Racing* intended to explore the value of designing games to be representationally congruent. Eleven players aged 8-14 were recruited from various informal organizations in a large midwestern US city. These players were told they would be helping us to evaluate a new game we were developing. Interviews with players were conducted before playing the game, then a week later participants played the game over two 1-2 hour play sessions before being interviewed again two days later. Of the eleven children that completed the pre-game interview, six completed the pre-game and post-game interview playing the same version of the game.

There are three main phases of FTR: skill development, racing, and constructing (a more detailed description of the design of FTR can be found elsewhere (Holbert & Wilensky, 2010b, 2011a). Of particular importance to this paper is the construction phase of the game, often referred to as the "pitboss" level. In this level, players are confronted with a birds-eye view of the entire track (Figure 2). Then, by clicking the track using the mouse (or touching the track on compatible devices), the player can paint it with different colors that each correspond to different vehicle velocities. Once the player has finished painting the track, the car in set in motion to drive around the entire track, increasing and decreasing its velocity as it moves over the player-added colors.

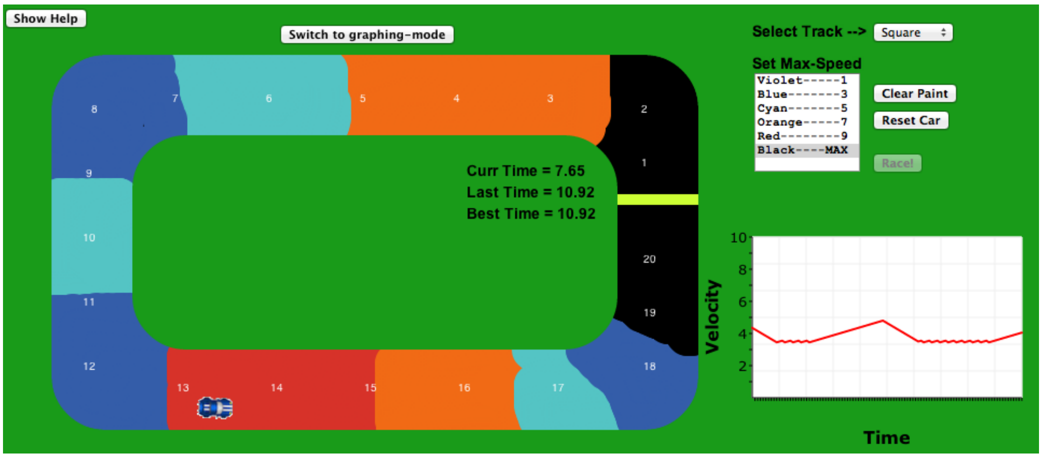

Figure 2. Players paint the track using colors corresponding to different velocities. When the car drives over the painted colors, it accelerates and decelerates until it's velocity matches that of the painted color.

After successfully completing the three included tracks by painting, the player then begins the second stage of the pitboss level. In this stage the player must construct a velocity versus time graph that the car will then use to drive around the track. Using numbered markers distributed throughout the track, the player adds nodes to a graph to indicate the speed the vehicle should be traveling at that point (Figure 3). However, rather than simply "clicking" to add a point at the chosen velocity, the player "accelerates" the point using a motion sensitive controller. The controller used is the same the player has become familiar with in the previous racing phases of the game (the racing phase plays like a traditional racing video game) to accelerate his car around the track. By rolling the controller forward or backward the player can add positive or negative acceleration to each point until he is happy with its location on the y-axis. Like the painting stage, here the player must accelerate points on a graph over the course of the entire race, rather than accelerating the car in-the-moment.

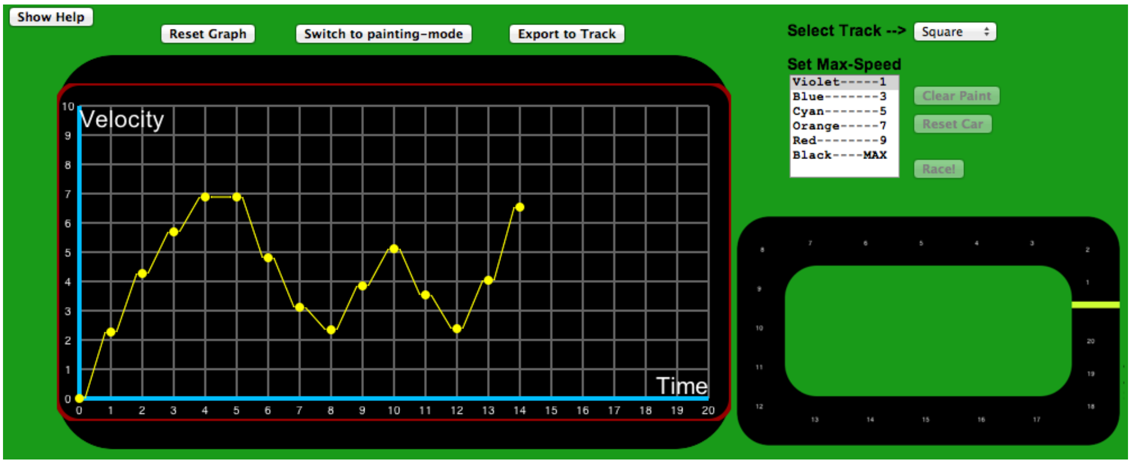

Figure 3. In the graph construction phase players accelerate points up and down the y-axis of a graph by rolling a motion sensitive controller forward (for positive acceleration) and backward (for negative acceleration).

In both the painting and graphing phases of the pitboss level, the player has the opportunity to make small or drastic changes to their constructions after the car has either crashed or made it around successfully. In previous work we have analyzed the systematic changes players made and found that players engage in sophisticated debugging of constructions and many even utilize complex repeating patterns, or "procedures," as they work to come up with a winning construction (Holbert & Wilensky, 2011b).

As previously mentioned, both before and after playing the game participants are interviewed by the first author and engage in a graphing task. In the graphing task participants are shown a paper speedometer (the term "speedometer" was never used by the interviewer though most participants identified it as such) with a movable needle. While the interviewer slowly manipulates the speedometer needle, participants are asked to "make a graph describing what I am doing with this meter." This is done on a piece of graphing paper with the x-axis pre-labeled "Time" and the y-axis pre-labeled "Velocity" (the interviewer takes time to ensure all participants are familiar with the term "velocity" ahead of time, and if they are not, informs them that it is "kind of like speed"). In the remainder of this paper we look at changes in pre- and post-game graphs created by players of FTR and argue these changes are due to interactions with the representationally congruent construction phase of FTR.

Results

Pre- and post-game graphs created by participants reveal that while many participants struggled in the pre-game graphing task (only two of eleven participants created qualitatively correct graphs in the pre-game interview), nearly all participants (five of six) were able to create qualitatively correct graphs during the post-game graphing task.

In the pre-game interview, most participants struggled to produce a graph of the changes being made to the speedometer. Once participants did begin constructing a graph, the graphs created were unlike those formally utilized by the physics and education communities. In one common pre-game graph, players utilized the pencil as if it were the actual car being described by the changing speedometer. In other words, while the researcher increased the speed on the speedometer, the participant would move his pencil across the paper faster, and when the speedometer was moved to a slower speed, the participant slowed his pencil down (Figure 4).

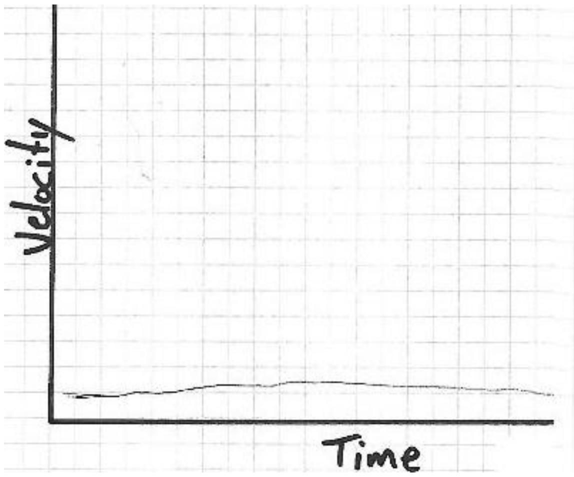

Figure 4. In the common pre-game pencil-as-car graph, the participant accelerates his pencil along with the changes to the speedometer as if the pencil is the car.

This common construction highlights the mismatch between intuitive ideas children have of motion and the formal representational system utilized by the expert community. Two explanations of what is happening seem possible. In the first, the pencil-as-car graph foregrounds acceleration, even though the representation itself only highlights this feature when it is constructed. Here, the participant knows that movement of the needle to a higher number on the speedometer means "going faster" and chooses to represent this *change* to a higher speed by gradually increasing his pencil movements. The other possible explanation is that the player is actually highlighting *velocity* rather than acceleration. In this explanation, while the player moves the pencil quicker when the interviewer changes the location of the needle, this movement only occurs due to his effort to show the pencil at a higher speed. Even though velocity could be made apparent by utilizing the y-axis of the graph, the participant's pencil movements are intended to show these discrete velocities, rather than the changes in velocity. Interestingly, both possible explanations point to a disconnect between acceleration and velocity. The participant is either showing *changes in velocity*, or *discrete velocities*, but makes no effort to coordinate the two. In this way the representation serves only to illustrate this one instances of motion, lacking the flexibility of formal velocity versus time graphs.

In the post-game interview, five of the six participants created qualitatively correct velocity versus time graphs. Two of the four participants that produced pencil-as-car graphs completed the post-game interview. Both of these participants created excellent velocity versus time graphs that contained important features such as differing amounts of acceleration and moments of constant velocity (Figure 5). A few features of these graphs stick out, notably, rather than simply draw a line to represent the motion, both participants added points at each time step. One participant that made a "correct" graph before playing the game, added points to his line in the post-game graphing task (points were not in his pre-game graph). While in any other circumstance this might not be very notable, the fact that in the graph construction level of FTR players accelerate "points" that are then connected by lines indicates the players are drawing directly on this in-game representation to accomplish this non-game task.

This point should not be understated. Players do not receive explicit instruction on creating graphs in the game and the tools (paper and pencil) and representations (speedometer) used in the interview protocol are completely absent from the game context. While it is true that player *do* create graphs in the game, this is done in a very non-standard way (accelerating points up and down the y-axis by tilting a motion-sensitive device) and no directions are given on exactly what a graph should look like. Instead, the game utilizes the interaction mechanism players have become used to throughout the game to drive the car. In this way the motion of tilting the controller becomes tied to the concept of enacting positive and negative acceleration, rather than game specific visualizations. This careful mapping of the interaction mechanism to the concept allows players to quickly map their ideas of a “successful run” to the kind of graph they want to create. The fact that participants were also are able to draw on this “graph construction” skill outside of the game context with different tools and representations is very exciting considering the large body of work that highlights the difficulty of learning to graph and even larger body of work that suggests transferring such skills or knowledge to a different context is an extremely unlikely occurrence.

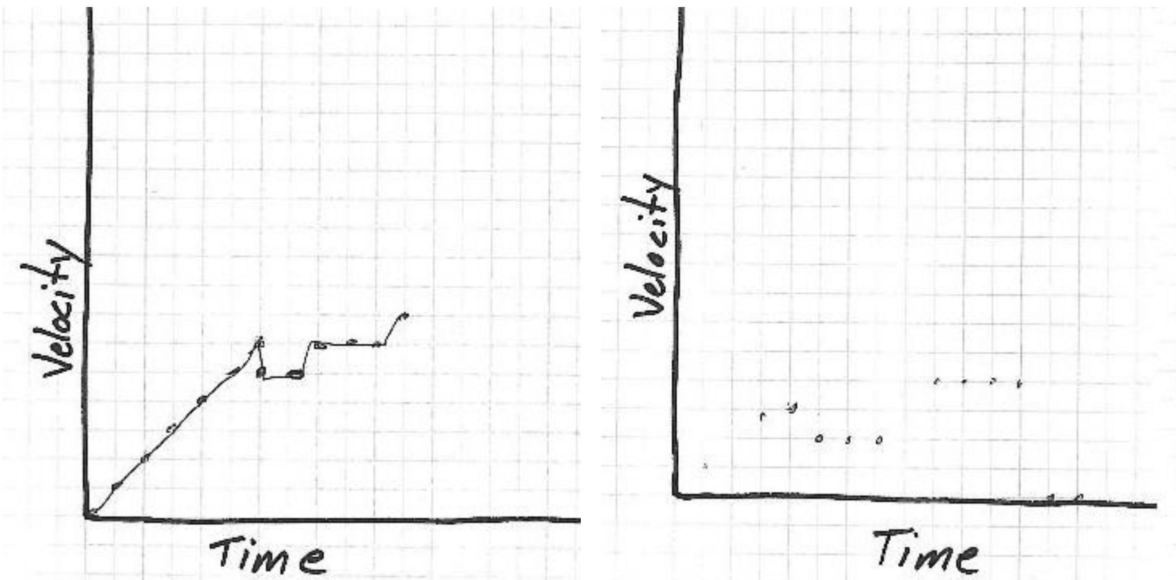

Figure 5. Two of the five qualitatively correct post-game graphs. These two graphs highlight the importance of “points” in the post-game graphs that was absent in all pre-game graphs.

Conclusions

Players of FormulaT Racing show a remarkable change in graphing ability between a pre-game and post-game graphing task. While players did see many, and even construct a few of their own, graphs in the game, the tools and representations used, as well as the context were completely different in the interview. We believe this data is evidence that as a representationally congruent constructionist game, FTR encourages players to see their experiences and constructions in-game as relevant in settings beyond the game.

But how does this happen? Since there is such a large body of literature that suggests “transfer” – using knowledge learned in one context in a new context – is so difficult, why were we so successful? A couple of different explanations seem possible.

One could argue that the context was not actually a new one – that the in-game graphing and post-game graphing task were not actually different contexts. This argument would likely be based on the one common feature between settings, the interviewer. One might claim that the participant has associated the interviewer with the game, and as such, the post-game interview was still an “in-game context.” While this is a possible explanation, we believe the large collection of literature that presents "failures to transfer" where contexts were even more similar than the one is our study would suggest otherwise (Gick & Holyoak, 1980, 1983).

Another possible explanation, and the one we believe highlights the value of creating representationally congruent games, is that participants, recognizing the graph representation from their formal education, saw the activity they engaged in during the pitboss level of the game as relevant beyond the game. In this way, because the final representation of player constructions resembles representations used by experts in the domain, the *processes* and *primitives* used by the player to *construct* the representation are also seen by the player as relevant and "real." Essentially, the recognition of the representation outside of the game contexts activates knowledge resources the player has associated with the representation. These knowledge elements constructed while players used conceptually integrated building primitives in-game are highly useful not only for making the formal representation, but also for reasoning about relevant domain content.

If this is true, and we believe it is, then the shared features of player-constructed and formally accepted representations provide a hook for players to bring knowledge and intuition built in-game to situations and experiences outside of the game context. Those powerful moments of construction in FTR when players coordinate velocity (represented by the painted colors) to acceleration (though interactions with the motion sensitive controls) and tie these ideas to the relevant track features (such as straight-aways and turns) enriches previously held intuitive notions of motion.

These results increase our optimizm that informal video game play can be a powerful space for the exploration of science phenomenon. By carefully choosing interaction mechanisms and primitives for the construction component of video games, and by ensuring the final constructions will be seen as relevant to contexts beyond the video game, game-related knowledge resources created and refined by interactions with such games are then free to be utilized in non-game settings. By including conceptually integrated and representationally congruent designs in popular commercial games, it just might be possible to make Mario as useful as the Turtle.

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