Racing Games for Exploring Kinematics:

A Computational Thinking Approach

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While a growing body of research shows a positive potential for video games as vehicles for learning, there exists a tension between popular games created solely for entertainment purposes and educational games designed to teach content first and highlight entertainment second. In an effort to overcome this artificial dichotomy, our research agenda is to explore, create, and assess design principles that can be employed to adapt popular commercial video games enabling players to connect intuitive experiences of embedded science content, to real world and formally-taught representations. This paper describes a study of six children (ages 7-13) interacting with a prototype game, FormulaT Racing (Holbert & Wilensky, 2010), designed to encourage players to develop computational strategies for successfully navigating the physics embedded in typical racing video games.

Review of Literature

There is a considerable amount of research literature examining children's understanding of motion. Much of this literature focuses on specific misconceptions, formed through repeated experiences with the physical world, that seem to be both consistent and coherent (Carey, 1988; Duit, 2009; McCloskey, 1984). This literature contends that these misconceptions must be confronted and replaced with correct concepts of motion (Carey, 1988; Clement, 1982; Driver, Squires, Rushworth, & Wood-Robinson, 1994; McCloskey, 1984; Posner, Strike, Hewson, & Gertzog, 1982; Trowbridge & McDermott, 1980, 1981). While science standards refer to Newtonian mechanics as "essential to understanding the natural world" (AAAS, 2002), research has shown an alarming number of high-school and college graduates fail to grasp these basic principles (McDermott, 1983). Despite our best efforts, intuitive notions of motion seem to be particularly sticky, and highly resistant to change through methods suggested by the misconceptions literature.

A separate group of researchers interested in physics education contend that in line with constructivist theories of cognition, learner's intuitive notions cannot simply be removed and replaced. Instead learning occurs most effectively when intuition is leveraged and refined (diSessa, 1993, 1996; diSessa & Sherin, 1998; Hammer, 1996). The importance of prior experience and salience of situational cues in this theory suggests that designs meant to help children make sense of Newtonian mechanics must consider common motion experiences.

In this paper, we argue that racing video games, a genre popular among youth (Lenhart et al., 2008), likely contributes to children's intuitive notions of motion and as such, is both a potentially powerful means of intervention and an important context for conducting research on students' developing conceptions of kinematics.

While video games have been decried as a "waste of time" and even "dangerous" by the popular media, a number of educationally focused games have become popular among psychologists and learning scientists (Barab, Thomas, Dodge, Carteaux, & Tuzun, 2005; Gee, 2003, 2007; Squire, 2005; Stevens, Satwicz, & McCarthy, 2008).

In the past few years there has emerged a consensus that it is important for 21st century students to be computational thinkers (diSessa, 2000; Guzdial, 2008; Resnick, 2001; Wilensky & Papert, 2010; Wing, 2006). While an official definition of computational thinking is still debated, Jeannette Wing (2006) defines it as, "solving problems, designing systems, and understanding human behavior, by drawing on concepts fundamental to computer science" (p. 33). The NRC has published two reports clarifying the nature of computational thinking and its role in student learning (2010, in press). Two core computational thinking practices on which we focus in this study are debugging and procedural thinking (Clements & Sarama, 1995; Noss, Healy, & Hoyles, 1997; Papert, 1980).

Games and software for building games have been proposed for teaching computational thinking (Kafai, 1995, 1996; Repenning, Webb, & Ioannidou, 2010). Few have argued that simply playing video games can be an effective way to practice computational thinking. Thinking procedurally involves chunking problems into smaller bits and recognizing patterns that can be effectively repeated (Papert, 1980). The NRC workshop on computational thinking (2010) suggests procedural thinking is about creating “a detailed step-by-step set of instructions that can be mechanically interpreted and carried out by a specified agent, such as a computer or automated equipment” (p. 11). Debugging involves systematic attempts to adjust a procedure or function in an effort to find the “bugs” or errors keeping a system from running properly. Papert (1980) claims that this process of debugging is central to learning: “Errors benefit us because they lead us to study what happened, to understand what went wrong, and, through understanding, to fix it” (p. 114). In this paper we argue for making opportunities for computational thinking central in the design of video games.

Theoretical Framework

FormulaT Racing was designed specifically to tap into children’s intuitive notions of kinematics and to connect these intuitions to formal representations while staying true to youth gaming culture. To be considered successful our design should look and feel like a traditional racing video game — one that participants could imagine sitting down to play after school, rather than in a classroom. However, we also intend FormulaT Racing to be a game that participants will draw on in formal learning contexts as well as in common everyday experiences — participants may not learn kinematics by playing FormulaT Racing, but they should be left with a sense that their experiences in FormulaT Racing are relevant to non-game experiences and should be able to utilize qualitative foundational knowledge provided by the game to reason through more complex kinematic problems. To do this FormulaT Racing foregrounds specific features of kinematics using tailored representations and controls embedded within typical racing game design, while also providing powerful construction tools that allow players to manipulate and debug these ideas in novel scenarios.

In a pilot study observing children playing *Mario Kart Wii* we was found that traditional racing game design led to a one-to-one mapping of game action — instantiated by controller buttons — to discrete kinematic concepts (Holbert, 2010). In other words, specific controller buttons became synonymous with game actions (such as a "gas button"), which in turn stood in for isolated physics constructs (such as "velocity"; Figure 1). In FormulaT Racing, we set out to rethink traditional racing game design so players would be encouraged to utilize computational strategies in the game ultimately leading to a more useful and flexible encoding of kinematic concepts. We refer to this new encoding as a computational encoding — by which we mean knowledge elements are relationally connected and function to describe and measure dynamic processes. We argue that a game that encourages this computational encoding should include the following set of design principles:

1) An interface connected to the player's intuitive and embodied understanding of physical phenomenon. (Barsalou, 2008; diSessa, 1993; Papert, 1980)

2) Representations that encourage a computation-based encoding of embedded content. (diSessa, 2000; Wilensky & Papert, 2006, 2010)
3) Opportunities to interact and create with these new representations. (Papert, 1980; Papert & Harel, 1991)

The following sections describe in more detail the theoretical underpinning of each design principle as well as how the principle is instantiated in the design of FormulaT Racing.

1) Intuitive and embodied controls

A large collection of research in the Learning and Cognitive Sciences suggests much of our intuitive notions of motion are created through physical experiences out in the world (diSessa, 1993, 1996; Nemirovsky, Tierney, & Wright, 1998; Piaget, 1952; Roschelle, Kaput, & Stroup, 2000; Wilson, 2002). Work by diSessa and colleagues with physics students indicates that the richness of experiences in the physical world lead to dynamic, yet extremely salient, intuitive explanations for most common phenomenon (diSessa, 1993, 1996; diSessa & Sherin, 1998; Sherin, 2006). A number of educational designs have also been introduced over the years showing that young children can be extremely effective at interpreting and constructing complex mathematical representations using motion-sensitive controls (Nemirovsky & Rasmussen, 2005; Nemirovsky et al., 1998; Roschelle et al., 2000). Drawing heavily from theories of embodied, or grounded cognition (Barsalou, 2008; Wilson, 2002), these designs provide tools that allow learners to use physical movement in the world — movement that can be felt and experience directly — to make sense of abstract mathematical principles.

FormulaT Racing makes use of the *Nintendo Wiimote*, a commercial video game controller that includes multiple accelerometers, for controlling the player car. The controls allow for continuous (rather than discrete) adjustments of acceleration as well as heading, and serve as a metaphorical carrier for the player's idea of acceleration connecting it firmly to bodily experiences (Papert, 1980, p. 63). In other words, the player's natural bodily reaction to lean forward when wanting to "speed up" or backward to "slow down" changes the acceleration of the in-game car. Players turn the car by leaning to the left or right respectively. In this way the control of in-game agents are naturally connected to conceptual "simulations" of motion (Barsalou, 2008; Wilson, 2002).

2) Designing Restructurations

While representations in the world are often created with the intent to store, or embody some specific way of thinking, external representations also "become in a very real sense part of our thinking, remembering, and communicating" (diSessa, 2000, p. 6). Taking this theory of external representations seriously implies that alternate external representations may fundamentally change one's thinking process. To this end, FormulaT Racing was designed to include what Wilensky and Papert (2006, 2010) call *restructurations*. The authors first describe the notion of a *structuration* as "the encoding of the knowledge in a domain as a function of the representational infrastructure used to express the knowledge" (2010, p. 2) and suggest that a *restructuration* is "a change from one structuration of a domain to another resulting from such a change in representational infrastructure" (2010, p. 2). In the case of FormulaT Racing, by changing traditional representations of kinematics and means of interacting with the player vehicle the game provides an opportunity for kinematic restructuration.

We have made two key design choices to facilitate this restructuration: including additional spatial representations of motion, and replacing discrete measures of velocity with formal representations that highlight change. FormulaT Racing builds on the traditional “passing background” visual cue to indicate vehicle speed but adds a new “color-trails” cue. In this cue velocity is represented by a color-trail left by the player vehicle that changes as the player car’s velocity changes. These visual color-trails provide a means to connect ones changing speed to the structure of the track. In other words, players can more easily see how they slowed down around sharp turns or sped up on straightaways. In addition, because early interviews with children playing popular commercial racing games suggested players rarely attended to provided speedometers, FormulaT racing substitutes a velocity versus time graph to provide an early connection to formal kinematic representations and to highlight the importance of change, rather than static speeds. This velocity versus time graph is then color-coded to connect it firmly to the left behind color-trails.

3) Construction Tools

Finally, FormulaT Racing also includes construction tools that fundamentally change the way the player *causes* motion further supporting kinematic restructuration. These construction tools are intimately connected to previously discussed controls and visual cues but are not explicitly introduced until the third phase of the game often referred to as the “pit boss level.” This level was designed as a constructionist environment (Papert, 1980; Papert & Harel, 1991). In this level players construct personal notions of motion by interacting with the representations of motion rather than the car itself. The player does this in one of two ways, either by painting the track different colors (that correspond to the color-trails they have become familiar with) or by constructing a velocity versus position graph.

In the “drive-by-paint” mode of the pit boss level the player utilizes the color palette of the color-trails to paint the track. The player can paint the track in any way they prefer, however, because each color corresponds to a particular velocity (the level can be changed so that each color represents acceleration rather than velocity), and the car’s ability to effectively turn is impacted by its current velocity, the choices they make in painting the track determines whether or not the car will successfully complete the race. Conversely, the car must complete the track within a specified time limit. In the “drive-by-graph” mode, players construct a velocity versus position graph using the *Nintendo Wiimote*. Once the graph is constructed, the car “downloads” the data and drives around the track according to the velocities defined in the player-generated graph. In this way players directly connect 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.

We contend that the construction tools included in FormulaT Racing encourage players to consider the track as a collection of functional units — units made up of both track features and corresponding velocity changes. As players build vehicle motion using previously seen visual representations, and plan successful races by enacting computational strategies such as procedural thinking and debugging, kinematic concepts such as velocity and acceleration become functional — ideas that are no longer about category membership, but concepts that “do something.” In the following sections we will describe a study exploring children’s interactions with FormulaT Racing. We argue, that rather than directly map game action to controller buttons, players of FormulaT Racing utilized game controls, novel representations, and construction tools in functional units leading to a computational encoding of kinematic concepts

(Figure 2). In turn, players showed evidence of utilizing game representations and controls to reason about non-game instances of motion.

Method

In this study, eleven children (ages 7-13), recruited from various informal organizations in a large midwestern city, volunteered to test and provide feedback on a prototype video game, FormulaT Racing. In a 15 minute pre-game interview session, researchers used a semi-clinical interview format to gauge participants understanding of kinematics and their interest in video games. Two 45 minute game playing sessions were conducted a week later. In these sessions participants played the prototype racing video game, FormulaT Racing. Finally, a 15 minute post-game interview was conducted using the same prompts as the pre-game interview. Interviews and game play sessions were conducted in the participants' homes or at an after-school program they were attending. All interactions with participants were videotaped. Screen recordings of the game play were synced and joined using video editing software to in-room recordings of players for analysis. Of the eleven participants, this paper will focus on six children that completed all phases of the study using the same version of the game.

While we have done a larger analysis of FormulaT Racing, this paper will focus on the players interactions with the pit boss level. Here, video data (along with the in-room recordings) was split into interaction units according to instances of strategy switching. In most cases the obvious point of strategy switching occurs after a failed run, however, occasionally verbal or physical cues from the player indicate a strategy shift between track resets. Interaction units were coded using a scheme developed in a bottom-up fashion from discussion with colleagues over repeated video views (Table 1). Game-play codes were verified by an independent researcher. Conflicts were discussed and resolved resulting in agreement of 97% of video time.

Results

The analysis suggests that players develop systematic computational strategies to be successful in construction levels by leveraging game experiences and representations from previous levels. Players typically begin by testing uniform motion on the entire track, such as "painting" the track a color that causes the car to drive extremely fast. Gradually, players utilize intuitive knowledge of motion and in-game experiences to systematically debug constructions. Ultimately players begin to notice and reuse patterns of motion and track features to paint and graph successful solutions. Figure 3 shows the percentage of total time players enacted a particular computational strategy while playing the pit boss level (one participant, Mike, did not complete the construction levels due to software problems) . While some players spent a little time simply exploring the model — painting the track all one color, "just to see what will happen," or to see how fast the car could go — most engaged in complex computational strategies a majority of the time.

Construction Tool Use

A detailed analysis of each player's progression with construction tools shows evidence of not only computational thinking in action, but also paints a picture of computational strategy evolution. One of the youngest participants, Collin, struggled early to understand the mechanics of the construction levels. When painting the track, Collin was very strategic about his designs though some of his choices seems unrelated to the vehicle's behavior. When his construction would fail, Collin would work to understand what went wrong and systematically debug his design. He might add a fast color in straightaways if he struggled to make it around the track in time or he may add a small strip of violet (a slow color) on a corner if he was crashing. However, if these small tweaks failed, Collin would often erase the entire track and claim "I have another plan!" These early debugging attempts, such as putting only a small strip of violet in the specific location of a crash, shows evidence of a disconnected understanding acceleration and velocity — Collin knew violet indicated a slow color, but he didn't take into consideration the time the car would take to slow down. As Collin continued to interact with the construction tools, "*strategic motifs*" — what we called procedures in the painting and graphing tasks — began to emerge. Before painting on a new track Collin thinks out-loud and states:

> **Collin**: Oh but that won't work because then I'll have to do it over and over again and it will crash...my idea is just going to make it crash again. Well, I'll test it.
>
> **Interviewer**: What's the plan?
>
> **Collin**: <u>Every corner is a slow color and every line like this is a fast one.</u>

At this point, shortly before constructing a successful run, Collin has begun to break his strategy down into small "procedures" (indicated by the underlined segment) that include multiple colors related to specific track features that he then used repeatedly at key track points (Figure 4). This procedural painting suggests Collin has begun to see acceleration as highly related to velocity and that together these kinematic concepts result in very specific types of motion relevant to different aspects of the race.

Collin's first attempt at the graphing level once again showed a very specific attempt to use repeating motifs. Rather than plot out each location point (there are 20 points) and consequently "fill" the graphing space, Collin broke the race up into only eight parts which directly corresponded to the number of straightaways and corners (Figure 5). When told he hadn’t filled all 20 points, pointing to different segments of the track Collin states, “Oh I see, I was going just like, uh...fast, slow, fast slow.” What at first looked like repeated spikes, or moments of high positive acceleration followed by high negative acceleration, turned out to be Collin’s reinterpretation of the track as a collection of repeated kinematic motifs rather than a continuous series of instantaneous motion. After editing his graph to include all 20 points, Collin struggles with the scale making the car go as fast as possible as soon as possible resulting in a spectacular crash early in the race. Seeing his failure he asks, “How do I know how fast it is? oh yeah! by using the other side [indicating y-axis labels]!” This case of mental debugging happened quickly and invisibly but led to success as the very next attempt showed clear evidence of a strategic plan complete with repeating motifs all at a perfect speed (Figure 5).

Brian engaged in a variety of different computational strategies, but spent a large majority of his time in FormulaT Racing debugging. Brian often began by painting the track one color, and then added and removed colors systematically. After being successful on a track the interviewer questions why he altered the paint at various points. Brian’s answers indicate a rich connection between the vehicle’s acceleration and the track features:

> **Brian**: Every spot that I picked blue, was all the spots where he crashed previously.
>
> **Interviewer**: Any idea why it crashed?
>
> **Brian**: Maybe it moved too fast and didn't have enough time to turn. So I slowed it down with some blue paint. And whenever it still crashes I'll just make the blue paint larger. At least large enough for it to have enough time to steer.

Interviewer: So I noticed before that it was crashing down here, and you added blue up here (points to a spot earlier than the crash point)... Any ideas? Cause that worked right?

Brian: Lets see...I think because this is a sharp turn...and...and you would have to drive very slowly for the sharp turn. And even at the beginning right here, it'll take a while for it to slow down. So I had to make this blue part a bit bigger. That way the car doesn't crash before it steers.

For Brian, the debugging done to make a successful run encourages him to focus on the change in velocity, change that takes time, as it relates to sharp turns and straightaways on the track.

The stories of the two FormulaT programers show instances of computational thinking in action as well as indicate that computational strategies were employed and refined as players continued to interact with the game. As players progress in the pit boss level insights gained early on in the painting version carried over into the graphing. In addition, as more sophisticated computational strategies were employed, participants showed signs of an important kinematic restructuration where acceleration and velocity shifted from being disconnected and continuous numbers to something more akin to “chucks” of highly connected types of motion. In this new structuration, motion motifs continually interact with the previous and next motif resulting in a highly dynamic series of kinematic patterns.

Pre- and Post-game Graphing

Pre- and post-game interview comparisons also indicate participants learned to construct qualitatively correct velocity versus time graphs and more coherent kinematic explanations of driving situations. In these interviews the researcher showed the participant a speedometer with a movable needle (the word “speedometer” was never used by the researcher though a number of participants identified it as such) and provided a sheet of graphing paper with a horizontal x-axis labeled as “Time” and the vertical y-axis labeled as “Velocity.” In this task the participant was asked to “make a graph describing what I am doing with this meter.”

Most participants produced a graph in the pre-game interview unlike those formally accepted 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 their pencil across the paper faster, and when the speedometer was moved to a slower speed, the participant slowed their pencil down. Two players, Walt & Brian, produced fairly accurate graphs right away in the pre-game interview. Another player, Collin, struggled with task and chose to not complete the graphing activity in the pre-game interview.

FormulaT Racing uses velocity versus time graphs explicitly in two ways. First, in every level a velocity versus time graph is created while the player drives the car. From a design perspective this graph was conceived as a substitute for the traditional speedometer. The second instance of a typical velocity versus time graph in-game occurs during the pit boss level. In this level the player is instructed to create a graph using the *Wiimote* that the player car will then use to drive around the track. No explicit instruction is given for “correct” graphing, and the only feedback provided by the game is whether or not the player car successfully completes a run using the constructed graph.

Four of the six players that struggled with the graphing task in the pre-game interview produced qualitatively correct graphs in the post-game interview (the other two produced correct graphs in the pre-game interview). Three participants, that each produced the straight-line speed graph in the pre-interview, produced excellent velocity versus time graphs that contained important features such as differing amounts of acceleration and moments of constant velocity (Figure 6). Collin (the player that did not complete the graphing exercise in the pre-interview), created what might be called an acceleration bar chart. In this graph Collin would count how long it took the researcher to move the needle to a specific speed and then stop. He would then move to the counted amount on the "time" x-axis and move up the "Velocity" y-axis to the speed at which the researcher paused. While not "correct" this graph has some interesting features. First, the graph highlights varying amounts of acceleration. Second, the graph handles constant velocity. The main flaw of this graph is that Collin was unable to handle the difference between accelerating from zero and accelerating from a positive speed such as 20. Collin recognized this flaw and stated "I was also doing it from where you stopped so only 10 and 20...so it...I wouldn't do like square after square […] It's just because you stayed at 10 and 20 longer than five, fifteen, and all the other numbers."

It seems likely that the game was the cause of this change in graphing. In fact, every participant but Walt mentioned the game when asked to create a graph. It's worth highlighting here that the interview question did not use the game in any way and the speedometer, whose motion the player used when constructing the graph, is a representation completely absent from the game. These facts suggest that the players were able to connect in-game representations to non-game instances of motion. Furthermore, the graphing success indicates players saw "everyday" instances of motion as being connected to kinematics and formal graphic representations, and that the virtual experiences provided by FormulaT Racing anchored this connection.

Conclusions

Arguing for personal exploration in mathematics Confrey (1991) claims, “if mathematics is viewed as functional, the emphasis is not with mirroring some unknowable reality, but in solving problems in ways that are increasingly useful in one’s experience” (p. 136). Tools such as graphing and kinematics are simply designed artifacts that help us make sense of phenomenon in the world. While it is likely that some representations are “better” at dealing with multiple situations, such as traditional forms of graphing, these situations must be anchored in concrete experiences and embedded with personal meaning. Our work with FormulaT Racing suggests that popular video games may be able to support this meaning making for scientific domains by leveraging computational thinking. The evidence presented here suggests that players utilized complex computational strategies when interacting with construction tools and ultimately created graphs of real world motion using virtual experiences and representations that they had imbued with kinematic meaning.

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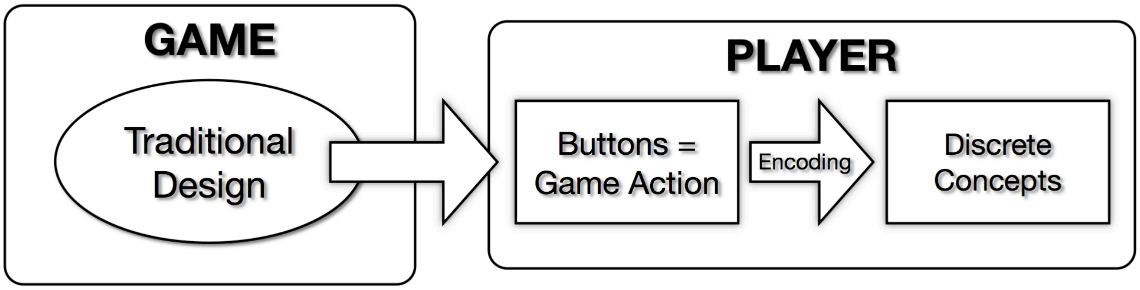

Figure 1. Traditional game design leads to a one-to-one mapping of game action and embedded concepts. Players begin to equate a button press with a complex idea such as velocity, leading to a disconnected encoding of concepts.

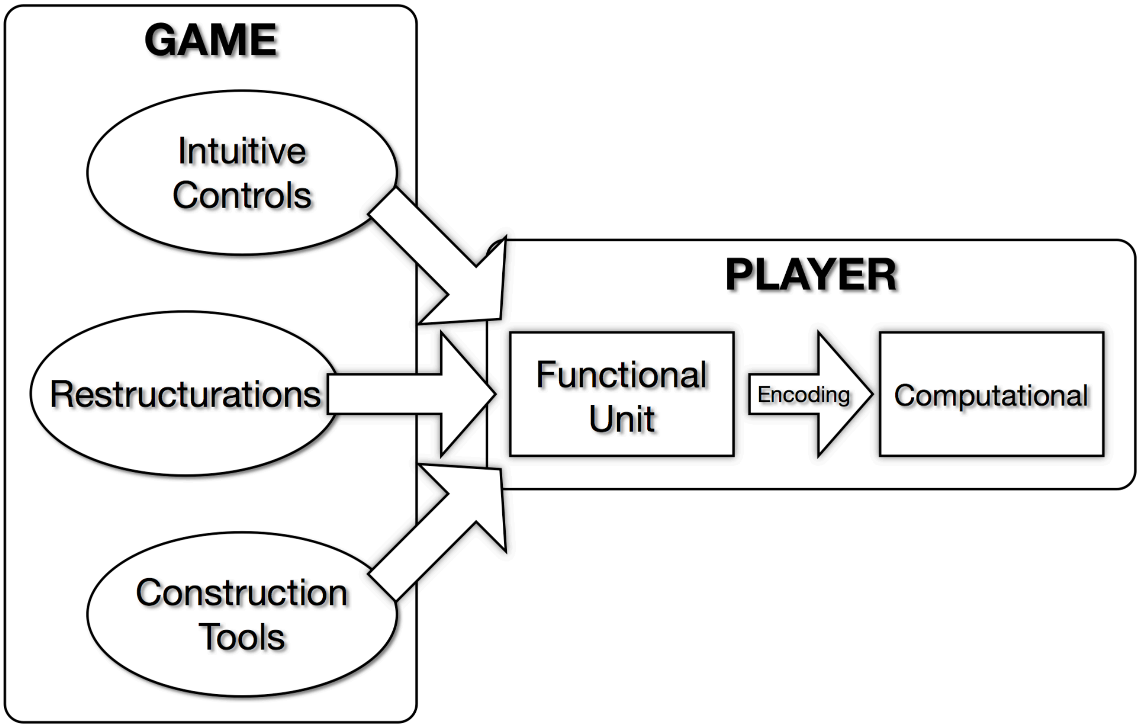

Figure 2. Contrary to traditional game design, we argue that the designs in FormulaT Racing encourage players to interact with embedded concepts and track features as a functional unit. The use of computational strategies when building representations of motion leads to a dynamic and functional computational encoding.

Code	***Description***	***Example phrases***	***Examples in-game***
Creative	The player seems to be painting simply to create an interesting LOOKING pattern. The pattern is for aesthetic value and not intended to lead to a successful run.	“I just think it looks cool”	Alternating two colors repeatedly Making one line of every possible color and then repeating for the whole track. (Less relevant in graphing mode)
Exploring System	Enacting colors or graph points to discover the rules of the system. This is more about exploring the controls of the game than trying to successfully get the car around the track. While the approach may seem extremely random it in fact may serve to let them find the boundaries of the system.		
1C(F/M/S) (1-color fast/ medium/ slow)	The player is painting the entire track one color or creating a graph at the same ycor to experiment. They may be doing this to experiment with consistency, or to lay down a foundation that they will later debug.	“I want to see what happens with all red” “I'm just gonna put the whole thing red, and then fix all the mistakes that come in.”	The entire track is one color or at the same ycor
Extremes	The player experiments with extreme values to test the limits of the system.	“I want to see how fast it can go”	Rolling the wiimote forward or backward as hard as possible.
Hack	The player has found a design flaw that they utilize for success.	“It's amazing I can actually do that! I'm going to move him as he goes. I'm going to paint the track while he's moving!)	The player paints the track while the car is moving.
Strategic	The player is painting the track in a strategic way. There is some indication that the player has an idea in their head they are trying to enact on the screen. There is a definite “plan.” being enacted.		
Ordered	The player implements their plan in an ordered fashion, from beginning to end.	“First I need to… and then…”	The player constructs his idea starting at the beginning of the track moving towards the end and may follow along with the track image using their finger
Motif	The player has created a strategic pattern that they are repeating — not unlike a procedure that’s being used at specific times.	“Every corner is a fast color and every line is a fast one”	Colors are clearly related to track features and repeated when the feature repeats. Peaks and valley’s are clearly related to track features.
Debugging	Attempts are made to debug a problem. Players may try to add or change colors (or graph points) in systematic, but small, ways. Sometimes this solves the problem, sometimes it does not.	“Maybe if I add some purple here…”	Player quickly adds or removes color in only one or two locations before running again. Graph is just “changed” rather than rebuilt.

Table 1. The above coding scheme was used to analyze video data of players interacting with the construction tools. Units of analysis were determined by moments of a strategy shift. In most cases the obvious point of strategy switching occurs after a failed run though occasionally verbal or physical cues from the player indicate a strategy shift between resets.

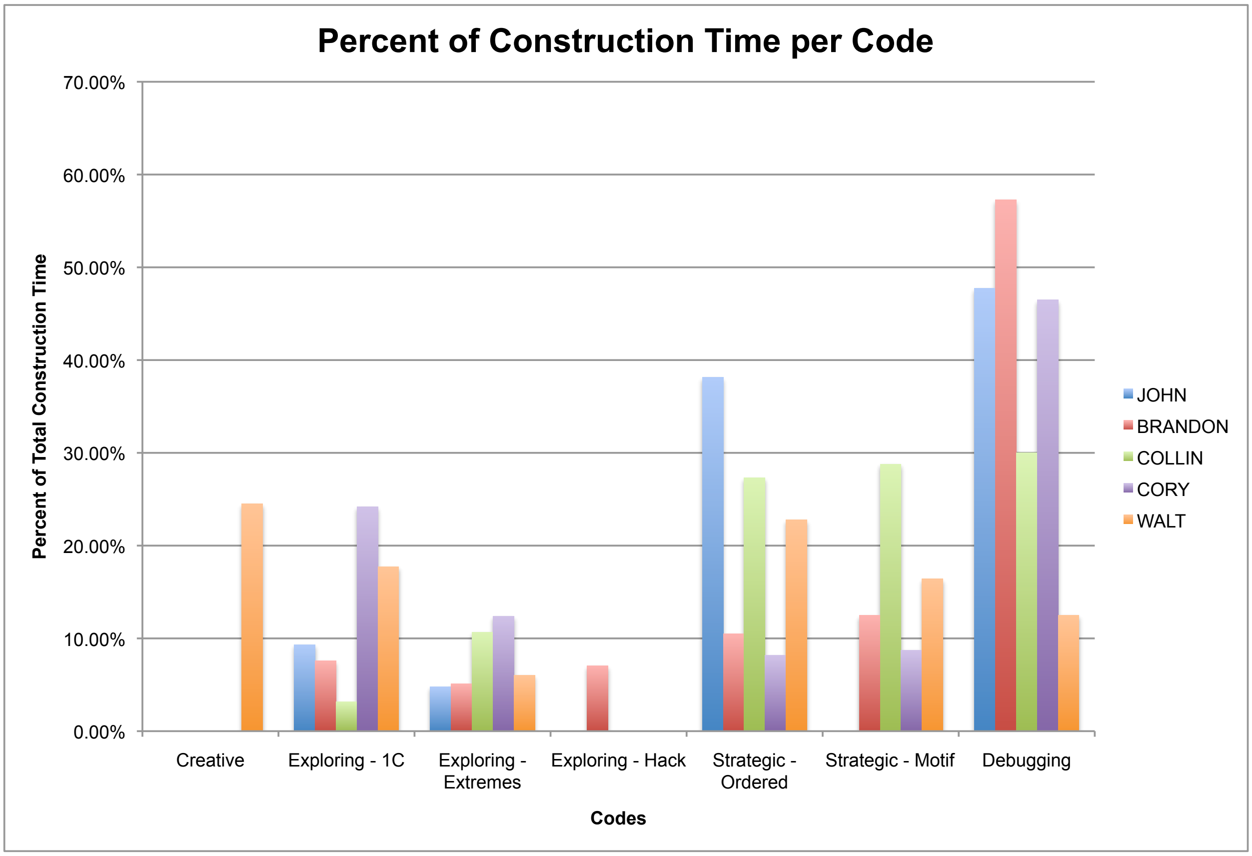

Figure 3. This graph shows the breakdown of time each individual spent engaged in the coded activities.

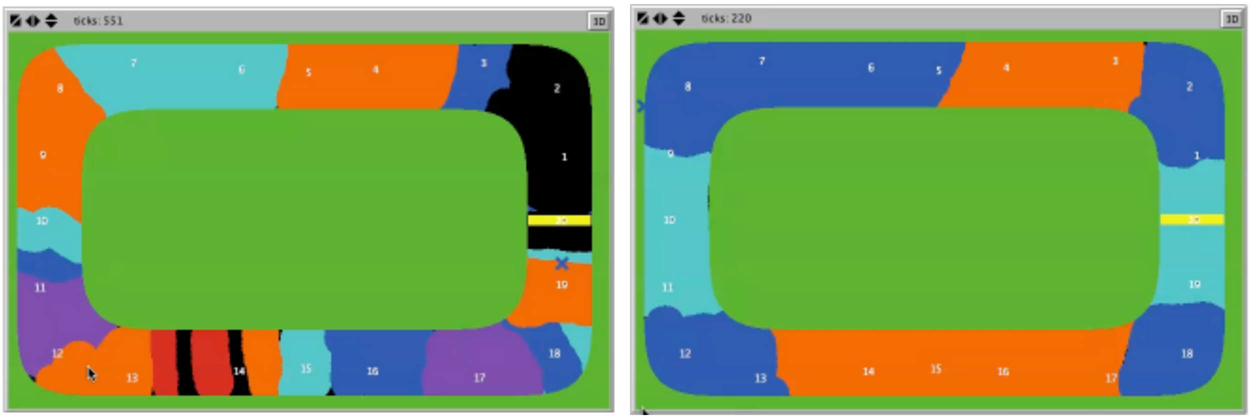

Figure 4. Collin’s early and final attempts at painting the square track. His shows some evidence of what was coded as “strategic - ordered.” The final and successful version indicates clear signs of “strategic - motifs” where slow colors are used in the corners and fast colors on the straightaways.

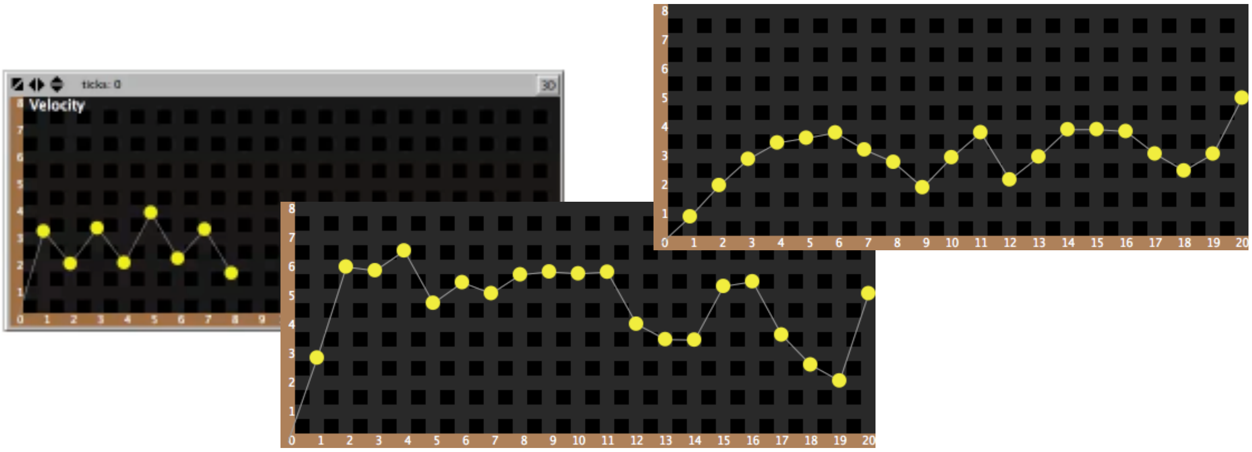

Figure 5. Collin's three graphs show an interesting progression. First, not knowing he needed to use all 20 points, Collin broke the entire track down into 8 pieces (corners and straight aways) of repeating motifs. When he constructed the entire graph he got a bit carried away with going very fast. Finally, Collins last graph shows a clear connection between changes in velocity and track features.

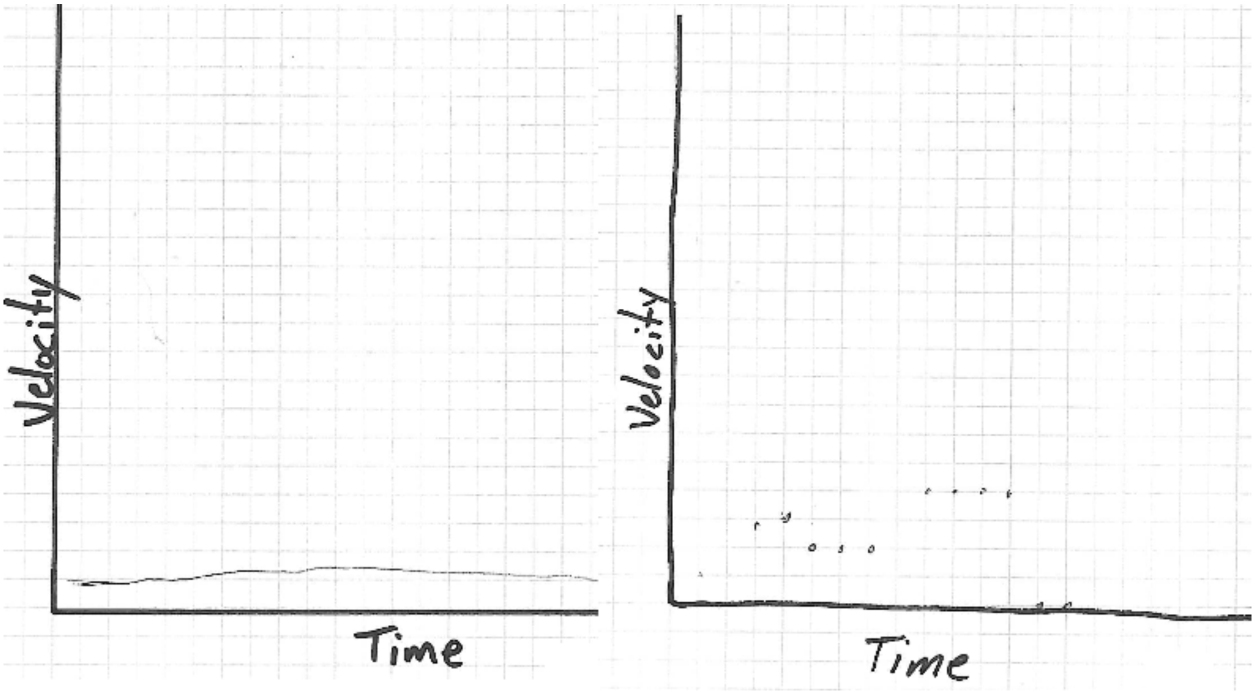

Figure 6. Examples from pre- and post-interview graphs created by participants. Many participants simply drew a horizontal line (moving the pencil faster or slower according to the value on the speedometer) for the pre-game interview graph. In the post-game interview all participants produced qualitatively correct velocity versus time graphs that included features like varying accelerations and constant velocity.