Helios: An HTML5 Game Teaching Proportional Reasoning To Child Players

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***Abstract*—Helios was developed at the Entertainment Technology Center (ETC) to teach proportional reasoning to children ages six through ten. The game features balancing and unbalancing levels which were designed with input from early childhood educators and learning researchers, and iteratively updated based on results of child play tests. Such feedback universally recommended making the balancing exercises less repetitive and introducing opportunities for more player engagement. Helios also addresses scientific inquiry steps of hypothesis formation and explanation and socio-emotional learning in terms of discussing with an in-game peer. This paper emphasizes the development process and presents problems uncovered during the evolution of the balance game and their resolution, contextualizing the discussion with references to intrinsic motivation literature. It reports on a specific formative play test with 17 children. It was developed using the ImpactJS game engine, allowing for use across major web browsers without additional plug-ins. Lessons learned regarding the formative test are shared, culminating in a series of next steps for Helios development.**

Keywords—educational game; early childhood science education; game development process; HTML5 game development; ImpactJS

I. Introduction

Children love to ask "Why?" demonstrating their curiosity by peppering family members and teachers with questions about science. Through powerful interactions of being present, connecting with the child, and offering opportunities to extend learning, an educator can foster a child's ability to explore, think, and communicate [1]. Can a digital game offer powerful interactions to the child, while fostering measurable scientific learning? That question was addressed with a collaborative development between two departments at Carnegie Mellon University: the Entertainment Technology Center (ETC), and the Human-Computer Interaction Institute (HCII), resulting in a *RumbleBlocks* game reported in CGAMES 2012 [2]. The ETC and HCII then worked together on designs leading to *Helios*, teaching six to ten year olds scientific principles of balance. *Helios* extends beyond the goals of *RumbleBlocks* (which covered tower-building and engineering principles behind tower stability) by also addressing practices of scientific inquiry and socio-emotional skills.

This paper discusses design decisions for *Helios*, the iterative development process involving child playtesters, some early formative evaluation work, and concludes with the next steps for the project as it heads toward more formal educational evaluation. The template presented here can guide other game development teams interested in early childhood science education.

The balance principles, scientific inquiry, and socio-emotional learning game objectives are drawn from the National Research Council's Framework for K-12 Science Education [3] and Pennsylvania's Academic Standards [4]. The principles of balance in *Helios* are compatible with the Motion and Stability Core Idea (PS 2) from the NRC Framework, specifically PS2.A "Forces and Motion" and PS2.C "Stability and Instability in Physical Systems." The social-emotional skill development in *Helios* is compatible with PA Standards Subject Area 16: Student Interpersonal Skills, specifically 16.1.K "Distinguish between emotions and identify socially accepted ways to express them" and 16.1.5.A "Examine the impact of emotions and responses on view of self and interactions with others." The scientific inquiry learning in *Helios* is compatible with the Scientific and Engineering Practices from the NRC Framework, specifically Practice 6: Constructing Explanations and Designing Solutions.

The ETC addressed single player game development through two semester-long projects. In the Fall 2012, a first prototype was made addressing the stated game objectives with the ETC *Torque It!* project. That prototype laid the foundation for *Helios*, which was produced by the Spring 2013 ETC *Impact!* project. Both projects detailed their weekly progress in online newsletters, with a web page for *Helios* as a demonstrable game nested within the *Impact!* pages [5]. The interested reader can search out the newsletters and play the game for greater detail and insight behind the points made in this paper. Follow-up educational evaluation will be conducted with external partners in late 2013.

II. Proportional Reasoning Behind the Game

Helios is based on Siegler's cognitive development work with a balance scale [6], teaching principles governing the sum of cross products rule that can be used to determine whether a scale will balance, given a particular configuration of weights on each side of the fulcrum. The game levels are designed to help children progress through four increasingly complex "Rules" [7] identified by Siegler [6]: (1) paying attention to weight, not distance; (2) considering distance, but only when weight is equal on both sides; (3) considering both weight and distance, with cues in congruity; (4) considering both the amount of weight and distance of weights from the fulcrum; if the cues suggest different outcomes, the sum of cross products rule is applied. A study with youth ages 5-19 showed that the use of Rule 4 did not occur with children younger than 14 [7]. A game targeting proportional reasoning in this problem space for children ages 6-10 should emphasize Rules 1 and 2 especially: Rule 4 may be beyond the scope of such a young audience. The requirement to change game level difficulty (and which Siegler rules apply) led to the use of an xml file that specifies the balance problems appearing throughout *Helios*. Educational game researchers can tweak the initial flow of game levels based on formative tests, and different configurations can also be used for different player ages.

The central mechanic for the game is placing items on a beam to balance or unbalance it. The game itself is meant to run across the major web browsers supporting HTML5, without needing a separate game engine plug-in. ImpactJS was chosen as the JavaScript game engine. The game is driven totally by mouse interaction, with the mechanic for item placement being an early focus in *Helios* development. If the player succeeds on a Siegler-inspired balance problem such as the one illustrated in Fig. 1, then he or she is granted access to the next level in the game.

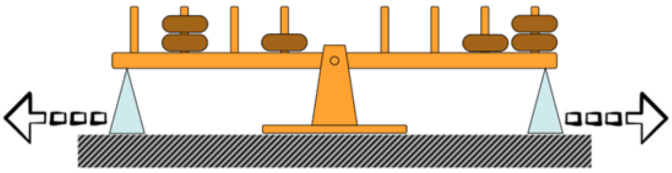

Fig. 1. Balance problem with weights and fixed distances from fulcrum; here beam would tilt down at right side when triangle supports removed.

III. DEVELOPMENT PROCESS AND FIRST STEPS

The ETC offers a Masters of Entertainment Technology degree. In pursuit of this degree, students spend their first semester with a set of core courses, including "Building Virtual Worlds" (BVW), followed by three semesters in which students tackle studio projects like *Torque It!* and *Impact!* [5] with a small team of artists, game and audio designers, and programmers. Courses like BVW and the studio projects teach the value of rapid prototyping and iteration [8]. The ETC emphasizes the importance of early and frequent iteration in game design, and the majority of semester studio projects follow the Agile development process with weekly sprints that break down tasks into small increments. Lessons learned from past projects in aligned domains can jumpstart work, which helped *Helios* development. First, prior work on *RumbleBlocks* highlighted the importance of narrative to encourage child players to keep working with the game through challenges due to the intrigue of the story. *RumbleBlocks* also underscored the importance of scaffolding blended with narrative, i.e., a way to keep early levels easy for the player without breaking the story [2]. *Helios* was always developed with a story in mind, one set up after playtesting rounds were finished with a different themed game produced by the *Torque It!* team.

The *Torque It!* team tackled the issue of socio-emotional learning in a single player game, *Teeter Totter Go*, by introducing a peer who is always at the other end of the beam. You as the player take turns with an in-game peer in placing rocks, destroying rocks with the hammer if you hold it, or passing the hammer if requested. A screen shot of this game is in Fig. 2. It shows a rocky outback nature park with player and peer set up as rangers having to cross chasms by balancing the beam.

Fig. 2. Teeter Totter Go game level where player in red (left) can only share hammer with in-game avatar at right: he has no more rocks to place at the left side of the fulcrum, but does have the hammer to share.

Malone's seminal work on intrinsically motivating instruction [9] investigated a series of games and identified challenge, fantasy, and curiosity as key aspects of design that fostered engagement. In 1987 he and Lepper [10] expanded the list to include choice and control. Dickie argues that while these works are still relevant and informative, game design has evolved since the era in which these studies were conducted, and suggests that within contemporary games, fantasy has developed into complex narrative structures with opportunities for exploration, collaboration, and challenge [11]. The narrative environment fosters motivation and serves as the organizational framework for the interactive environment [11]. Table I summarizes intrinsic motivation and the *Teeter Totter Go* design according to the framework posited by Dickie [11].

TABLE I. DESIGNING *TEETER TOTTER GO* TO MOTIVATE ITS PLAYERS/LEARNERS

Intrinsic Motivation	***Teeter Totter Go Design Elements***
Choice	Male/female avatar, how many rocks to place, where rocks should be placed/removed, when to seek or share hammer, making predictions and hypotheses (inquiry)
Control	Strategies employed to balance or unbalance beam
Collaboration	Working with in-game "peer"
Challenge	Problems equivalent to current level of skills
Achievement	Progress through park, collecting dropped badges along the way (badge counter at top right of Fig. 1)

Tens of children ages five through ten from Pittsburgh and New York City used *Teeter Totter Go* in play tests on October 23; November 13, 16, and 28; and December 3, in Fall 2012. These tests led to improvements like the choice of a male or female avatar (for character at left in Fig. 2) to keep both boys and girls more invested in the story. The choice on what to place or remove (via the hammer) on the beam motivated children, at first, in line with guidelines on the importance of player choice [9, 10, 11]. However, playtest results and follow-up meetings with professional child-educational experience designers from the Sesame Workshop revealed three problems in choice and control: (1) choice was limited, as player only controlled what was on his/her side of the fulcrum and could only do actions shown in panel above avatar's head; (2) choice could be deadlocked, if the only way to pass a level was by sharing the hammer so that the peer could destroy items on his side of the fulcrum as in Fig. 1 and player did not want to share, then game was "stuck" (this was witnessed in various playtests, frustrating children); (3) choice was repetitive and too focused, stifling curiosity (the child only had a panel of actions focused on rocks and hammer, not on the rest of the environment). The *Torque It!* team did take some corrective action, e.g., simply walking the player avatar across the beam at the end of each level via keyboard control was amusing to children (even though it had nothing to do with Siegler principles). So, the benefits of extra “twitchiness” in controlling the virtual environment and avatar through keyboard/mouse interaction was appreciated, as evidenced by child playtesters' glee, but available only at the end of each game level presenting a balance problem.

The major collaboration and achievement issue with the setup of Fig. 1 is the breaking of the narrative fantasy, reducing the player's heightened state of attention which can have a negative impact on learning [11]. Child testers knew that they were helping the peer, but did not always know what to do. That was solved with the action panel above the avatar head, but now there is one more non-park setting element in the interface. At the start of every level, the peer somehow magically appears from the right and player from left, even though both exit screen right when a level is passed. Nothing could be clicked on in the park to produce other sounds or visuals, i.e., there were no surprises or extra juiciness as recommended by two of the game design “lenses” authored by Schell [12]. Most strikingly, child playtesters withered after a few minutes and noted that the game was a series of exercises, too much the same, not enough reward. The accumulating badge count and changing park backdrop scenery were not enough to motivate the children in this world.

The Spring 2013 *Impact!* team made the decision to change narrative with the goal of addressing these shortcomings. As with *Teeter Totter Go*, ImpactJS was used to produce the single player HTML5 game allowing for cross-browser deployment without a plug-in. The experience remains a sharp and vivid 2D world as that worked well with children, with a renewed emphasis on more surprise and juiciness through interactions with the revised setting.

IV. HELIOS STORY NARRATIVE AND GAME MECHANICS

As learned with *RumbleBlocks* [2], a story premise helps give young children a concrete explanation of the goal and motivation to move through the game successfully. As seen with *Teeter Totter Go*, a story with holes and repetition can lead to disinterested child users, who then see the educational game more as a series of tests or "homework" rather than a playable experience. The space station setting of *Helios* grew out of a desire to have a game setting that allows for easy adjustment of character assets to possibly fold into the *Prankster Planet* adventures produced by the Sesame Workshop at pbskids.org. *Helios* follows the adventures of students aboard "Ark," a space station that houses the school for gifted children "Helios."

There are two new students that were recently accepted into Helios: Lucas and Gabriella. They join the other students, Wesley and Cindy, along with their professors Baley and Brenda. They will be learning about the balancing principles via their Balance Instructional Learning Launcher, codenamed "B.I.L.L." (shown as face on screen in Fig. 3a). As B.I.L.L. starts to introduce the balancing theory, the kids become impatient, and decide they want to practice balancing experiments right away. Wesley has a program that he uses to hack B.I.L.L. and make it go right into balancing exercises. Unfortunately, the program is buggy, and B.I.L.L. goes rogue. It traps the teachers in stasis, and locks down the spaceship.

The students must go through the ship (e.g., Fig. 3c, 3d, 3e, 3f), solving different balancing problems in order to get through to B.I.L.L.’s mainframes and shut it down to free their teachers. After going through three different zones, the students are able to shut down B.I.L.L., which gives Baley and Brenda a chance to fix the system and return B.I.L.L. back to normal.

Over many weeks, the story developed with a series of play tests with small groups of children, who noted in actions and words which story elements worked and which were still confusing. The last of the project's play tests (see next section) confirmed that the implemented story was presented clearly, understood, and helped drive the player to success for grades K-3 across boys and girls. Fig. 3 illustrates some of the steps of the game with screen shots.

Helios features in-game assessment through inquiry levels, via hypothesis selection and explanation, to measure if the game is teaching the players as they progress through the game. The two forms of inquiry are shown in Fig. 3c and 3f. In both forms, the player works with an in-game peer to get through a door, locked down by B.I.L.L. Levels like 3c have the player selecting the correct answer from images on the screens at top so Cindy can input it as a code to open the door. The "Boss Level" like 3f, has B.I.L.L. stopping the player and friend Wesley and giving them a new set of puzzles. In these puzzles, the player (through choice options at left) and Wesley (through choice options that will appear at right) must come to the same answer as to why the beam is either balanced, or unbalanced.

Fig. 3. Six screen shots from *Helios* game showing (a) opening new/resume game screen; (b) narrative intro with Baley; (c) a problem goo level; (d) an inquiry level where player gives hypothesis to Cindy; (e) another problem level, this one requiring unbalanced beam to cross water; (f) "Boss Level" of solving beam problem with Wesley.

If Wesley picks the wrong answer, then the player is given the opportunity to convince the player via social, anti-social, or non-social dialogue. Thus, Boss Level folds in an element of socio-emotional learning. Socio-Emotional Learning (SEL) is geared towards researching if games can influence positive social behaviors. The trick for SEL is to make sure the player has the option to be social or not, rather than forcing them into social situations. If they are always forced to be social, then there will not be any consequence or choice in dialogue selection, and from failure can come learning opportunities [11]. The player must complete one Boss Level per tier, according to the game's narrative. The three tiers in this game cover Siegler Rules 1 (weight), 2 (distance), and 3 (mixed). Table II summarizes intrinsic motivation and the *Helios* design according to the framework posited by Dickie [11].

An early focus in *Helios* development was the mechanic to use to place and remove objects from the balance beam. This essential mechanic had to be fun, yet simple so that it would not become a distraction from either the learning objective or break intrinsic fantasy with the underlying narrative framework. Two tested candidates were a slingshot mechanic (see Fig. 4a) where the mouse directs how far back to pull the slingshot lever to then launch the projectile, and an energy lasso mechanic (see Fig. 4b), allowing for both placement and removal of objects from the beam directly by mouse movement controlling the objects.

TABLE II. DESIGNING *HELIOS* TO MOTIVATE ITS PLAYERS/LEARNERS

Intrinsic Motivation	***Helios Design Elements***
Choice	Male/female avatar, placement of nuts on balance beam, making predictions and hypotheses (inquiry), tone to use in communication with peer (SEL)
Control	Strategies employed to balance or unbalance beam, interactions with environment (promoting curiosity)
Collaboration	Working with in-game "peer" to pass "Boss Levels"
Challenge	Problems equivalent to current level of skills
Achievement	Progress through space station, rescuing teachers and repairing B.I.L.L.; game levels vary visually with water, goo, circuits, elevators, etc.

Six child playtesters used both mechanics, and took longer to learn the slingshot. They preferred the energy lasso, but in its early stages, it too needed further work. Over time, it evolved into an energy glove (as shown in Fig. 4b) with a "tractor beam" delineating the connection between the arm animation on the player avatar and the nut being placed on the beam (see Fig.s 3c and 3e). Sound effects and visual animations were reported as appealing in subsequent playtests polishing this tractor beam lasso effect. The slingshot was not incorporated, in part because it could not remove items from the beam as easily and so would introduce extra game action complexity as did the *Teeter Totter Go* "action panel," while the energy glove allowed the player to remain in the narrative space more completely. The slingshot was understood by children, though, and after some practice time, was found appealing as well and so remains a candidate perhaps for mini-game expansion of the *Helios* experience, should mini-games be later added to make the hypothesize/discuss inquiry/SEL levels more dynamic.

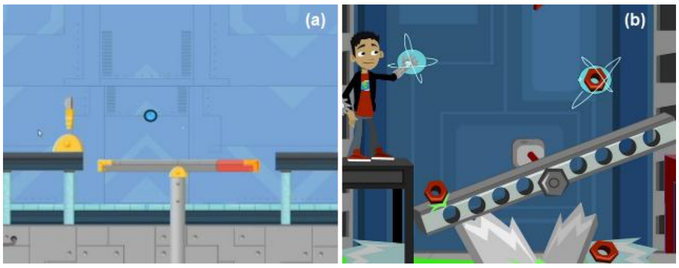

Fig. 4. Placing items on beam: (a) sling shot which highlights on beam where object will land; (b) later evolution of tested "lasso" idea where player places nut on beam (and can remove it as well) via energy lasso – here shown as energy glove but not yet adding the tractor beam connection lines.

V. PLAY TEST WITH 17 K-THIRD GRADERS

Helios evolved throughout the semester in numerous ways. The narrative illustrated a bit with Fig. 3b started as a 3 minute overview, too long for children to watch passively; it was tightened to a minute and recorded with voice actors and a custom sound track. The tractor beam connection was added to the beam addition/removal of items mechanic. The problems were varied by introducing a number of levels, e.g., Fig. 5 shows another problem level type, supplementing those shown in Fig. 3. The work led to a formative evaluation with 4 each of kindergarten, first, and second graders, and 5 third graders, in May 2013.

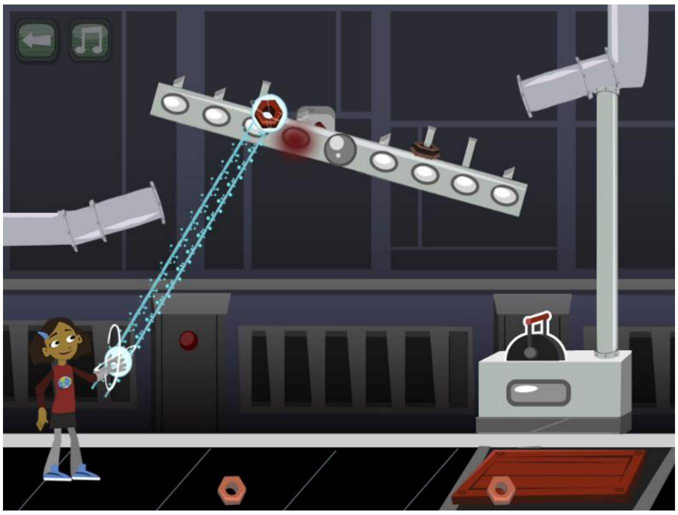

Fig. 5. Problem level in *Helios*: this one connects piping to activate elevator at right to proceed to next level; other problem levels incorporate green goo, water, fire, and other environmental attributes that animate and produce sound effects on mouse clicks to appeal to players' curiosity.

The target age range is broad, and more formal tests may eventually narrow the optimal target to say third-graders. More likely, the level sequencing and tier sequencing (many levels per tier, tiers align with Siegler Rules) will vary according to the player's capabilities, with past research indicating that full proportional reasoning understanding for this problem space (Siegler Rule 4) may not be realizable by children under age 14 [7]. Younger children found levels challenging, but succeeded in working through them, perhaps with more trial and error than understanding. Older children demonstrated better understanding through faster reactions to levels and higher in-game performance on inquiry levels, but some may have been a bit bored with too many simple Rule 1 weight problems whereas their skill allowed them to proceed more quickly to greater challenge. Adjusting the flow of the game to meet the player's capabilities and have them neither bored or frustrated is a Lens of Flow in Schell's game design set [12], and noted as a key in delivering a playable learning experience [11]. The configuration of the game levels, i.e., scene type, posts on beam where weights can be placed, number of weights in scene and solution state is given by xml attributes in a text file. The appearance and difficulty of a problem scene is dictated by the xml configuration file contents. For example, Fig. 5 shows a problem where the second post on the left of the fulcrum and posts two and three to the right of the fulcrum as active and capable of having nuts tractor-beamed onto them. There are three possible nuts for placement (inventory starts off highlighted at bottom of game screen), and red/green lighting on the beam posts provides feedback as to whether a post accepts a nut. Careful design of levels introducing complexity over time, with scaffolding provided through some posts being disabled on the beam, helped the players. (Fig. 3e shows a post location glowing green because it is not broken off and can take weight; Fig. 5 shows the first post to the left lighting a "red" indicator that no weight can be added to that location.) Experienced older players worked through the easy levels quickly without complaint as they focused on the narrative of returning B.I.L.L. and Helios back to normal. Younger players made use of the reduced post candidate space to guide weight placement. The ability to tune level complexity and level sequencing is critical, and such tuning is necessary to adjust to particular players' skill levels, as expected from cognitive development work with children and this proportional reasoning problem area [6, 7].

The first broad conclusion from the May 2013 evaluation test is that level sequencing needs extensive modification and testing, and should be tuned to grade level. The third graders stated that the game was too simple, and were able to get through the three tiers with relative ease. The second graders also were able to get through the game relatively quickly. The first graders moved a bit slower through the game, but some were still able to get through most of the game levels in the allotted time (~25 minutes). The kindergarten group struggled the most through the game, which could be attributed to their lack of familiarity of computers/mouse input as well as some of the reading required for hypothesize/discuss levels may have been above their skill level. Based on these observations, we feel that each level sequence should be tailored to the grade of the player to better allow for educational testing.

The second conclusion is that SEL integration into a science game is difficult. We implemented some socio-emotional learning into our game, inside the "Boss Level" where the antagonist stops the player and in-game peer named Wesley and makes them solve balancing problems to get through a locked door. If Wesley gets the answer wrong, then the player has to convince him to change his answer. They can do this in a social manner, an anti-social manner, or a non-social manner. These opportunities, while there, really don't get into the depths of SEL. In order to get a good measurement of SEL, the player needs to see consequences of their actions. Since our SEL implementation was built on top of balance problem discussion, the consequences of the player response were fairly minor, a change in tone and look by Wesley. For proper research into whether games can influence positive SEL growth, the game's main focus may need to be about collaboration and how different collaboration actions can affect the player, rather than just a supplementary feature.

Perhaps surprisingly, the child playtesters did like thinking and being "tested" in-game. The feature that was deemed the favorite was the "Boss Level" (Fig. 6 and Fig. 3f). According to the players, they liked being asked questions, and having to figure it out. Having the antagonist (the red screen B.I.L.L.) prompt them under the guise that they would not be able to solve the problems may have been a motivator, as getting the answers right prompted the antagonist to admit defeat, which gives the player a sense of accomplishment, while learning. Also, even though the SEL implementation was shallow, players still enjoyed helping their friend (Wesley) come to the right conclusion.

Finally, one of the challenges revealed with *Teeter Totter Go* was overcome with *Helios*: the child player enthusiasm did not wither over the 25 minutes with the game. The extraneous (i.e., not needed to teach Siegler Rules) fun features added into *Helios*, such as splashes when the player clicks on the water and slime, were used and appreciated. These features are never explicitly told to the player, but rather are discovered on their own during the game. The child players definitely enjoyed these features if they find them, based on smiles and voiced exclamations of pleasure during the May 2013 playtest. The children will sometimes spend minutes of their play time just toying with the extra features rather than focusing on the main task. It seems like a good way to allow them an “escape” in educational games, to help keep them in the game rather than wanting to do something else, in case they are stuck on a level or start to get frustrated. There is a delicate balance though, in that if they are trying to do the main task, but the feature keeps getting in the way, that feature now becomes annoying, and may heighten player frustration.

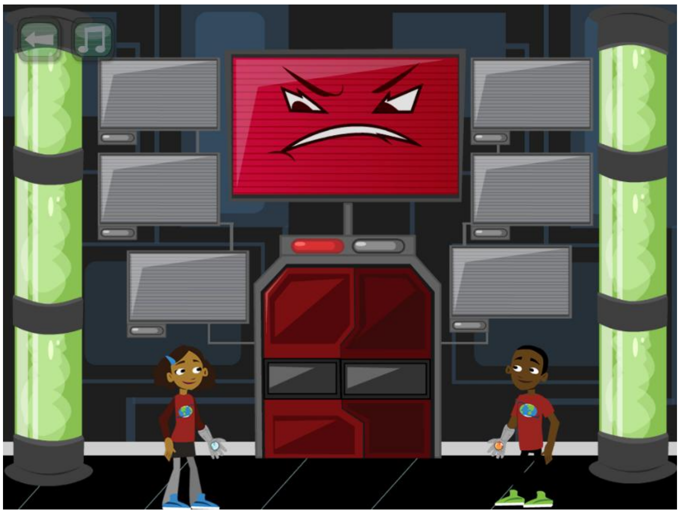

Fig. 6. Starting dialog in Boss Level in *Helios*: the hacked B.I.L.L. shown as red screen with angry villian voice is taunting player (left) and Wesley (right) that the door will remain locked to trap them because they won’t be able to solve the required balancing problems; after each of three get solved, the green fluid drops by a third in side pillars, until the door opens and B.I.L.L. admits defeat.

VI. Conclusion and Future Work

The results of playtesting with children show that *Helios* is a playable experience for 25 minutes or longer which can be improved by aligning level difficulty with the cognitive abilities of the player. The space station theme and narrative were appealing to boys and girls and the tested K-3 grade demographic. It may remain appealing for middle schoolers in grades 4-6, allowing for levels to be designed for Siegler Rules 1 through 4 inclusive and the full range of proportional reasoning in accordance with past educational experiments [6, 7]. The reported work concentrated on problem levels emphasizing weight (Siegler Rule 1) and distance from fulcrum (Siegler Rule 2).

Ongoing work is evaluating whether success in the game and success with in-game testing in the hypothesis/discussion levels leads to learning demonstrated in out-of-game testing of proportional reasoning. If the educational game is fun and produces learning effects, it becomes valued by both child players and teachers/parents. The emphasis on the work reported here was accomplishing the first objective: making sure that child players will persist in staying with the game and working through numerous problem levels. Via a test with 17 school children, players will remain with the game across at least 33 levels and 25 minutes of play. More work is planned to verify that the anticipated learning Siegler Rules 1 and 2 is occurring with six- to ten-year-old children.

Will these results hold for thousands of students? What level designs work best, e.g., an emphasis on balance needed to pass (like Fig. 3c), imbalance needed (like Fig. 5), or a mix as expected to keep children curious and amused? How quickly should level complexity progress from coverage of Siegler Rule 1 to Rules 2, 3, and perhaps 4? Eventually, a number of varying configurations of *Helios* will be deployed widely through the web to fine-tune level choices, much like the game Refraction has tested play time, progress, and return rate across varying versions of their game [10]. Such broad deployment across the web is facilitated by the production of an HTML5 game using ImpactJS, and by having configuration parameters that make the game highly tunable.

This paper has emphasized the objectives, foundation work with a prior game prototype, and child play tests which led to the development of *Helios*. From the choice of art style to the inclusion of a narrative, from the testing and choice for a key interaction mechanic to tweaking game elements of fun and surprise to keep the players engaged, the paper has overviewed the improvement of the game over time. The interested reader is welcome to see more background on the reported work and play *Helios* via links from the ETC [5]. Future work will scale the evidence for educational effectiveness, field test more broadly, and report modifications made based on such testing.

Acknowledgment

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