Mobile Movement Mathematics (M3): Discussing Iterative (re)Design of a Digital Tablet Tutor-Game for Learning Fr*actions*

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Abstract: Researchers developed Iteration-1 (i1) of a digital tablet tutor-game exploring the impact of *narratives* (strong (*S*) vs. weak (*W*)) and *gestural mechanics* (conceptual (*C*) vs. deictic (*D*)) on players' understanding of mathematical fractions. Tutor-log data revealed that students using conceptual gestures were significantly more accurate at estimating and denominating fractions than students using deictic gestures and a possible interaction between narrative and gesture. We discuss how these findings, combined with observational notes, student exit surveys and clinical interviews informed revisions for the redesign of assets, mechanics, pedagogy (instructions/scaffolding/feedback) and narrative for Iteration 2 (i2).

Introduction

How do narrative and gesture impact learning on digital-tablet tutor-games? Learning, in its native state, is situated in contexts (Lave, 1988; Brown, Collins & Duguid, 1989; Anderson, Reder, & Simon, 1996; Schwartz & Bransford, 1999) and emerges from the experiences that learners *identify with* and take an *active role* to "recognize the value of concepts as tools useful for understanding and solving problems central to the context in which one is embodied…" (Barab, Sadler, Heiselt, Hickey, & Zuiker, 2007). Digital-tablets are virtual portals that leverage the visual, auditory and haptic channels of perception (Baddeley, 1986; Richer, AuBuschon & Cowan, 2010) and afford (Gibson, 1977) developers, educators and learners opportunities to situate experiences (Lesh, 1981; 1985) in game-like problem spaces and ground experiences (Barsalou, 2008) by utilizing the physicality of the gestural mechanics to embody concepts (Riconcente, 2011; Alibali & Nathan, 2012; Segal, Tversky & Black, 2014, Kang, Tversky, Black, 2014; Vitale, Swart & Black, 2014). The challenge in tutor-game research is controlling for the impact of manipulations and making adequate comparisons (Chi, 2014).

For narrative, Jiminez (2014) created a fractions game that assessed the impact of story using a single game architecture to create three variations that differed in asset depiction and story-level. This allowed Jiminez to control for all other factors and attribute the positive correlation between gain scores, story and enjoyment. For M3, we investigate whether narrative facilitates learning and mental model construction (Black, Turner & Bower, 1979) by creating a *personally meaningful project* (Papert, 1972) that fosters intrinsic interests and motivation (Cordova & Lepper, 1996; Prensky, 2001) or, if it simply adds to cognitive load (Sweller, 1988) as a seductive detail (Harp & Mayer, 1998; Adams, Mayer, MacNamara, Koenig, & Wainess, 2012)?

For gesture, Segal et al. (2014) also created multiple variations of a single tutor-game architecture to determine that learners performed better at simple arithmetic using functionally enactive and conceptually congruent gestures compared to static and identifying gestures. However, Byrge & Goldstone (2011) found better transfer of physics concepts (e.g., momentum) when gestures were transformed and incongruent (i.e., swipe right to move left). These different findings highlight the multidimensionality and functionality of gestures (McNeill, 1992) and the need to clarify what constitutes a beneficial intrinsic link between game mechanics and curricular concepts (Habgood & Ainsworth, 2011).

The current study, *Mobile Movement Mathematics* (M3), uses design-based research (DBR) to develop a tablet-based tutor-game for learning mathematical fractions and investigated two research questions: (a) How will situating learning using a narrative arc (characters, setting, plot) impact learning and motivation compared to a weak non-narrative structure? (b) How will conceptually enactive gestures impact performance and learning compared to pointing gestures? Crafting curriculum and designing contexts in an applied field like education, according to Brown (1992), must consider many research agendas in order to adequately capture learning. Thus, the current study presents performance data from the game-tutor, formal assessments, researcher observations, survey data and clinical interviews to quantify and qualify the impact of the game, its narrative, gestures and assets on student learning and to inform the redesign of M3 from i1 to i2.

Designing the Game: Iteration 1 (i1)

Fractions begin with fractures; the metaphors of mathematical thinking are grounded in our actions (Lakoff & Núñez, 2001). For example, the simple act of sharing an apple, splitting it in two equal parts underlies humans' *Number Sense* (Dehaene, 1997; Norton & Wilkins, 2009). The natural abilities to estimate, meter magnitude, apportion and compare objects are all essential for fracturing. The curriculum for the M3 tutor-game is contoured around this *situated embodied* approach: Five levels with 5 fractions in each level. In Part 1, players estimate, denominate and numerate fractions by fracturing objects (i.e., an enerchi bar – a hybrid between a rectangular area model and number line). In Part 2, players determine equivalency between the previously 5 constructed fractions by ordering them from least to greatest: First along a horizontal axis left to right (magnification), then vertically bottom to top (verification) (Figure 1).

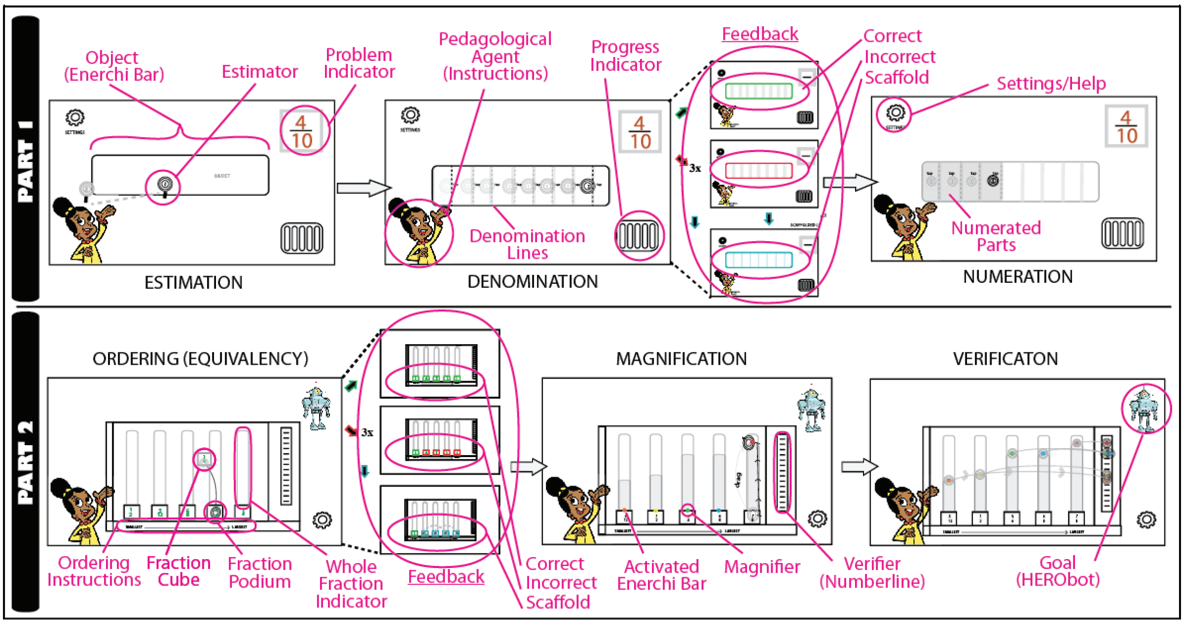

Figure 1: Wireframes for Part 1 - *Object Fracturing* and Part 2 - *Object Equivalency*.

Developing Gestural Mechanics

Gestures represent ways for learners to reactivate (simulate) the perceptual states associated with underlying concepts and strategies (Goldin-Meadow, 1999). For example, Goldin-Meadow, Cook and Mitchell (2009) demonstrated that a pairing gesture (i.e., two fingers to identify two numbers as a pairing) facilitated elementary students strategies for arithmetic problems and how gestures as abstractions are rooted in relation to the body. Alibali and Nathan (2012) documented how gestures represent structure, orientation, action and correspondence in fractions learning. For i1, the tactile gestural interface of the digital tablet serves as a bridge between action and concept.

Echoing Hostetter's and Alibali's (2008) *Gestures as Simulated Action*, the tutor compares *deictic gestures* (i.e., pointing) that index the environment, to *conceptual gestures* (metaphorical / enactive / symbolic) that embody simulated actions for fractions (Figure 2). The gestural mechanics for M3 come from an exploratory study by Swart et al. (2014) that observed students fracturing objects, sets, containers and distances and used their actions as the bases for M3's gestural mechanics. We hypothesized that conceptual gesturers would show better performance and learning than deictic gestures.

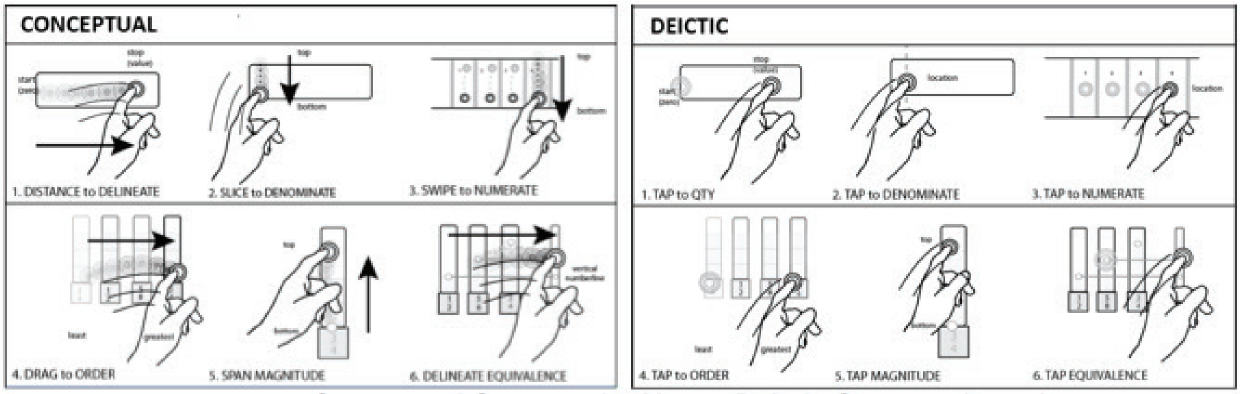

Figure 2: *Conceptual Gestures* (Left) and *Deictic Gestures* (Right).

Developing Narrative

Developing an effective narrative invests the audience in the continuity of the characters, locations, objects, actions and themes and invests them into the plot's trajectory (Graesser, Singer & Trabasso, 1994). The integration between the microstructure (details) and the macrostructure (abstractions) is especially important when building an interactive narrative if the details are the access points to concepts. Designers must situate players in problem spaces that foster mental model constructions (Johnson-Laird, 1980). Since narrative has been shown to help learners formulate coherent scripts into schemas and chunk them into coherent mental models (Black, Turner & Bower, 1979), investing players' in the narrative will hopefully motivate their exploration of the problem space and encourage their practicing the procedures for creating and comparing fractions that leads to discovery learning (Brown, Collins & Duguid, 1989). Figure 3 shows the two narratives for comparison. The *strong* narrative is based on the television series Cyberchase and titled, *Fix the Climatron.* In the game-tutor, the player embarks with the agent, Jackie to a fictional land called Penguia to defeat the evil villain Hacker by energizing the enerchi bars that activate the HERObots. The *weak* narrative is titled *Fractioneers!* It is the same tutor-game but without characters, settings, story or explicit context. We hypothesized that a strong narrative will improve student performance, motivation and engagement better than the weak narrative.

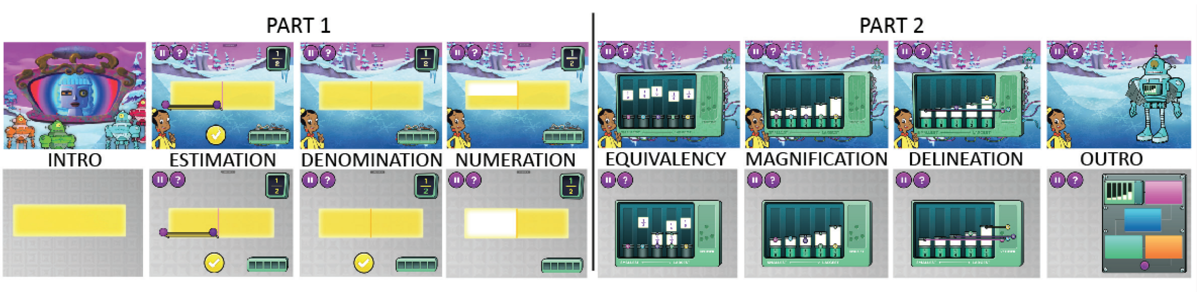

Figure 3: Characters, Assets, Scenes of *Strong Narrative* (Top) vs. *Weak Narrative* (Bottom).

Testing Iteration 1

After developing i1, researchers tested seventy-two students from grades 3 (n3 = 24), 4 (n 4=22) & 5 (n 5=26) grades (NTTL=72; $\bar{x}$age=10.31 years [1.64], 67% female) at an afterschool program in Harlem, New York City. In a mixed-methods 2x2 randomized factorial with repeated measures, students were assigned to play one of the 4 tutor environments (*SC*, n=17), (*SD*, n=18), (*WC* n=19), (*WD*, n=18). Each student completed a total of 3 one-hour sessions that included *pre/post direct assessment* using the rectangular area model from the game tutor to assess estimation, denomination, numeration and equivalency between fractions; *pre/post transfer assessment* using rectangular area models, shapes, collections, number lines, numerical fractions, equivalency, arithmetic, and word problems to assess estimation, denomination, numeration, equivalency (including ratio, proportion, scale), addition, subtraction and multiplication); *log data* from tutor play (estimation error, denomination-parts error, numeration error); written *exit surveys* (likert and free-response items assessing manipulation of narratives and gestures, comprehension, self-efficacy, motivation, engagement, persistence, preferences and concept learning) and pullouts for video-recorded *clinical interview* pullouts. Two groups of 10 students each day (5/condition) extended over multiple weeks and portions of tutor play were also video-recorded.

Quantitative Data

Repeated measures ANOVA of pre-post assessments revealed that the tutor-game overall is effective at improving learners understanding of fractions with significant learning gains across all conditions for both the direct assessment ($F_{(1, 71)} = 48.9$, $p<.001$, $\eta_p^2 = .408$ as well as the transfer assessment ($F_{(1,71)} = 57.51$, $p<.001$, $\eta_p^2 = .448$). Moreover, there was a significant positive correlation between the *direct content* and *transfer* assessments ($r = .774$, $n=38$, $p< .01$), thereby confirming a strong relationship between the tutor content and more general fractions concepts and principles.

Tutor-Log Data: Estimation. Estimation error was lower for conceptual gestures than for deictic gesture users across strong and weak narrative. Means for groups C and D were 23.04 and 24.1; the distributions in the two groups differed (Mann–Whitney U = 248, Wilcoxon W= 477, $n_C =26$, $n_D = 20$, $p < 0.08$) and revealed a trend towards an interaction between gestures and narrative that requires further study. For *unit fractions,* estimation errors were lower for conceptual gestures than deictic gestures and approaching significance, $\bar{x}_C = 23.04$ and $\bar{x}_D = 24.1$, Mann–Whitney U = 231, Wilcoxon W= 462, $n_C =21$, $n_D = 29$, $p < 0.15$ and there was a similar trend towards interaction between narrative and gesture.

Tutor-Log Data: Denomination. Student performances denominating wholes into parts were more accurate for conceptual gestures than for deictic gestures. For levels 1 – 3, students using conceptual gestures denominated (i.e., correct number of divisions) with significantly less error than students using deictic gestures $\bar{x}_C = 18.66$ and $\bar{x}_D = 25.24$, Mann–Whitney U = 164.5, Wilcoxon W= 345.5, $n_C =19$, $n_D = 25$, $p < 0.10$. The number of denominations cuts that students made in error (e.g., 3 slices of the bar, 4 parts, for a denominator of 3) suggests a similar recurring trend towards an interaction between gesture and narrative. Students were also significantly more accurate denominating unit fractions using conceptual gestures than deictic gestures; $\bar{x}_C = 17.95$ and $\bar{x}_D = 30.97$, Mann–Whitney U = 146, Wilcoxon W= 377, $n_C =21$, $n_D = 29$, $p< 0.01$.

Qualitative Data

Exit-Surveys: *5-Point Likert Scale.* Items found strong indications that students across all conditions were highly motivated to play ($\bar{x}_M = 4.62$ [.72], enjoyed playing ($\bar{x}_E = 4.59$ [.67]) and that they would persist in playing more levels ($\bar{x}_E = 4.62$ [.70]). Overall, student's indicated that they liked learning on the iPad ($\bar{x}_L = 4.44$ [1.00]) even though they found the game moderately difficult ($\bar{x}_D = 3.79$ [1.11]). Their self-efficacy judgments for their performance on the game ($\bar{x}_{EF} = 3.90$ [.94]) showed a moderate correlation with difficulty ($r = .479$, $N =71$, $p < .01$).

Exit-Surveys: *Free Responses.* Students' revealed important aspects about narrative and gesture. When students were asked to describe the game they played, only 12 students out of 37 (32%) mentioned aspects of the narrative (e.g., robots, penguins, Cyberchase). This reinforced the notion that the narrative needed to be strengthened. When students were asked to describe how they made fractions in the game, their descriptions of the fracturing process were more enactive (i.e., embodied) for the conceptual gestures (75%) than the deictic gestures (38%). However, there was overlap between the two conditions in their verbiage with words like "cut", "split" and "break". We hypothesize that while conceptual gestures are more enactive of the processes of fractions, the gestural affordances of the digital tablet, even for the deictic condition, also contributed to an embodied mental model.

Redesigning Iteration 2

ReDesigning Strong Narrative

While 94% of all the students' reported they "liked" the game and thought it was "fun" or "cool", their responses also highlighted important points for re-developing the strong narrative. For example, only 32% of the students' recalling proprietary narrative elements like the *climatron* highlighted the need for a simpler and more connected narrative. To simplify the narrative in i2, players embarked on a new mission to stop the villain Hacker and his mind machine from subduing the Penguins of Penguia. To reinforce the players' involvement in the narrative, interstitial scenes were added at the top of each level to perpetuate the narrative and the players' objective to fracture all the enerchi bars and activate the HERObots to stop Hacker. Another change included replacing the pedagogical agent Jackie with the affably anthropomorphized character Fluff the Penguin. Sixteen of the 37 students in the strong narrative (43%) complained about Jackie and her incessant instructions. Thus, in i2, players in the strong narrative must work with Fluff to save Penguia (Figure 4).

Figure 4: Narrative revision between i1 (top) and i2 (bottom).

ReDesigning Assets.

Revising the narrative affects every aspect of game design. For example, revisions to the narrative included changing the scenes for Parts 1 & 2. The icy exteriors from i1 were replaced by the interiors of a laboratory to engender the precision associated with mathematics (Figure 5). Moreover, developers designed a device, the *fractivator*, to encapsulate the process for fracturing the enerchi bars. This includes a conduit line that feeds enerchi in and out of the fractivator in Part 1 and transfers it to canisters inside the HERObot for Part 2. Figure 7 reviews many of the redesigned elements between i1 and i2, including backgrounds and assets for gestures, curriculum, game-play, instructions, feedback and scaffolding.

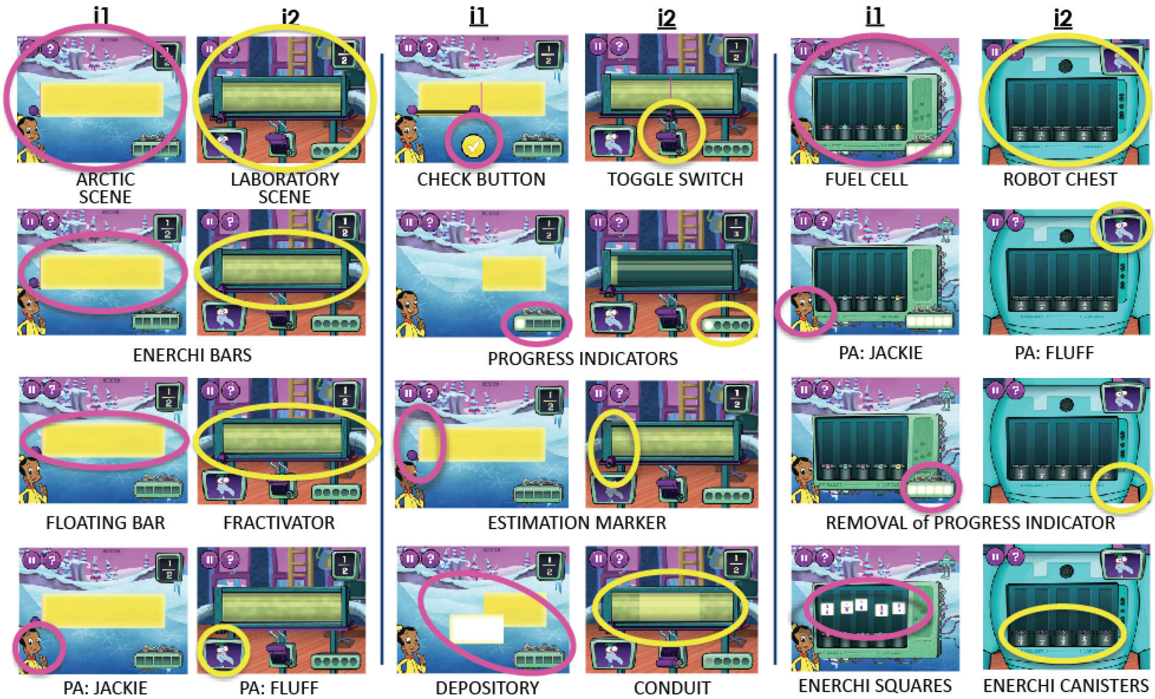

Figure 5: Redesign of Assets between i1 and i2.

ReDesigning FrActivities.

In i1, the development team thought it would be prudent for players to deposit the fractured enerchi bar into a receptacle (i.e., to embody the process) and in Part 2, deposit the power cell into the chest of the HERObot. However, these deposit steps proved to be unnecessary *seductive details* (Harp & Mayer, 1998) that detracted from the tutor's focus on fractions and were thus removed from i2.

ReDesigning Pedagogy/Scaffolding.

In i1, students intentionally received no feedback for their estimates to prevent biasing students' subsequent attempts to denominate and numerate the fraction. However, tutor play and clinical interviews revealed numbers of students' expressing inherent desire for feedback. Thus, i2 introduced a new step for students to adjust their original estimate once they had successfully denominated and numerated the fraction. This allows students to compare their original estimate to the actual value to reinforce the connection between the parts-to-whole, the continuous real number on the number line, and its numeric representation (Siegler, Thompson & Schneider, 2011).

In the original development of i1, the process of constructing fractions in Part 1 was to serve as a foundation for sorting fractions from smallest to largest in Part 2. However, observations of tutor-play corroborated the data log that showed students were largely unable to determine equivalency between fractions strictly by number and resorted to a guessing strategy (n= 9 students, 14%, determined equivalence between fractions correctly on 1^{st} Attempt). In the progression of the game, students' mental models of the magnitude of each fraction were not yet robust enough to determine equivalency solely by number. Thus, for i2, researchers developed a scaffolding mechanism by which students could connect numerical fractions to their area-model depictions. By depressing the magnifier on the canisters in Part 2, students previewed the numerical representation followed its area-model (Figure 6b) to help students devise visualize the correspondence between the size of the enerchi bar and the value of the fraction and make bifurcated comparisons as they put them in order.

Figure 6: Redesign for Parts 1 & 2 from (a) i1 to (b) i2.

ReDesigning Instructions.

In i1, all instructions were delivered audibly via the agent, Jackie (circled in magenta, see Figure 7). If students' needed to hear the instructions again, they could hit the "?" on the screen. Nonetheless, many players (n=32 students, 44%) still requested help from experimenters to play and conveyed that the instructions at times were unclear. Consequently, instructions in i2 are delivered by a ghost hand (circled in yellow, see Figure 9) that demonstrates the gestural mechanics. Additionally, this makes the tutor more accessible to children with hearing difficulties and ESL learners.

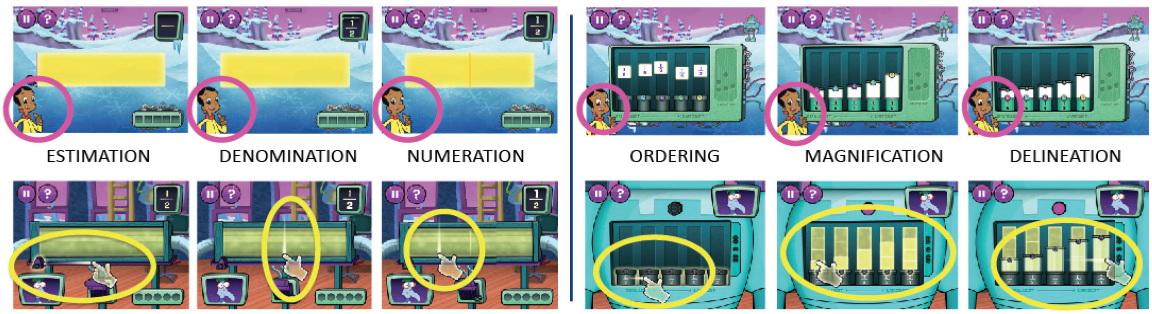

Figure 7: Instruction redesigns from i1 (top) to i2 (bottom).

ReDesigning Scaffolding/Feedback.

For i2, all scaffolding and feedback was delivered through visual feedback and SFX and any text was removed. For example, in Part-2, feedback for incorrectly ordering the enerchi bars was revised from turning numbers red to a brief visual depiction of the fraction for comparison (Figure 8). Testing these revisions to i2 will provide important lessons for the design and delivery of scaffolding and feedback.

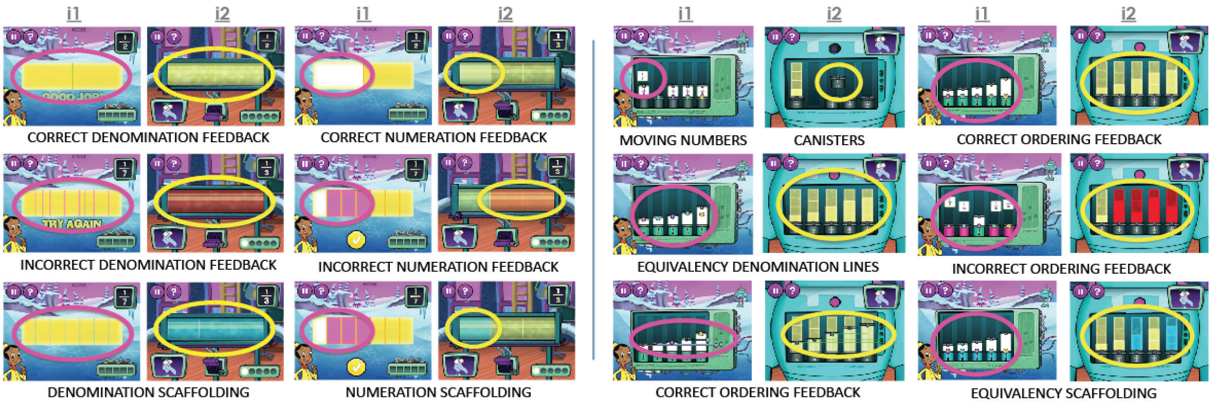

Figure 8: Scaffolding/Feedback redesigns from i1 to i2.

Future Study

Overall, mixed methods iterative-design experiments are effective ways to create contextually situated embodied experiences of mathematical thinking (Lesh, 1985). The current study presented empirical evidence for the benefit of utilizing gesture and narrative in tutor-game development for digital tablets and discussed many of the issues surrounding effective design, implementation, testing and re-design. In the meantime, researchers look forward to testing the impacts of these revisions on i2 and reporting results in the near future.

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