Go Math! How research anchors new mobile learning environments

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***Abstract*—A reciprocal research and design process (RR&D) became central to the development of mobile learning environments for families. Go Math! applications were developed to support families in the situations they face in their daily activities where problem solving involves mathematics. The RR&D process is effective for synthesizing design and development choices with consideration of the results of basic research on mathematics in everyday life, the voices of users, the social context of use, and mobile affordances. The RR&D process is described, and two mobile mathematics applications illustrate how the process maintains fidelity among research, the development of design criteria, and user voice and practice. We consider the process important in the development of mobile learning environments.**

Keywords-Mobile learning; Computer Supported Collaborative Learning (CSCL); Mathematics; Problem-solving; Family Learning; Co-design Processes

I. Introduction

The findings of a "basic" research study for the Family Math project anchored the development of mobile learning environments by identifying design criteria, development considerations, values and trade-off spaces. In the basic study, we interviewed 74 people in 23 families and identified the many mathematical problem-solving activities they engaged in [1]. Our data set was filled with the narratives and conversations of our participants. Throughout data analysis, we strove to keep the first person voices of our participants, and whether we were conducting quantitative or qualitative analyses, we continually had the participants speak to us by returning to our primary data: video recordings of the interviews and family activities. When we embarked on the research, we sought to identify the contexts, activities, and resources brought to bear on learning mathematics in families. Our hope was that our findings would lead to the creation of resources to support mathematical practices in daily life. The findings were meant to be the foundation for later design and development efforts.

When we began to shift towards development, we culled our results, engaging in a process with fidelity to our findings, and our participating family members are informing our design. We have used the reciprocal research and development process (RR&D) for designing the Go Math! mobile apps since it facilitates interaction at the nexus of basic research findings, the voices of our research participants, and our user test informants. Even the idea that we would develop environments for mobile platforms came from our families, who told us about all of the math involved practices they engaged in while they were "on the go" each day. From the first ideation activities, the design and development processes drew on what we learned about the family as a setting for mathematical activity and the imperative that any development would need to build on and support family practices if they were to further extend the family as a social setting for mathematical activity and learning.

Go Math! mobile applications were designed to support collaborative activity and encourage mathematical talk and activity among family members. For example, in Go Play Ball children and parents use mobile devices to calculate youngsters' statistics after each baseball or softball game, such as their on-base percentage, and to use graphs to track progress over time. They can also track the statistics of a major league player and compare the two records. Go Road Trip provides an infrastructure for mathematizing traditional family car activities, such as guessing the time of arrival at a destination, playing math/road games, and maintaining records of family road trip activities. Go Route Planner is a tool to help families record data about different routes between common destinations, such as school to the soccer field. Plotting the time data collected over multiple trips helps the family decide the best route at a given time of day. The mobile platform was chosen because family members carried mobile phones with them in daily activity, making use of them anytime, anywhere [2]. Mobiles are becoming the future globally ubiquitous learning platform, in part because advanced computing and communications on mobiles are integrating formerly disparate consumer devices such as cameras, music players, game machines, phones, email, SMS, and browsers. We also sought to capitalize on existing social uses of mobile phones for learning [3,4].

II. Go Math! The Reciprocal Research and Design Process and its impact on mobile environment development

Two major tenets provide the foundation for the Reciprocal Research and Development process (RR&D). First, the process has a reflexive and reciprocal relationship to research. The designs originate in research findings, and the designs then become the impetus for research questions and agendas going forward. Second, it is an approach to development defined and informed by people and situations for which we are designing in ways that extend the usual user-testing cycle. We consider the daily problem solving situations of the families as the primary forces behind the use and efficacy of environments once they are in situ; therefore we employ a reciprocal and collaborative RR&D process that balances contributions from the voice of our participants, mobile platform affordances, and research results. We relied on what our participants' accounts of their mathematical activity told us and derived our design mission and criteria from these results. These collaborative and research-based methods evolved traditions that preceded this hybrid development effort. Our RR&D design practices are rooted in traditions of participatory design and user studies in computer science, and design research in the education field. The participatory design movement has spawned an array of methods, processes and orientations for involving multiple stakeholders and end users in design processes [5,6,7,8]. In computer science there is concern for user-centered design [8]; in education, ideas are taking hold at the intersections of research on learning and curriculum design [9,10,11,12] and assessments [13], and in K-12 children's technology [5,11,14,15]. The Family Math research and collaborative development process draws on the participatory tradition, yet is distinctive from it by attention to the familial environment, an elevated emphasis for the voices and feedback of parents and children in platform choice, design criteria, and effectiveness of the tools in their situated practices.

We used the RR&D process to drive the design and development to a "third space" in technology [16] as well as learning [17]. Third space is a synergistic place for imagining new ideas and solutions—a place for vision that comes from multiple perspectives and places, and dominant and non-dominant factors or positions all have equal sway, making hybrid solutions possible. In our case, it is the place where the reflective and reflexive nature of the RR&D process is realized. It is the nexus for negotiating and achieving insights about the institution and cultural settings for the designs, the specific situations for use, the assumptions about family math practices, and mobile affordances and constraints.

Attention to the reciprocal research and design process was instantiated in several ways. Our team conducted the basic research phase that led to designs. We interviewed families, videotaping the interviews and tasks. We conducted various analyses of the data set, and had results that were vetted for relevance to the mobile design process. We retained access to our primary video data sources to constantly capture, listen to, and compare the voices of our participants and users to our design and development decisions. We saw this reflexive interrogation of the findings from basic research, user voice and feedback, and the technological considerations. For example: Our goal was to design environments to support more interaction with math in families, and the research results indicated that it would be beneficial to help families accomplish daily life problem solving while they were on the go and in situ. This finding connected directly to the decision to develop for mobile applications. With mobile capabilities in mind, the team next engaged a review process to summarize the areas of relevant findings, and develop the design mission, design criteria, and a list of considerations and trade-off spaces. Research results and direct instances from the primary data were extracted and examined as each design decision was made.

We illustrate the RR&D process in the following ways. First, we highlight the findings of our initial interview study that had implications for the Go Math! development and research process. Second, we show the design criteria and trade-off space considerations we derived from consideration of the basic research findings for the mobile design space. Third, we illustrate the reciprocal and generative nature of the process via examples from our mobile applications. In closing, we present a short discussion of the RR&D process and its implications for the development of mobile learning environments.

III. The Contributing Research Findings

The Family Math research findings in three areas were applicable to the Go Math! mobile designs: (1) the characteristics of problem solving in the family; (2), the participatory nature of activity in the family and, subsequently, of mathematics; and (3), the significant differences between math at home and math in the school.

(1) The nature of problem solving had specific characteristics. The first finding was that, in the family, life problems lead the math. Life problems are context and situation determined. The problems to be solved can be complex, involve many steps, and often are nested inside larger problems as well as leading to other problems. Knowledge and solutions derived must also align with situations and real constraints. People generally conceive of their problems and secondarily imagine how to solve them and then when to use math.

Math in the family also requires people to evaluate their own solutions, and they have to decide if their solutions are correct, and if the correct solution is really relevant or appropriate to the particularities of the situation. Values steered the problem definitions, problem solutions, and the imperatives for solutions [18]. Values answer the "why bother to solve this problem" question for family members. They also lead to many of the "how" questions. When families spoke about their problem solving strategies and gave examples of the kinds of problems that arose in their lives, family members consistently talked about what they valued. They talked about what was important to them when they talked about their decisions, social activities, projects, and relationships. What stood out as unique in family problem solving was the role their values played in structuring their problem solving. They brought social and cultural norms to the forefront of problem solving.

(2) Problem solving practices in the home were social, involving multiple people and tools as resources. Stories of mathematical activities in the home revealed how problem solving was a social activity, involving multiple people coordinating activities over multiple instances or contexts, and with many chances for revision and success. The family members were often chosen to collaborate in problem solving practices based on need for one family member's expertise (e.g., a child asking a parent for help in solving a problem), or when family members found what they believed to be important learning opportunities for their family. Although we had asked the interviewers to tell us about their own experience, most of the stories told involved more than one person, and those events as recounted across family members also tended to be the most lively and rich in mathematical discourse.

(3) We found several central distinctions between how people talked about math use at home and at school [19]. School mathematics stories were often structured around mathematics as an end in itself, involving external evaluation. Home enabled a wide range of allowable solution methods, resources and attempts at solutions. People cited examples of mathematics being used to support one's sense of personal and of social responsibility (e.g., being fiscally responsible, caring for others, and desire for making family decisions). We also saw that math was an integrated part of fun hobbies and activities. In low-risk settings like a family car ride, parents and children engaged in playful problem posing and problem-solving activities together. In these instances, mathematics was the means to a valued end.

The three categories of findings: (1) that the problem space in the family was complex, related to values, issues, and desires, (2) that mathematics was most often socially distributed, and (3) that family math offered an entirely different constellation of problems and structures for success and identity-building—became key factors to become embedded in design for mobile math environments.

IV. From Research to Ideation and Development

The translation from research findings to design considerations and development engaged the team in a series of specific steps and activities: starting with the interrogation of the research, to ideation, to working on functionality and features, to user testing and field research, to revisions, and finally to a restart of the process. The process began with a review of all of basic research findings and literature in the field. The team also looked specifically at "relevant" cases from data by returning to primary video of the sessions with families. Of specific interest were highly referenced contexts for mathematical problem-solving that many families mentioned (e.g., shopping, budgeting, home improvements, and times they spend in leisure). For each, we analyzed the math up to the level of pre-algebra that was covered.

The research analysis helped us develop our mission for "on the go" mobile tools and to establish design principles that organized the possible development space and defined desirable features of the environments.

We deduced that the mobile environments needed to be:

1. Situation-driven
2. Promoting enjoyment of mathematics
3. Demonstrating the value of mathematizing experience by helping parents and kids discover the math in everyday situations and contexts
4. Driven by values (if people do not see it as an important problem, they will not engage it)
5. Reinforcing the family as a social unit of mathematical activity and learning
6. A complement to school: math activities in the applications are complementary and supportive of school math up to first year algebra
7. Designed for mobile affordances: they are not simply miniature applications but use the collaborative/social capabilities of mobiles
8. Based on and relevant to results and the charter for Family Math

The findings and a study of narrative accounts of our participants also helped us develop a set of trade-off space questions we answered regularly:

- Does the environment adhere to a problem solving orientation?
- Is the application encouraging collaboration and promoting social arrangements and

conversations that are either intergenerational or peer-based?

- Is it reinforcing or making familial-community-school links possible?
- Is it fostering the ability of children and families to be successful in bringing math to their daily activities and problem solving?
- Have we checked for feedback from middle school children and their families?
- Is it supporting users and giving them control over some aspect of their activities?
- Are we developing in user-centered ways?

The complexity of the design criteria led to a decision to experiment by designing a series of mobile math applications that would instantiate different combinations of the design criteria. For example, one environment, Go Play Ball, would support peer-based activity; while Go Road Trip would strive to support math in an intergenerational activity setting. It also led us to examine the possible mobile platforms. We reflected on the extra resources we needed for different technological development tasks, such as money, additional partnerships, or programming capability.

We moved into a process for brainstorming and storyboarding of possible applications based on mobile platforms, our design principles, and trade-off spaces. We rated the difficulty for our development efforts and narrowed the choices to a priority list of seven applications we could eventually create.

We did a round of user-tests with our top seven applications as paper prototypes. Correspondingly, we made choices about our development platform based on the mobile access potential of our participant families. The ideas for priorities came from negotiations that considered any application concept, platform, development capability, and participant feedback data. For example, we looked at the trade-off between the costs of different mobile platforms and our agenda to promote broader access.

There were many trade-off conflicts needing resolution. Each had implications for the development of the environments and for the kind of learning environments they could support [20]. For example, in supporting social activity, decisions needed to be reached about "how much social" would be built into an application. Would this be an application that worked across single or multiple users and multiple mobile devices? Would any particular application be self-contained or networked? Would an application be used in the short term or the long term, and what capability would be needed for either choice? Would there be recordkeeping or communication with the server as part of supporting the learning goals?

Decisions on trade-off spaces came after consideration of findings, careful attention to how family members interacted, and considerations of our team's ability and resources for reaching development goals. Remaining true to the RR&D process and experimenting with it, we started with the development of the two applications that would allow us to run and evaluate the full process cycle and have applications in new participant study cycles.

The RR&D process enabled the team to stay involved with design iterations for improvement of the mobile applications and continued knowledge feedback to the research knowledge base. Data collection, analysis, and redesign was ongoing in concert with development activities. Two studies, one with a complete round of the RR&D process (Go Play Ball), and one in progress (Go Road Trip) provide examples.

V. TWO MOBILE MATH APPLICATIONS

The resulting mobile environments are compelling instantiations of reciprocal research and development process. We present two environments and tell their development story through the RR&D lens by examining the design criteria and trade-off dimensions that were culled based on research, and show how the process resulted in development, user-testing priorities, and revisions.

A. Go Play Ball

1) From Research to Mobile Application. Many families from the study identified sports as an arena for math, both in keeping score in games they were watching and in games that they played themselves. Our team recognized that baseball and softball offered an excellent opportunity for families to use ratios and percentages as well as graphical representations to enrich their enjoyment of the game and to help them track their own improvement.

Go Play Ball allows players to enter information about their softball or baseball performances. The players first enter general information about the game such as date and opponent. Then, they are taken through a screen that prompts them for the information for Batting Average and On-Base Percentage while being shown the process for the resulting computations. Finally, the players enter runs scored, how many hits they made and whether they won or lost the game. At any time, the players can track their progress by viewing graphs or charts about the individual statistics. GoPlayBall will help players solve the real problem they often have of keeping track of their performance and analyzing their data.

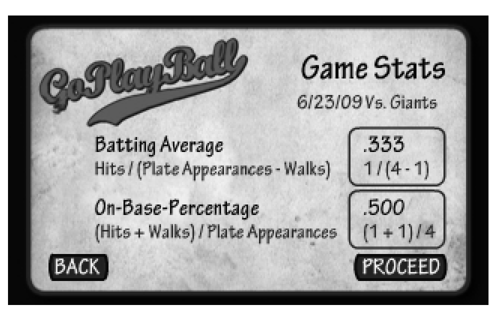

Figure 1: Average vs. On Base Percentage

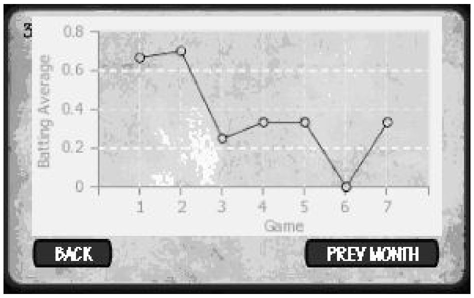

Figure 2: Graphing Batting Average

Go Play Ball was designed with our research results in mind. It is situation-driven around individual baseball and softball games as well as the season as a whole. By providing an environment for keeping records of progress and calculating player statistics, players and their families are able to see and interact with the multiple ways that math is used in the game with attention to their personal statistics and those of their favorite professional players. It is a context-and situation-specific application.

Go Play Ball evolved based on real usage constraints. The original design of the application was for it to be used by the players at their games. The development team thought it would allow for greater accuracy of record keeping. Unfortunately, in our study, the team organization we partnered with asked that the players not bring the phone to games in order to prevent competition among them.

Initially we envisioned the application being used socially, in the family and among peers. Yet indications from our research had us concerned about competition among the young players. Once the team managers indicated concern about competition among the players as well, we changed the ways that the youngsters could compare baseball statistics. In order to maintain the math opportunities fostered by the comparisons, we created a feature that linked our youth to one of their favorite Major League Baseball players. To preserve the link to the baseball community, our application reshaped itself by changing the user's community from their peers to the players in the Major League. We would have to see how this removal of competition affected the use and satisfaction with the application. This answered a trade-off space question: the application would primarily encourage collaboration between family members.

2) User Study Research: Six families from a predominantly low-income neighborhood of Boston used the Go Play Ball application for 3-4 weeks of the Little League baseball season. User studies included:

- Pre and post-surveys that included baseball statistics questions, questions about attitudes towards mathematics, and questions about family participation in little league activities.
- User interface interviews and surveys that provided insight into user's experiences when navigating through the application.
- Logging information, including the time and duration of access, and the data participants entered and plotted, and the number and types of comparisons with professional players.

3) Analysis: In Go Play Ball we saw how students understood the math behind their baseball performances and the performances of professional players. Results indicated that Little Leaguers developed in understanding how batting averages were established and how they changed in relation to number of games played and number of at-bats.

Across applications, a focus of our analyses is on how the mobile applications supported activity and conversations among family members. In the Go Play Ball study, we found that mathematical problem solving was distributed among family members. Results from one of our surveys demonstrated that the little leaguers discussed their little league activities 3-10 times a week, with family members including parents, grandparents, siblings and extended family members. Each player had a family member who went to games and discussed their play. The Go Play Ball application positively mediated collaborative activity across family members in relation to baseball statistics, addressing one of our initial design questions as being a familial and intergenerational collaborative tool. Results also revealed that orientation to the mobile phone use was consistent with familial interaction patterns prior to introduction of the mobiles [21], creating additional opportunities for tracking and analyzing baseball statistics. The applications did not facilitate player to player conversations, and that may have been caused by the league's reluctance to allow the mobile at the game or the fact that the application did not support player-to-player statistic comparisons.

The findings from this round are being revisited to determine what changes will be made in our application for the next baseball season.

B. Go Road Trip

1) Description of the mobile Application: The inspirations for Go Road Trip were specific instances in which we found families that provided scenarios for their children to think about distances. One family played a game in which the daughter in the family wondered whether or not she could hold her breath while crossing the Golden Gate Bridge in San Francisco, and the family together decided they would have to drive faster to make it possible for her to win the challenge. The challenge related to the distance and time problems and was a way for the family to pass time in the car, and for her to practice the ‘mental mathematics’ that her father valued.

Figure 3: Allowing multiple players to guess

Go Road Trip is a mobile application designed to promote math awareness and fun with math during long road trips for families. The application is meant to help solve the often asked questions by the children of "are we there yet? Initially designed as a trip estimator tool, Go Road Trip has evolved into an application that families can play constantly throughout a trip. Keeping in line with our research based design criteria, the application is a suite of mini games intended to draw on game-like play directly rooted to the car context. They are meant to be both inter-generational and peer-based, playing across all family members in the vehicle, both competing and sometimes collaborating with each other.

Go Road Trip is currently a set of nine mathematics games designed for families to play while traveling in the car. A central estimation game that involves multiple family members in a rate/time/distance problem lasts for the duration of the car trip. Each family member enters a guess about the time of arrival at the destination, and tools such as route plotting help family members generate their estimations. During the trip, status updates indicate the percentage of the trip completed, the number of miles remaining, and the average speed necessary for the remainder of the trip. Eight mini games surround the central challenge, designed for multiple family members to play simultaneously. These include logic games, code generation and breaking games, word problems and puzzles, road sign games focusing on shape, smaller estimation games (e.g., how many silver cars will you see in three minutes), prime number guesses, and number pattern games using license plate values.

Figure 4: Estimation Challenges

Go Road Trip has evolved to address the criteria posed initially. No one game or face of this application addresses all of our criteria. We feel that the use of the application is driven by being in a car. We specifically concentrate on making games that involve math to both promote the enjoyment of mathematics and demonstrate how the road has inherent math problems. Having tools in hand such as timers and graphs, and records of play demonstrate how mobiles enable activities that would otherwise be too cumbersome. The mini games complement school math topics, yet are not a rehash of school. For example, the main estimation is a problem that children often face when in the backseat of a car. Our traffic light game has each family member work with others (See Figure 3) to try to solve a number mystery.

2) User Studies: Seven families with middle school students will field test the Go Road Trip application while traveling by car. The application will automatically log each family member’s actions within Go Road Trip. In addition, we will audio record the family’s interactions in the car to understand the conversation and social negotiations occurring around the application and the particular challenges. This is a trade-off space that will be addressed through the user-testing part of the RR&D cycle. Analysis will focus on whether Go Road Trip supports and encourages mathematical talk among family members, how the mobile device mediates the family's mathematical interactions, and if the application needs to enable play from multiple devices.

VI. DISCUSSION AND SUMMARY

The first value of the RR&D process is that it helped our team to understand the conditions and features of the learning environments under development. The mobile math environments had the potential to be extremely complex, and being able to rely and double-check design and development decisions against the knowledge base developed from the basic and user tests was extremely helpful in our ideation phase. It helped us delineate our development space and evaluate the many "learning environment interface issues." Second, exercising our design and development team through research, technological development, and user testing concerns had huge influence on each mobile environment. It enabled us to do design and development work that was research based and real-world tested, and we found this to be important in understanding how mobile platforms can best be developed as learning applications. The RR&D process caused us to have rigor in our process and also take chances that would please our users. It allowed us to work in the third space between the hypothetical and the practical. Third, because our work is being done in a university setting, the nature of the work we engaged created links between the theories of learning research we are involved in and the real-world mobile environments we hope to contribute and bring into the lives of families. This is not an accidental arrangement; it is in the spirit of a rigorous and reciprocal approach to research-based design.

We recognize that a lengthy and complex basic research phase is not a realistic goal for some development processes, although we contend that the value of timely, on-topic, and relevant research should not be denied by developers. The value of developing designs and development goals based on research has been proven to us on our own work. We are quite aware that changes in mobile platforms and capabilities drive development teams to a fast-paced development schedule, where even user-tests can seem like a luxury. We believe that it is possible to use research results from relevant studies in a field in a reciprocal fashion in order to ground mobile development—in our particular circumstances, where there is an agenda for learning to be supported with mobile technology. The reciprocal research and design process has helped us ideate our designs, generated our design criteria, and helped us deal with trade-offs in a confident way.

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