MUSHI: A Multi-Device Framework for Collaborative Inquiry Learning

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Abstract: We present the MUSHI (Multi-User Simulation with Handheld Integration) framework, which was designed to support middle and high school students in the acquisition of scientific concepts rooted in complex, multi-scalar phenomena. In designing a learning environment that is conducive to collaborative inquiry learning, we have combined a dynamic simulation with wirelessly-connected handheld devices. This is a novel use of technology, so we first had to ensure that this new multi-device paradigm would not, via extraneous cognitive load, interfere with inquiry learning tasks. In this pilot study, we confirmed that the multi-device interface can be used by the lower age range of our target demographic, and that its use does not impair the execution of inquiry learning tasks of the sort we have designed for the learning environment. We also observed the collaborative behaviors that naturally emerged from the use of MUSHI, to develop recommendations for scaffolding collaborative inquiry tasks.

Introduction

Many scientific phenomena are complex, emergent systems: systems wherein many small, individual items (like atoms and ants) operate according to simple rule sets, and the interactions of these items result in the emergence of larger, complex patterns (like crystallization and ant colonies). Because these complex systems operate at different levels of scale, one must understand how these different levels interrelate to truly comprehend the phenomenon. It is this learning challenge that we are tackling with the design of MUSHI (Multi-User Simulation with Handheld Integration). We endeavor to create a learning environment, grounded in both cognitive and social theories of learning, which fuses inquiry tasks and emerging technology into a unique framework (Figure 1).

Figure 1. In this illustration, three students are depicted inspecting regions of the MUSHI simulation. The simulation, running on a tablet PC, wirelessly delivers content to their handhelds.

While engaged in inquiry learning activities within MUSHI, students have the opportunity to (1) engage in multi-scalar system learning by making connections between the different levels of granularity, (2) maintain individual agency within a shared learning experience, and (3) collaboratively engage with one another. These opportunities are provided by (1) Multiple Linked Representations (MLR), (2) furnishing private, individual interfaces in addition to public, shared interfaces, and (3) the structure of the inquiry learning tasks and the form-factor affordances of the computational devices used. In this paper, we present results for preliminary studies of middle school students using MUSHI-Life, a natural selection and evolution simulation created for the MUSHI framework, to establish the feasibility of this approach.

Background and Prior Work

Supporting Multi-Scalar System Learning

Science curriculum designers aim to help students construct a schema or mental model of the subject from which the students can make predictions (Johnson-Laird, 1983; Sweller et al., 1998). To properly understand a complex, multi-scalar system as a whole, the student must (1) construct a model of each level of granularity, and (2) be able to link the models of different levels based on how they relate to one another (i.e., have good intra-representational coherence formation) (Seufert, 2003). This second task is often the most challenging, and the one most prone to errors and misconceptions (Johnstone, 1991; Krajcik, 1991). One method used in science education to help link disparate mental models is the use of multiple representations (Kozma, 2003).

MLRs show promise in the instruction of complex systems, such as those comprised of different levels of granularity (Goldman, 2003), and they have successfully been used in educational software. GenScope and Biologica use MLRs to help students understand the relation of genetic makeup to phenotypic expression, and 4M:CHEM contains linked representations of chemical reactions occurring at different levels of scale (Horwitz et al., 1996; Buckley et al., 2004; Russell et al., 1997).

Supporting Individual Agency in a Shared Learning Experience

In any shared learning experience, students play different roles within the participation structure (Greeno, 2005). In traditional co-located computer-supported learning experiences, only one student can use an input device (such as a mouse or joystick) at a time. Not only can this limited access cause conflict, it has been found that the student who controls the mouse for the majority of the time is also the student who is best able to transfer his or her acquired knowledge to subsequent activities (Inkpen, 1997). Although some students will always be more dominant than others, distributing control equally amongst students prevents disenfranchisement.

Control distribution is a key component of participatory simulations (Collella, 2000), wherein students play the role of "agents" in a simulation. Each student has his or her own device (like a ThinkingTag or handheld) to aid in the execution of the simulation, and thus every student has a private interface to the simulation. Control is more explicitly distributed in the Gridlock participatory simulation, which has a public, shared interface in addition to private, individual interfaces (Wilensky & Stroup, 2000). In Gridlock, students use networked calculators to control individual signals in a traffic simulation that is projected onto a screen in front of the classroom.

Supporting Collaborative Learning

The degree and quality of collaborative learning in a learning environment are impacted by tangible aspects, like the form-factor of technology, and by intangible aspects, like the task structure. Studies have shown that students in fact benefit from working together at one computer (Mevarech, 1994), but the physical arrangement of the desktops can make it difficult to speak to anyone aside from immediate neighbors. Alternatively, collaborative learning can be promoted by deploying educational software on small, mobile computing devices, such as Palm™ and PocketPC™ handheld computers, which allow students to move around the classroom and look at one another while conversing. However, we know that merely providing a learning environment *conducive* to collaborative learning does not guarantee that such learning will occur. In Fostering Communities of Learners, students were provided with anchoring experiences to help their joint work cohere, and individual Jigsawing tasks to give everyone a unique contributing role (Brown & Campione, 1996).

In simulations like the Palm™-based Geney™ (Danesh et al., 2001), handhelds have been used to encourage students to engage in collaborative problem solving, allowing students to work together in changeable groupings, but there is no anchoring and the students adopt whichever roles they see fit. Gridlock provides unique roles for the students, but the collaboration is less autonomous: it's a teacher-guided classroom-wide activity. The projected image of the shared simulation serves as a useful anchor for the problem solving activity, however – it is a shared reference around which action and attention can be coordinated (Crook, 1994).

MUSHI: Multiple-User Simulation with Handheld Integration

The MUSHI framework was designed to take advantage of the collaborative and individual agency benefits of handheld-based participatory simulations while incorporating anchors, MLRs, and collaboration-inducing tasks. Part of the framework is a tangible architecture (which wirelessly links handhelds to tablet PCs) and part is learning environment design (with particular attention paid to the simulation, inquiry learning tasks, and participation structures). An explanation of the framework is best done in the context of an example: MUSHI-Life.

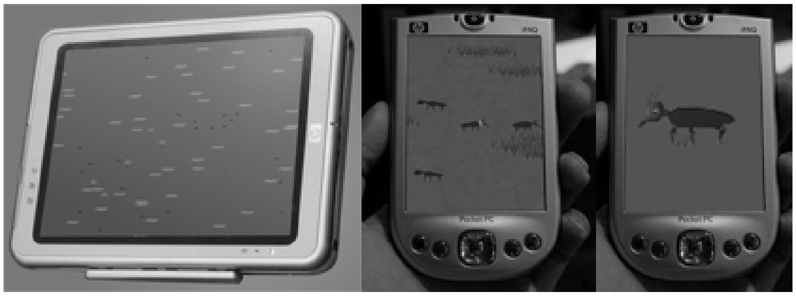

Figure 2. Image of MUSHI-Life simulation running on a tablet PC and on a handheld.

MUSHI-Life

MUSHI-Life is a survival / inheritance simulation built to explore the benefits of the MUSHI framework. The simulation runs on a laptop or Tablet PC, and depicts an environment populated with insect-like creatures that eat, fight, and breed according to a simple rule-based system (see Figure 2). Each "bug" possesses its own unique genetic makeup, which gets expressed as different phenotypic traits that can either help or hinder its survival in the ecosystem.

Handhelds are provided to each student and are used as "microscopes" to inspect the creatures or their environment in a high level of detail (see Figure 2, second and third images). The simultaneous presentation of the overarching ecosystem (via the tablet screen) and a "bugs-eye-view" on the student's handheld challenges the student to (1) make connections between the different levels of granularity in a complex system. An inquiry-learning based curriculum constructed around the MUSHI-Life simulation takes students through different stages of the inquiry learning process: observation, interpretation, prediction, and experimentation. Because the simulation is rule-based, many different lessons can be taught merely by adjusting the simulation parameters.

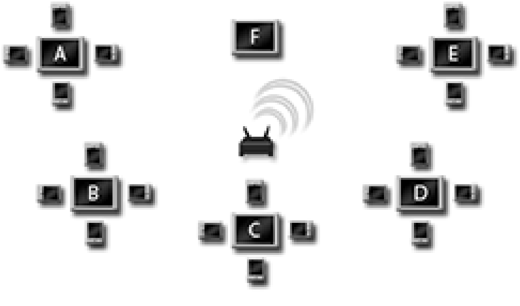

Figure 3. A schematic depicting the use of the MUSHI framework in a classroom of 20 students. The students each have a handheld computer and are divided into five groups of four, labeled A-E. The remaining tablet or desktop PC, F, is reserved for the instructor's use.

MUSHI in the Classroom

Implemented in a classroom, the MUSHI learning environment divides students into small groups. Each of these groups clusters about an anchoring tablet PC running a MUSHI simulation (see Figure 3).

Every student has his or her own handheld computer, with which they log into the simulation, which gives them (2) individual agency within the shared learning experience. Simulation data is wirelessly transmitted to each handheld computer, and conversely, actions performed by the students on their handheld computers are transmitted back to the simulation. The actions of the users have the potential of altering the simulation in real-time, allowing MUSHI to become an interactive experimental testbed. The non-view-obstructing tablet PC provides the students with a shared reference that the students can use as an anchor to coordinate their actions, helping them to (3) collaboratively engage with one another.

Investigating MUSHI

While MUSHI's design principles are theoretically-based, some of the implementation details are unproven (and may have a negative impact), and thus had to be investigated before investing time and resources in a long-term study of learning with MUSHI. For example, GenScope, Biologica and 4M:CHEM presented their MLRs on a single computer monitor. Because our dynamic, real-time multi-device approach is so different, there was concern that it might increase students' cognitive load to the point where they couldn't concentrate on the task at hand. Therefore, we had to establish early on if (1) a multi-device dynamic visualization would confuse or overwhelm the user. Specifically, we needed to answer if students (1.a) were able to integrate the information presented on both displays, and (1.b) were able to perform tasks characteristic of an inquiry learning investigation. We also needed to determine if, when confronted with a shared anchored simulation *without* Gridlock's teacher guidance, students do in fact take advantage of their personal interfaces to (2) exercise agency within the activities. Finally, we needed to build a picture of how (3) students innately behave while executing a collaborative inquiry learning task with MUSHI, measuring the degree of (3.a) coordinated, complementary actions, (3.b) high-level process management, and (3.c) debate of results, to determine what scaffolding may need to be put in place to help manage any of these activities.

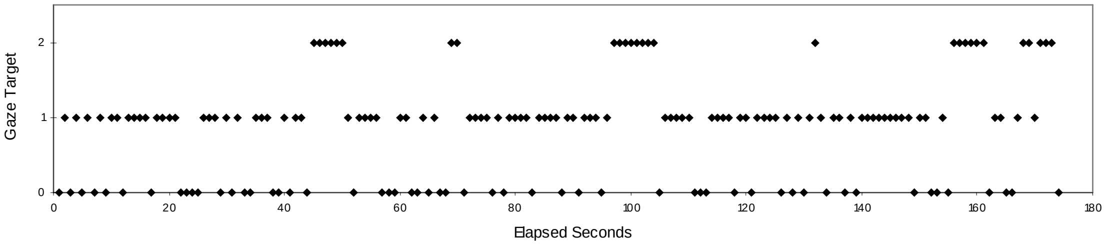

Figure 4. A plot of a subject's gaze targets during Task 2. Gaze target 0 is the subject's handheld device, target 1 is the tablet PC, and all other foci comprise target 3. The high frequency of gaze shifts between the two displays suggests a vigorous attempt at integration.

Investigating Multi-Device Multi-Scalar System Learning

We selected 6 students (3 male, 3 female) from a 6th grade class to comprise 3 paired focus groups, which were varied by gender (female-female, male-male, and female-male) because other studies found gender-based differences with task sharing in shared computer activities (Inkpen, 1997). Each group was videotaped in a testing room where a tablet PC and two handhelds were running a MUSHI-Life simulation. The subjects were supplied with a sample inquiry-learning task to be completed with MUSHI-Life, divided into progressive subtasks. The first subtask assigned a distinct "bug" phenotype to each student. Each student was asked to record observations regarding the preferred food source(s) of their assigned "bug". The second subtask was a cooperative undertaking: the students were instructed to work together to survey the relative abundance of food sources in the environment. The third task was identical to the second, but the simulation was altered to have a different distribution of food sources. The fourth task asked the students to draw upon their unique individual discoveries to predict which of the two "bug" phenotypes they had studied would be more likely to survive in the new environmental conditions. Observations for all subtasks were recorded on paper worksheets for later scoring.

We were hoping to observe subjects (1.a) integrating the two displays by (1.a.i) shifting gaze between the two displays, which would indicate an attempt to coordinate the information in both displays, and (1.a.ii) providing input via the handheld device while gazing at the tablet interface, showing that the subject's understanding of the simulation interface spanned both devices. We found that by and large the subjects displayed (1.a.i) a high frequency of gaze shifting between the handheld and the tablet PC, as exemplified by one subject's behavior (see Figure 4). The subjects switched their gaze between the two interfaces an average of 14.2 times a minute (σ =2.8), and the average gaze lengths for handheld and tablet viewings were of similar duration (3.2s, σ = 2.8, and 2.7s, σ = 0.73, respectively) showing that all were engaged in an attempt to integrate the information in two displays. (This pattern of rapid gaze shifting occurred in all later trials as well). We also found evidence that (1.a.ii) the subjects perceived the two interfaces as part of a larger whole: every subject navigated their view using the handheld buttons while gazing at the tablet PC at least once, and for three of the subjects, this was their preferred method of navigation. Despite the high frequency of gaze shifting, which might be seen as cognitively demanding, the subjects were all able to (1.b) successfully engage in the inquiry learning task. All participants completed the observation subtasks with greater than 80% accuracy, and all groups correctly answered the final prediction subtask, providing acceptable evidence and reasoning in the written explanations. This high performance leads to a ceiling effect, making it impossible to gauge the true cognitive load of the dynamic multi-device interface, but accomplishes the purpose of the pilot study by determining that inquiry learning tasks of this difficulty level are not hampered by the interface.

Investigating Agency in a Shared Learning Experience

In the prior study, all students exhibited agency while engaged with MUSHI-Life. Every student made use of his or her handheld to inspect the simulation, and often used their inspections as fuel for assertions (e.g., "I haven't seen one mushroom."). The "look-and-see" task structure didn't require much overt coordination and conversation, however, and it was hard to measure individual contributions, so we designed another task that required more active coordination from partners and allowed us to more accurately diagnose individual contributions. Nine new pairs of students (8 boys, 10 girls) were asked to conduct a thorough assay of an environment, recording their observations on worksheets with different-colored pens, within a time limit. Students had to coordinate their actions in order to perform well at the task within the time limit, and by analyzing the differently-colored marks on the worksheets, we were able to tally the individual contribution of each student to the tallies. We videotaped all sessions, and in four later trials, recorded the users' actions within the software.

Of 75 possible observations, the groups made 61.1 observations on average (σ = 15.4) within the time limit, showing that whatever their coordination strategies, they were able to function as a group. More important to our assessment of agency, the worksheets also provide evidence that both partners contributed equally to those comprehensive tallies of observations: the absolute difference in the number of observations *between* partners averaged only 6.2 (σ = 8.1). Encouragingly, there were no significant gender-based differences in agency: regardless of the group's gender composition both members were relatively equal in their contributions, although contribution was slightly more equal (an average contribution difference of 3.8) and with less variance (σ = 3.0) in female-female groups than male-male (7.3, σ = 10.9) or mixed groups (9.8, σ = 9.5). This difference doesn't seem to be overtly problematic, but it does indicate that we should continue to pay attention to gender composition trends in future work.

Investigating Collaborative Behaviors

The equal contributions of partners, as measured by the worksheet markings mentioned above, also suggested that the subjects in the second study engaged in (3.a) coordinated actions. This suspicion was further confirmed by recording traces of the subjects' inspection patterns. In the four sessions wherein the partners' inspections of the simulation were recorded, the inspection areas of the partners overlapped by only 10.2% (σ = 0.071), indicating that the partners were avoiding inspecting the same territories.

In all but one of the nine sessions, the subjects also engaged in (3.b) high-level process management by discussing task breakdowns and allocations (for example, "I'll do the mushrooms and snails and you do nuts and berries," or this exchange: "I'm gonna head up to the top," "All right, I'll head down to the bottom."). Process management remarks were identified by coding utterances in the dialogue transcripts for evidence of planning or task allocation. The number of process management remarks made within a session correlated very strongly with the amount of the environment that got inspected by both partners, showing that through discussion and planning they were better able to coordinate their efforts to inspect the entire environment ($p < 0.01$, $r = 0.974$, $r_{crit} = 0.882$). The groups also made use of the tablet as an anchor during task allocation: in 6 of the 9 groups, participants pointed to regions of the tablet environment for coordination purposes, Neither trial showed much evidence for (3.c) debate of results, probably because the tasks were straightforward for all subjects, but at least two of the groups made use of both interfaces to resolve other disagreements. In one interesting exchange, the partners used representations on both interfaces while debating the identity of food sources in the environment:

> A: "Yep, all of the orange things are mushrooms."
> B: "No - one's like that one - " (Points to region on tablet with a high distribution of nuts)
> B: "One's on mine [meaning on her handheld] and one's a mushroom." (Points to handheld, displaying a detailed image of the indicated region on the tablet, containing both nuts and a mushroom, for partner to inspect)
> B: "[But] some of them are nuts" (Points again to region on tablet)
> A: "Oh yeah"

Discussion and Future Work

The results of the pilot study demonstrated that despite the novelty of MUSHI's dynamic multi-device framework students can (1) use MLRs on multiple devices to make connections between representations at different levels of scale, (2) maintain individual agency within a shared learning experience, and (3) collaboratively engage with one another. Problems with any of these elements would have called MUSHI's utility into question, so we are now free to investigate the framework further. It is now time to engage in a design experiment that explores how students learn with MUSHI in a classroom setting, using a lengthier trial period that will take students through an abbreviated curriculum.

A lengthier trial will allow us to tackle content that is not as straightforward, allowing us to observe how forms of collaboration, more meaningful than the mere task coordination seen here, unfurl (or – if they fail to appear altogether). It is clear from these pilot tests that students perform better when they explicitly coordinate their actions through discussion, but that not all students do so to the same degree, and so this behavior is one that will need to be scaffolded. We will also need to consider how increasing the group size (from pairs to groups of 3 or 4 members) will impact collaboration – we anticipate that the personal dynamics of small groups are likely to be very different from that of dyads. This change in dynamics will necessarily affect the task design (and our scaffolding of it), so it is best pursued in the context of a design experiment where we can explore alternate and evolving solutions. We have many different options for intervention: having the teacher model and coach task coordination, creating guiding artifacts (like instruction sheets), or adding dynamic prompts to the software are just a few. Although in these experiments we made use of paper-based worksheets for data collection, the intention is to include a data recording feature within the MUSHI framework itself, so students may use their handhelds to inspect, capture, and share information. The more fully handhelds are integrated the inquiry learning activities, the greater the options we have for dynamic, individualized assessment and intervention.

Looking farther afield, one advantage of a wireless multi-device framework is that we can dynamically assess and diagnose individual performance, a crucial feature of true scaffolding. This "real-time" assessment could be used to keep the teacher abreast of student performance, or even to provide individualized scaffolding prompts to the students via their handheld devices. We will explore these ideas as we learn what types of intervention are most useful to students as they execute collaborative inquiry tasks.

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Acknowledgements

M. Kawamura and R. Vath helped create MUSHI-Life, which was funded by a University of Michigan GROCS award. We would like to thank M. Shorr, S. Gossalear, L. Kendall-Knox, and J. Williams for their support. This material and is based on work supported by the National Science Foundation under Grant No. IIS-0328797. Any opinions and findings expressed in this material are those of the authors and do not necessarily reflect those of the National Science Foundation.