Towards Utopia: Designing Tangibles for Learning

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ABSTRACT
We describe a tangible user interface-based learning environment for children called *Towards Utopia*. The environment was designed to enable children, aged seven to ten, to actively construct knowledge around concepts related to land use planning and sustainable development in their community. We use Towards Utopia as a research prototype to investigate how and why tangible users interfaces can be designed to support, augment, or constrain learning opportunities. We follow a design-oriented research approach that includes a theoretically grounded analysis of design features of Towards Utopia to understand how and why design choices influence the kinds of learning opportunities created. We also describe the results of our empirical evaluation of learning outcomes in order to validate the effectiveness of our design. We conclude with general guidelines for the design of tangibles for learning.

Categories and Subject Descriptors
H5.2. Information interfaces and presentation: User interfaces. K.3.m Computers and education: Miscellaneous.

General Terms
Design, Human Factors.

Keywords
Learning, children, design, tangible user interfaces, tangible computing, sustainability, sustainability education.

1. INTRODUCTION
The human computer interaction and interaction design communities are increasingly suggesting the suitability of Tangible User Interfaces (TUIs) and other forms of Natural User Interfaces (NUIs) to support children's learning (e.g., [3, 15, 19, 25, 36]). A major review work in 2004 summarized research work that included overviews of prototypes, applications, and informal evaluations conducted to date [25]. Since then, researchers have continued on this trajectory. For example, in 2009 there was a call for papers for a special issue of Personal and Ubiquitous Computing dedicated to tangibles, children, and learning. Despite focused research efforts on this topic, there are still few studies that explore how design decisions impact learning opportunities or that provide evidence of benefit related to specific learning outcomes (see [4, 13, 21] for exceptions). There are even fewer studies that analyze the theoretical underpinnings of learning in order to better understand how TUI design choices create, support, or augment learning. Both empirical and analytical work are required in order to better understand how and why TUIs might be designed to support children's learning in ways that are better than, or different from, other kinds of learning environments.

One area that scholars have suggested might be fruitful for TUI learning applications for children is tasks that are rooted, either directly or indirectly, in spatial domains [3, 19, 35] (This is not to suggest that more abstracts domains do not lend themselves to TUI designs. For example, see [9]). In order to investigate the effectiveness of TUIs for spatial domains, we present Towards Utopia, a TUI learning tabletop environment designed to facilitate children in learning about key concepts in sustainable development. The environment supports a hands-on exploratory approach to land use planning for a river basin. Our main research question is: What design features are important to enable the kinds of interactions that support children's learning using a tangible tabletop environment? We address this question by using a design-oriented research approach that includes a design case methodology. The design case is comprised of theoretical underpinnings that inform our design choices; a detailed description of Towards Utopia, our tangible tabletop learning game; a design analysis and rationale; and a summary of a pre-test and post-test, clinical style learning evaluation with thirty children. Our design rational uses theoretical concepts to argue for the importance of specific design features that support the kinds of interactions that provide opportunities for learning. The use of both theory and empirical data provides rigor to our design-oriented research. We conclude with design guidelines that can be used to inform design for tangible learning activities for children.

2. RELATED WORK
There are still relatively few studies that focus on understanding how design choices affect the kinds of learning opportunities that can be created using TUIs [28]. While there are many TUI prototypes for children and learning, few studies provide empirical evidence of benefit [4, 19]. Even fewer studies use a theoretical lens to analyze how and why design choices impact information and interaction in the context of learning. We briefly summarize several studies that address some of these deficits.

Fails et al. developed two versions of the Hazard Room Game in order to explore the benefits of a TUI versus a desktop implementation [13]. They ran a study with eight pairs of children. Their design distinguished between didactic learning and exploration-based learning. Results showed some benefit in terms of engagement and some qualitative measures of learning.

However, the pre-test and post-test assessment showed no significant differences in learning measures.

Zuckerman et al. presented "Montessori-inspired Manipulatives" in the form of SystemBlocks, allowing young children to simulate dynamic accumulation, and FlowBlocks, allowing slightly older children to collaboratively model probabilistic behavior [36]. They conducted a learning evaluation using a clinical interview approach. The interviewer had children do standard tasks and then probed their understanding based upon their response to the tasks. Results showed that children were able to grasp abstract concepts related to these topics.

Antle et al. investigated the benefits of using interactional metaphors (based on image schemas) for learning about abstract concepts related to sound. They found evidence that leveraging schematic structures in the coupling of input actions to output representations (i.e. in the interaction mappings) had performance and preference benefits [4].

Antle et al. also explored the relation between interface features and cognitive strategies children use when they use their hands to manipulate puzzle pieces to solve a spatial puzzle. They investigated how specific design features impact puzzle solving performance and approaches by comparing behavioral patterns between a non-augmented jigsaw puzzle, a desktop version, and a tangible tabletop version [7]. Findings suggested that direct physical interaction with pieces offers performance benefits and that digital feedback provided a shared focus for collaboration and incentive for problem space exploration, both of which improve performance throughout a session. This study provided evidence of benefit of the hands-on TUI approach but their findings were limited to spatial problem solving.

Price et al. analyzed two tangible learning prototypes in order to understand how design choices impact engagement, action, interaction, and subsequent learning opportunities [28]. Their work provided insight into the relation between design choices and resultant collective and exploratory interaction patterns. However, the analysis focused on description rather than explanation of such effects, and learning outcomes are not assessed. Without a learning evaluation, it is unclear that the systems being analyzed support the intended learning outcomes.

3. THEORETICAL FOUNDATIONS

There are multiple perspectives on what it means to learn and each lens can provide important insights for TUI learning design. While there can be a debate about whether the different perspectives on thinking and learning are epistemologically compatible, from a pragmatic design stance we find that they are each useful in informing design decisions at different levels. In this section, we draw on our analysis of these theories as initially described in [8].

3.1 Cognitive Load Theory & Multimedia Learning Theory

Cognitive Load Theory is relevant to TUI design because it explicates processes related to how efficiently individual children (and adults) can process different modes of external representations, such as text, images, sounds, voices, and objects [34]. Working memory is conceptualized as having three main components: an executive control system, a visual-spatial sketch pad (responsible for holding and processing visual-spatial information), and an articulatory or phonological loop (responsible for holding and processing auditory information). This theory is based on the premise that working memory, where information is temporarily stored and processed before potential transfer to long term memory, is limited [34]. All learning makes demands on this limited resource. However, while some demands are intrinsic (i.e., required to learn the material), others are imposed by the characteristics of the learning environment, and may be germane (contribute to learning) or extraneous (distract from learning). Building on Cognitive Load Theory, Mayer and his colleagues have proposed and empirically tested design principles for multimedia learning environments that can be applied to reduce extraneous load [22]. While these principles were developed for multimedia environments that were primarily visual and auditory, we discuss them in the context of TUI-based external representations. Mayer's principles suggest several important design guidelines for TUIs, which we summarize in the following sections.

3.1.1 The Multimedia and Modality Principles

Mayer's Multimedia Principle suggests that children learn better when core material is represented using both images and words. Mayer's Modality Principle suggests that children learn better when words accompanying images are presented verbally rather than textually [22]. If we extrapolate to TUI design, we might suggest that physical and digital representations used in TUIs will also benefit from these principles. Children will learn better because it is more cognitively efficient to process information distributed across modalities including haptic (form), visual (images, text), and auditory (voice, sound). While the benefits of using multiple modes of information representation in learning materials are not unique to TUIs, TUIs provide unique opportunities to present information in forms that can be processed using a combination of three (or more) modalities.

3.1.2 The Spatial and Temporal Continuity Principles

Mayer's Spatial Continuity Principle suggests that integrating information from different locations requires more cognitive effort [22]. Children learn better when related words and pictures are presented in the same space. Mayer's Temporal Continuity Principle suggests that children learn better when related content is presented simultaneously. If we extend this to TUI design, we suggest that the potential for spatially co-located input and output spaces can be utilized to reduce extraneous cognitive loads.

3.1.3 Reducing Extraneous Load through Coherent Mappings

Cognitive Load Theory also suggests that the learning task should be clearly outlined so that children know what they need to do and have support to achieve these goals. For example, a user interface that requires children to learn how to use it before they can tackle the learning material imposes an extraneous demand on working memory, and makes learning less efficient. Conversely, coherent mappings between input and output that facilitate interaction with the material rather than the tool make learning more efficient. Others have conceptualized this principle through Heidegger's notion of ready-at-hand [20].

3.2 Constructivist Learning Theories

Constructivist learning theories are relevant to TUI design because they provide information about how children construct understanding through personally meaningful interaction in and with the world [2]. Epistemologically, a Constructivist perspective suggests that information is not "out there" in the world, but that meaning exists as it is constructed by individuals and groups. This shifts the focus of learning design from designing materials to creating environments in which learners will interact. Both object and subject must be considered in the design [33]. This broadens the scope of theory from thinking about how children process external representations, to including how they interact with those representations in ways that are personally meaningful in order to construct knowledge. Taken from this perspective, learning incorporates an active involvement with learning materials and a learning environment. The learner processes sensory input and actively constructs meaning out of it. TUIs provide opportunities for children to enact a wider range of actions than traditional desktop configurations [3]. The ability to augment everyday objects with computation also provides opportunities to create personally meaningful learning systems.

3.2.1 Dewey's Experiential and Reflective Learning

Dewey and others adopt a constructivist stance when they emphasizes that learning occurs when the learner is actively engaged with some aspect of the world rather than being a passive recipient of information [11, 27]. Dewey also suggests that while physical actions and hands-on experience may be necessary for learning, the act of constructing meaning is mental, especially for children. He calls this reflective activity. Both experiential and reflective activities are required for knowledge construction [1].

3.2.2 Mutual Adaptation

Schwartz and Martin's description of distributed learning theory suggests that learning involves an interdependence of learners and their environments in ways that can be stable or adaptable [31]. Learning differs based on the relative degree of stability or adaptability of individuals and/or their physical and social environments. For example, children learning to use an abacus have unstable ideas about arithmetic and use the stable properties of the abacus to construct arithmetic knowledge. While the beads on the abacus can be moved, the structure remains stable. Schwartz and Martin provide empirical evidence that learning environments that support mutual adaption (the learner adapts their ideas by adapting the structure of the environment) better support knowledge transfer and adaptable thinking. These findings suggest that TUI objects and input space should be designed in ways that allow for reconfiguration to support exploration and active construction of knowledge in domains where children still have unstable ideas.

3.2.3 Image Schemas and Conceptual Metaphor Theory

An embodied view of cognition and constructivism share a focus on the importance of perception, action, and cognition situated in a personally meaningful world. Lakeoff and Johnson's work on image schemas and conceptual metaphors suggests that image schemas are developed from experience in the world and are involved in metaphorical interpretation of new experiences [18]. New conceptual knowledge is constructed based on existing mental structures (i.e. image schemas) formed from repeated patterns of experience.

4. TOWARDS UTOPIA

In this section we outline our learning and design goals for Towards Utopia, as well as provide an overview of the activity, describe the system implementation, and present a usage scenario. We follow this section with a design analysis of Towards Utopia through the lenses of Cognitive Load Theory and Constructivist learning theories.

4.1 Learning Goal

The importance of educating children about sustainability is highlighted by the growing number of agencies who have suggested that making positive changes to support a more sustainable world can best be promoted in an educational context [14]. Many of these initiatives are still in the earliest planning stages and require curriculum and learning materials development [12]. The International Baccalaureate program's learning outcomes for this topic involve understanding key concepts related to resources, development needs, and spatial allocation; understanding models of cumulative causes and subsequent effects; and practice utilizing these concepts in spatial decision making and problem solving tasks [16]. Our learning outcome goals are consistent with this international curriculum.

4.2 Design Goals

Environmental psychologist McKenzie-Mohr suggests that the best time to begin to foster ecologically sustainable behavior in children is between seven to ten years old [23]. At this age children are developing a sense of self. They begin to feel a connection to a larger community and can easily be motivated to learn about and take on challenges related to "saving the world." As their ability to think abstractly emerges, they are well positioned to learn about environmental issues. Our design strategy was for learning outcomes to drive the design process (rather than say the technology). Thus, we began the design process by an examination of what we wanted children to learn and by familiarizing ourselves with age-appropriate content and materials about sustainability for children in this age range. We interviewed teachers, read learning materials, and reviewed curriculum details. In the end we worked closely with a teacher to develop the content set for Towards Utopia. More details of content creation can be found in [24]. Our design focus was to create an interactive activity that provided opportunities for children to engage with this content. In order to successfully enable children to engage with interactive content about sustainability, we proposed six specific design goals as follows.

Learning: Individual children should gain an improved understanding of how various land use types individually and cumulatively impact a local environment.

Usability: The system must be easy to learn to use and to use so that the focus is not on the system but on learning with and through the system.

Interaction: The system should support a range of simple actions with everyday objects.

Adaptation: The system should enable spatial reconfiguration of its components (to support knowledge transfer and adaptable thinking).

Reflection: The system should enable reflection that facilitates learning.

Personal: The activity should be personally meaningful.

Since Towards Utopia is a research instrument rather than an educational tool intended for classroom or public use, we further constrained our design space to support a single child (rather than groups of children) to avoid the problem of assessing individual learning in collaborative conditions.

4.3 Overview

Towards Utopia is a TUI tabletop learning environment for children to learn about concepts related to sustainable land use planning. With our system, children learn about key concepts of sustainability through building a community along the Coquitlam River Basin (Canada). They can assign various land uses and activities to specific locations on a topographic map displayed on an interactive tabletop. Children do this by using physical stamps to "stamp" land use types onto the interactive map. Children may learn more about each land use type by placing each stamp on a reader that triggers the display of multimedia information including text, images, and voice over narration. Once children have used the stamps to plan their community, the system calculates the cumulate environmental impact based on the quantity and locations of the land use types. The impact is displayed as a pictorial representation of the degree of flooding such a community would be likely to experience over time.

4.4 Implementation

The Towards Utopia learning environment consisted of a set of TUI stamp tools and two distinct but interconnected stations designed to facilitate learning using a hands-on exploratory approach, which involved learning about land use types, using this information to design a community, and receiving feedback on the impact of their decisions on their community from a sustainability perspective.

4.4.1 Stamp Tools

Fifteen physical stamps were designed; thirteen for each land use type in the content set, one for erase, and one for generating the overall impact (see Figure 1). Land use types included renewable energy source, forest, wetlands, nature reserve, community gardens or farms, apartment or condos, townhouses, single family homes, roads, retail buildings, industrial buildings, and non-renewable energy sources. The eraser tool was used to remove stamped land uses. The impact tool was used to assess the environmental impact of the current state of the map. Pictorial tags were used to associate each stamp with a specific land use type or tool function. Each stamp was computationally augmented with both a unique RFID tag and a fiducial marker. The RFID tags were used by the Information Station to identify each stamp, and the fiducial markers were used by the Interactive Map Station to identify each stamp, as described below.

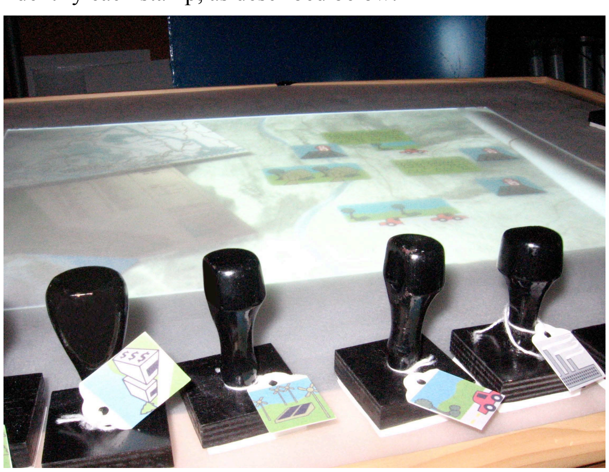

Figure 1. Stamps.

4.4.2 Information Station

The Information Station includes an RFID reader, a display screen, and speakers (see Figure 2.The purpose of this station is for children to access multimedia information about each land use type. The focus of this station is on providing children with the main conceptual information about sustainability. Information is communicated by one of two cartoon narrators using images and sounds. The cartoon characters narrate the core concepts to the children using animation and voice-overs. One narrator was a human figure of the engineer. He was used for any learning content that had human implications or direct human activity (e.g. roads). The other narrator was a duck, named Lucky Ducky, who was used to present concepts that were related to nature, natural resources, and conservation. Each land use information screen also contained supplementary information presented in text and images related to the land use activity.

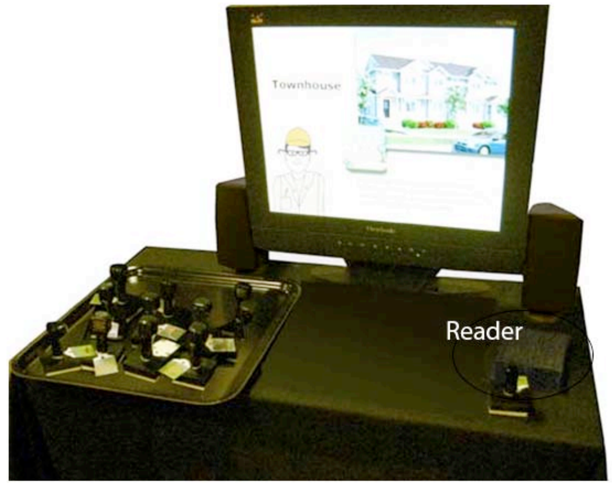

Figure 2. Information Station.

4.4.3 Interactive Map Station

The Interactive Map Station was implemented on an interactive digital tabletop. The surface displayed a topographic map of a local river basin that is the area where the children in the study live (see Figure 3). The map depicted an area that includes a flood delta that would potentially experience flooding in the future based on human activity at a local and global level. The interactive map interface provides an exploratory environment where children use the stamps to duplicate and position the thirteen land use types associated with stamps (see Usage Scenario below).

The tabletop contains a camera vision system implemented using the EventTable prototyping platform (see Figure 4) [5]. EventTable utilizes reacTIVision, which is an open source, cross-platform computer vision framework for the fast and robust tracking of fiducial markers attached onto physical objects [5, 17]. Each stamped instance of a land use is identified by the reacTIVision engine that passes identity and location information to a custom application written in Processing, an open source programming language. The Processing application uses this information to control the simulation parameters and manage the display space. Each land use type is assigned a value based on its potential environmental impact. The processing application uses this information as well as information about the quantity, location, and type of each instance of a stamp, to calculate the cumulative effect of land use activity on the environment. This result is then used to modify the display of the map.

There are three outcome map states based on the environmental impact of the land use choices. Each outcome is based on the calculated total impact of stamped land uses types on the landscape in terms of a simulation of the degree of flooding that such a community would be likely to experience over time. The regions of the map likely to be destroyed by flooding were depicted in a light blue colour distinct from the surrounding territory (see Figure 5). Voiceover narration was also used to explain the impact result. While local land use decisions do not directly or immediately cause flooding, providing a graphical depiction of flooding of the region where the children live provides a representation of environmental impact that is salient and easily understood. Nobody wants to have their home flooded!

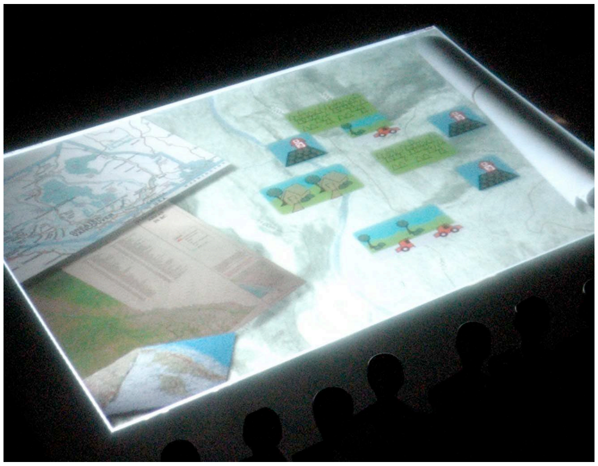

Figure 3. Interactive Map Station.

Figure 4. EventTable digital tabletop with stamps.

While we recognize that this is a simple simulation of land use impact on the environment, the quantity and impact of each land use type allows the system to provide direct feedback to the learners about the impact of their decisions. It does not provide feedback on how well the plan supports the balance of supporting a population while making sustainable choices. This suggests that a low impact strategy would be to place little or no human-related land uses on the map. This strategy was not observed in the test sessions. In part, this is likely because the scenario used to set up the land use planning task explicitly informs the child of their job to plan for future development (described below under Usage Scenario).

Figure 5. Massive flooding impact screen.

4.5 Usage Scenario

A facilitator oriented the participants to the Towards Utopia environment first by showing them the tangible stamps and the two different stations. Each participant was asked to assume the persona of a "sustainability engineer" while having his or her turn at creating a sustainable environment. Each participant was given a brief and standardized explanation of what was meant by the term sustainability engineer, and that their job was to design a community that would be sustainable. Each participant was offered the opportunity to wear a white lab coat and engineers hat. Then they were shown the Information Station (with the RFID reader) and the Interactive Map tabletop. They were told that the map was of the local river basin (where they live), and that their goal was to create an environment that was sustainable so that the environment would not be subject to flooding over time. They were shown how to use the eraser tool and the impact tool that showed the impact of their decisions by displaying a final map with some, little, or no flooding. Each participant was given as much time as needed and was allowed to continue until they felt they were finished.

5. DESIGN ANALYSIS AND RATIONALE

We now analyze Towards Utopia through the lenses of Cognitive Load Theory and Constructivist learning theories, focusing on how specific design choices and features enable interactions that we have identified from theory as beneficial for learning. We draw on our analysis of Cognitive and Constructivist theories in [8] in our analysis.

5.1 A Tangible Simulation for a Spatial Domain

A core aspect of learning about sustainable development is understanding how the allocation of resources and land uses affect a community. A TUI coupled with a computational model can be used to create a simulation that demonstrates the interplay of various land use activities and cumulative sustainability impact on a land base. The physicality and spatiality of a TUI environment facilitates the construction of understanding through hands-on exploration of alternatives using the simulation that provides digital feedback about impact based on land use types, quantities, and locations.

5.2 Using a Scenario and Everyday Tools

Design choices that support immediate access to both the goals of the activity and the tools to achieve these goals are in alignment with Constructivist principles, and specifically a Constructionist approach to learning [26]. The flexibility of using everyday objects and surfaces as tools supports this strategy. For example, the inclusion of everyday objects in the environment and interface of Towards Utopia contributes to making the task goals clear. The TUI utilizes a stamping paradigm on one of two surfaces: either the RFID reader at the Information Station or the Interactive Map. Together the scenario and tools make the system immediately usable. Children then expend cognitive resources learning about concepts of sustainability and exploring how different land use types affect the environment through the flooding simulation rather spending time and energy learning about what to do or how to do it.

5.3 Controls: Consistent Tool Mappings

Antle describes three kinds of mappings between physical and digital spaces [3]. Perceptual mappings are about how things appear physically versus digitally. Behavioral mappings refer to the mapping between input behaviors and output effects of the physical and digital elements of a system. Both the perceptual and behavioral mappings of the physical stamps to the tangible stamps are consistent with the everyday world. The TUI stamps function consistently with physical stamps in the world. A child picks up a stamp and uses it to make a copy of the object is represents. This is in contrast to the design of Jabberstamp in which augmented stamps enable children to place recorded sounds on drawings [29]. However, in the Jabberstamp design, the stamps look but do not behave like stamps in the real world, and children had to be shown how to use them.

Consistent perceptual and behavioral mappings support an active trial and error approach to exploration on the interactive tabletop. This strategy has found empirical support in Sheridan's Wittingness framework that describes the benefits of participants going through a stage of 'trial and error' where they are engaged in simple and repeatable actions [32]. We suggest that the ability to utilize consistent mappings between physical and digital actions has usability advantages that enable children to focus their attention on learning concepts instead of learning to use a system.

5.4 Interaction: Tangible versus Digital Stamps

Instead of using tangible stamps, it would have been possible to design the Interactive Map Tabletop component of our system using digital stamp icons for land use resources. With a mouse, only one token could be placed at a time. However, with a multi-touch tabletop, a child could use both hands in a similar manner (in 2D space) as the tangible stamps. Digital icons for each resource type could appear around the borders of the map. We have used this strategy with a multi-touch, multi-player tabletop sustainability game for the general public called *Futura* [6]. We showcased Futura at the 2010 Winter Olympics and a University Open House. We decided not to use tangible stamps primarily because we were concerned that the stamps might be damaged or would go missing in such busy and unmonitored public settings (although museums often find ways to secure small physical objects). In the Futura field studies we observed that users (of all ages) needed some instruction or time to experiment with digital (multi-touch) land use tokens in order to learn how to duplicate and position them on the map [6]. However, every child in the Towards Utopia study knew immediately how to use the stamps to place land uses on the map, thus minimizing extraneous cognitive loads. In addition, the stamps provide a physical means to access multimedia information at the Information Station. Digital land use icons are not be portable in this way. In Futura, we also provided conceptual information using digital information cards, triggered by holding down resource icons. Again, we found that users of all ages had to be shown how to trigger the cards. For these reasons we suggest that TUI stamps enable even young children to immediately understand what to do and how to do it.

5.5 Content: Multimodal Digital Representations

Our information design is consistent with Mayer's Multimedia Learning principles. Related information is presented using different representational forms (i.e. objects, images, voice, text, and sound) combined in a temporally and spatially contiguous space [22]. The thirteen land use stamps are labeled with pictures of each land use type. Stamping the interactive map produces a digital copy of this image and a related sound (e.g. traffic noises for roads). At the Information Station, the stamp objects trigger related images, text, and words presented through character narration.

The stamps also provide limited haptic information through the tactile nature of holding a wood form, and the kinesthetic nature of stamping. In this way, a child gets a haptic impression of the quantity and location of land use activity. In general, it is not known whether the addition of the haptic information interferes with visual processing or complements it. The amount of haptic information in Towards Utopia was small and no apparent interference was observed. This question remains to be explored in TUI research.

5.6 Interaction: Metaphor-based Stamping

Children interact with the system using a metaphor-based stamping paradigm where land use planning is treated as if it is stamping. The metaphor is based on simple image schemas that are part of a child's repertoire of common actions and understandings in the world. The activity of stamping on the interactive map instantiates the container schema. Land use activities are stamped onto (or into) the land (map) or taken off of (out of) the map with the eraser stamp. Thus, our model of appropriate activity is structured using the metaphor of planning as an activity where objects (land use activities) are stamped onto or erased from a surface (a map). The everyday pattern of building by placing objects onto a surface is almost so trivial it escapes our notice as a conceptual metaphor. However, it contributes to low extraneous cognitive load and supports an approach to exploration through construction based on children's existing patterns of action and understanding.

5.7 Interaction: Enabling Spatial Reconfiguration

The stamping paradigm combined with a simulation of environmental impact at the Map Station enables children with developing (unstable) ideas about land use activity and environment impact to explore the structure of causes and effects. By altering the structure of land use locations, types, and quantities as well as triggering the impact, they can alter the structure of the map environment. In doing so, they use Schwartz and Martin's distributed learning strategy of mutual adaptation to construct knowledge about the relations between land use types and their impact on the environment [31].

5.8 Integrated Input/Output Space: Supporting Exploration

The stamps are used with the Interactive Map Station to both to represent information and simultaneously produce digital effects in the same space. This is in contrast to using a mouse to control digital representations on a GUI in which neither the mouse nor cursor carry domain information. In addition, a user's actions with a mouse on a horizontal surface produce digital effects in a spatially separate and often vertical display. We suggest that the spatial continuity of stamps and map information contribute, through reduced cognitive load, to ease of use. This spatial continuity provides learners with contiguous digital feedback which also supports an active, exploratory style of learning that is consistent with a Constructivist learning paradigm [10].

5.9 Non-Integrated Input/Output Space: Pausing Action

Placing the stamp in the Information Station reader in order to trigger digital effects on a vertical display operates more like a traditional mouse and GUI design. The results for each stamp are displayed on a vertical screen with words, voiceover narration, and pictures, which describe the land use types and explain how they relate to sustainability. The output display contains spatially contiguous images, words, and voices that are efficiently processed. However, it requires children to suspend their stamping activity in order to trigger the information display. This pauses or slows down the activity and makes room for listening and reflection, which is required for later knowledge construction [10].

5.10 Two Stations: Action and Reflection

The spatial separation of the two stations breaks Mayer's Spatial Contiguity Principle but adds a germane cognitive load that facilitates movement between different modes of learning. The spatial separation of the two stations encourages children to move from an active, experiential mode of learning at the Interactive Map Station to a more reflective and receptive mode of learning with at the Information Station. This movement between spatially separate stations supports the child to step into and out of the action, supporting the kind of perspective taking required for knowledge construction [1]. We suggest that if the Information Station reader had been part of the interactive tabletop, then children may have remained actively engaged in "stamping", but may not have stepped out of an active mode to stop stamping and reflect on the impact of each land use type. We suggest that this separation combined with the information content of the materials makes room for and motivates reflective activity that contributes to the effectiveness of the Towards Utopia design. Various other empirical studies support the need for TUI designs to enable stepping out (reflection) and stepping in (experience) (e.g. [30]). Breaking children out of activity in order to reflect may be achieved by spatial separation of two different kinds of learning activities. This idea requires further investigation.

5.11 Creating Personal Meaning

The Towards Utopia system includes the social environment as well as the TUI learning environment. The child is asked by the facilitator to assume a role of a sustainability engineer and to learn to create a sustainable environment. They are invited to put on a sustainability engineer costume. The interactive map is of a river basin where most of the children in the study live. These design choices contribute to creating an opportunity for children to actively engage in a task that has personal relevance and meaning. To customize the activity to another locale requires only changing the map image.

Design choices that support meaningful interaction with the world are also in alignment with Constructivist principles [10]. The ability to personalize learning using the combination of digital media and everyday objects is key.

6. LEARNING EVALUATION

In order to validate the effectiveness of our design, we worked with a teacher to conduct a learning evaluation. The study design involved assessing individual children's level of understanding of basic sustainability concepts before and after a session with the Towards Utopia system. We use a clinical interview style assessment similar to that used in [36] to assess learning outcomes related to sustainability. We also took observational notes during each session.

6.1 Participants

The evaluation was conducted with thirty children aged seven to ten, who volunteered to participate from the visitors to a science-oriented museum located in an urban area. The participants were gender balanced. Each child participated on their own to avoid the difficulties of assessing individual learning in collaborative conditions.

6.2 Measures

We measured the participants' knowledge of sustainability concepts related to the thirteen land use types and their impact before and after their experience with the Towards Utopia system. Learning outcomes were assessed with a pre-test and post-test of children's understandings of sustainability concepts. We used a clinical style, orally administered interview consisting of standard questions that were developed by a teacher. Each test contained thirteen open style questions. We use the pre-test to establish each child's base level of understanding. After their play session with Towards Utopia, we reassessed them. This allows us to compare their scores in order to determine whether they learned additional material related to the sustainability concepts. A limitation of this approach is that we measured only short term learning gain. However, short term learning is a step towards longer term learning and supporting behavior change in environmental practices. Verbal responses to the questions as well as general comments were recorded on audio tape and were later transcribed.

6.3 Procedure

The procedure began with a pre-test consisting of thirteen open questions administered orally. After the pre-test, each child was instructed to interact with the prototype described in the Usage Scenario (above). The session concluded with the administration of the post-test. Sessions ranged from 20 to 30 minutes.

6.4 Data Analysis

Participants' responses to all thirteen questions were transcribed and then scored using either a pre-test or post-test rubric. For each question, the answer was scored by using the rubric to assign the answer to one of six categories, which were assigned a value of one to six. Six was the best score for each question. A perfect score is 78, which was calculated by multiplying thirteen questions by a perfect score of six. The six rubric categories were based on the quantity and quality of the explanations given for each land use type in relation to sustainability. For example, a simple description using adjectives of a land use type is scored lower than a response that infers how the land use type impacts or is related to the concept of a sustainable environment. For example, if a participant had been shown a picture of a farm, and said, "This is a farm where farmers grow food for us to eat and buy at the store," then the participant's response would have been assigned a score of four because the participant made the inference about the growing of food in response to the image. This demonstrates that the participant has comprehended the function, meaning, and importance of the farm. If the participant had also mentioned a key concept related to sustainable farming practices then the answer would have be assigned a score of five.

In order to account for participants improving their test performance simply through exposure to the pre-test, we used a variant of the pre-test rubric for the post-test rubric. The post-test rubric required a higher number of descriptions or inferences and/or more detailed inferences related to land use descriptions or sustainability concepts in order to be assigned to the same score. This means that in the post-test a participant must demonstrate an improvement in their ability to describe and understand the importance of land use types relative to sustainability in order to receive the same score as that of the pre-test. If a participant had answered the pre-test and post-test questions identically, they would receive a lower score in the post-test. This was done to reduce the effect of the potential confound that children might improve their score by simply being exposed to the pre-test as opposed to learning from the TUI system.

Using rubrics ensured that qualitative data could be transformed to quantitative data related to learning outcomes consistently across participants. For each participant the total learning outcome score was summed for the pre-test and post-test. We also calculated learning gain, which is the difference between pre-test and post-test scores. We analyzed results using non-parametric tests since we cannot assume that the rubric scores are interval numbers.

6.5 Evaluation Results

We present both the mean and median scores since the data are not presumed to be interval (see Table 1). These values show an increase in post-test scores compared to pre-test scores. The average learning gain score is 17.5, which is a 22% increase. The standard deviations for pre-test and post-test are relatively small, indicating that participant scores were fairly tightly clustered around the mean scores.

Table 1. Descriptive statistics for learning scores

	Pre-test	Post-test	Gain
Mean	46.9	64.4	17.5
Median	47.5	68.5	19.0
Std Dev	8.3	10.0	10.7

The Wilcoxan signed ranks test of significant difference for related groups indicated that there was highly significant difference ($Z=-4.662$), at the $p<0.001$ level, between the pre-test and post-test scores. This indicates a significant short term learning gain after the exposure to the Towards Utopia intervention. Participant's comments also reflect this learning gain. For example, one participant said, "It made me think about things a little more. I like planning out how the world could be a better place."

While these results provide evidence of short term learning benefit through using the Towards Utopia system, we do not have a control group or a comparison with other learning approaches or materials. Thus, we cannot say that children learned better or differently with our system compared to another. However, it is clear that students significantly increased their scores after using Towards Utopia.

From our observational notes, we suggest that children easily learned the functionality of both stations, and used the system with ease. There were no major usability issues.

Since gender differences are often important in work with children, we explored gender effects using the Mann Whitney test of significance difference for unrelated groups (i.e. male/female). Results indicated that there was no significant difference between male and female participants in either pre-test or post-test scores. This suggests that the Towards Utopia design was effective in supporting both boys and girls to learn about basic sustainability concepts.

6.6 Study Limitations

Several known limitations of this research affect our ability to make general claims that attribute learning effects to specific TUI design decisions or interface elements. For example, the learning evaluation does not provide evidence directly related to any specific design feature but to the environment as a whole. Children may have learned through exposure to the concepts regardless of learning environment. The improvement in learning scores could be related to the intervention triggering pre-existing knowledge rather than supporting children to construct new knowledge. Based on these limitations we cannot make strong claims about TUI causes and learning effects. However, the positive evaluation outcome is important because it means that Towards Utopia was an effective learning intervention and research instrument. We are less interested in trying to find irrefutable evidence that TUIs are better than other forms of learning materials, and we are more interested in proposing guidelines to leverage the affordances of TUIs effectively for learning. The positive evaluation outcome provides validity for our research instrument that was used in our theoretical analysis and to derive our design guidelines.

Another limitation relates to scope. The learning system is designed to support single user interaction rather than collaborative learning, which is common in computational environments. We leave this to future work.

7. IMPLICATIONS FOR DESIGN

Based on work presented in [8], we summarize our design rationale as general guidelines that may be used to inform TUI design decisions for spatial domains. We suggest that these guidelines should not be viewed as predetermined, prescriptive heuristics. Consideration must be given to the pedagogical philosophy, details of the desired learning outcomes, specifics of the learning environment, and design situation, which will co-determine the relevance and appropriateness of each guideline. As with all guidelines, there will be times to specifically break them to engender a particular learning effect or opportunity.

While some of our guidelines are specific to TUIs, others might also apply to the design of other forms of learning materials. However, the specific characteristics of TUIs facilitate implementing these general learning design guidelines. For example, the ability to link learning to real world contexts and objects, which is fundamental to Constructivist pedagogy, is facilitated by TUIs because they support the augmentation of a variety of everyday objects and environments with computation (e.g. stamps, local maps).

The ten guidelines we draw on in our design rationale (many of which are discussed at length in [8]) can be stated as:

1. Distribute information across modalities, including haptic, to increase effective working memory capacity.
2. Integrate spatial sources of information across and within modalities to minimize the extraneous cognitive load imposed to synthesize inputs.
3. Use world-based scenarios to enable children to quickly understand the activity goals.
4. Use everyday objects to make the TUI tools that support learning goals through immediate use.
5. Relate tasks to images and objects from children's lives to enhance personal relevance of learning activities.
6. Make the mappings of objects and digital effects consistent with the everyday world to ease learning to use the system by reducing cognitive load.
7. Using spatial, physical, temporal, or relational properties can slow down interaction and trigger reflection.
8. Leverage primary schemas in input actions to improve usability and system learnability.
9. When available, use embodied metaphors to structure interaction mappings to improve usability and bootstrap learning of abstract concepts.
10. Design objects that allow for spatial re-configuration to support exploration and subsequent adaptation of ideas.

8. CONCLUSIONS

A contribution of this work is the combination of theoretical framing, design rationale, and learning evaluation in order to generate design knowledge. We use two theoretical lenses (Cognitive Load Theory and Constructivist learning theories) to analyze how and why specific design decisions create opportunities for learning. We present our prototype design that exemplifies ten guidelines derived from theory, and describe the results from a quantitative learning outcome evaluation with 30 children. We did not use an experimental research design since we are not trying to make strong claims about TUI causes and learning effects or generate evidence that TUIs are better than other forms of learning materials. We leave this to other researchers. However, we can infer connections between TUI design features and learning effects based on our theoretical analysis. Few previous design studies have specifically assessed learning outcomes in order to ensure that the prototype supports effective learning. It is this in conjunction with our theoretical analysis that provides valid design knowledge about how TUI features can be designed to create effective, efficient, and personally meaningful opportunities for children's learning. We present our work with the hopes that our guidelines will be used by researchers of tangible and natural user interfaces as well as design practitioners in industry who create learning materials and games for children.

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