Getting down to details: Using theories of cognition and learning to inform tangible user interface design

Abstract

Many researchers have suggested that tangible user interfaces (TUIs) have potential to support learning. However, the theories used to explain possible effects are often invoked at a very broad level without explication of specific mechanisms by which the affordances of TUIs may be important for learning processes. Equally problematic, we lack theoretically-grounded guidance for TUI designers as to what design choices might have significant impacts on learning and how to make these choices in an informed way. In this paper, we build on previous efforts to address the need for a structure to think about TUI design for learning by constructing the Tangible Learning Design Framework. We first assemble a taxonomy of five elements for thinking about the relationships between TUI features, interactions and learning. We then briefly review cognitive, constructivist, embodied, distributed and social perspectives on cognition and learning and match specific theories to key elements in the taxonomy to determine guidelines for design. In each case, we provide examples from previous work to explicate our guidelines; where empirical work is lacking, we suggest avenues for further research. Together the taxonomy and guidelines constitute the Tangible Learning Design Framework. The framework advances thinking in the area by highlighting TUI design decisions important for learning, providing initial guidance for thinking about these decisions through the lens of learning theories, and generating a blueprint for research on testable mechanisms of action by which TUI design can affect learning.

Keywords: Tangible user interfaces; tangible interaction; tangible computing; physicality; cognition; learning; cognitive theories; learning theories; embodied interaction; design framework; design guidelines; design knowledge; design research.

1. Introduction

Tangible user interfaces (TUIs) are a computing paradigm in which the real world is augmented by embedding computation into physical objects and environments that are linked to digital representations. For example, a physical jigsaw puzzle piece might be associated with a digital image of part of the jigsaw puzzle picture. TUIs rely on a form of interaction in which physical objects are manipulated in space to directly control computation. The form of both the objects and their associated digital representations carry representational information that is important in some way [108]. Thus, in the example above the orientation (rotation) of the physical jigsaw puzzle could be recognized by the system, and only correctly placed physical pieces would show up in the digital image.

Researchers have suggested that TUIs have great potential to support learning for a variety of interrelated reasons. They offer a natural and immediate form of interaction that is accessible to learners (e.g. [65, 77]); promote active, hands-on engagement (e.g. [69, 83, 84, 87, 114]); allow for exploration, expression, discovery and reflection (e.g. [38, 69, 82, 83, 85, 89]); provide learners with "tools to think with" [88] that allow for learning of abstract concepts through concrete representations (e.g. [6, 77]); and offer opportunities for collaborative activity among learners (e.g. [4, 6, 36, 82, 104]). However, little empirical work exists that provides evidence for these claims, and much of what has been done has found no evidence for enhanced learning (e.g. [21, 66]) or is primarily anecdotal in nature [12, 65].

Even more problematically, we lack a theoretically grounded framework that outlines how and why we might expect different features of TUIs to mediate learning interactions and thus affect learning outcomes. Much recent research invokes learning theories to explain possible effects at a broad level without explaining specific mechanisms by which the unique affordances of TUIs might affect learning processes (for exceptions, see [8, 11, 20, 89]). In addition, TUI designers do not have detailed guidance about what design choices might have significant impacts on learning and how to make these design decisions in an informed way. Finally, efforts to create TUI-based learning experiences have often focused solely on the design of the TUI artifacts, ignoring the critical and interdependent design of the learning activity in which they will be used (for exceptions, see [9, 25, 46, 66, 86, 115]).

There have been some valuable initial efforts to address the need for a framework to think about TUI design for learning. Marshall [65] compiled six perspectives for thinking about learning with respect to TUIs: possible learning benefits; typical learning domains; exploratory and expressive activity; integration of representations, concreteness and sensory directness; and effects of physicality. His work identifies gaps in knowledge and provides some sensitizing concepts; however, the framework does not provide explicit design guidance. O'Malley and Stanton-Fraser [77] provide a good conceptual overview of some educational and psychological theories that are applicable to learning with tangibles but the information is rarely specified at the level of detail needed to inform specific TUI design decisions. Edge and Blackwell [34] present a TUI framework as an analytic design tool which may be used in rapid prototyping to create an information structure in the form of a manipulable solid diagram. They explicate their framework through application to several children's TUI programming environments; however, the framework focuses on representation in design rather than on learning. Price et al. [84] present a taxonomy for conceptualizing tangible learning environments with respect to issues of external representation. This taxonomy presents clear category descriptions and illustrative empirical research for some of the categories; however, the framework provides little prescriptive guidance and only addresses one of several dimensions of TUI learning design. In this paper we build on prior work that has taken a learning perspective on TUI design. We first present a taxonomy delineating five elements of TUIs that are important to consider during the design of TUIs for learning, and then we use theories of cognition and learning to generate guidelines that can be used to inform the design of each of the five elements. Together the taxonomy and design guidelines constitute our Tangible Learning Design Framework.

Our Tangible Learning Design Framework contributes in three ways. First, the taxonomy provides a perspective on what aspects of TUI design are important to consider in learning contexts either because they present unique opportunities to support learning interactions or because they relate to critical elements of learning that the design of any TUI with learning as a goal should take into account. Second, the guidelines characterize the dimensions of the design space in terms of cognitive and learning theories at a level of specificity that allows designers to use them not simply as a justification for why TUIs should be used in learning but to inform specific design choices. Finally, by laying out the connections between TUI design choices and cognitive and learning theories, we propose testable explanations about how and why TUI design is expected to affect learning. In summary, there is a dual payoff: the framework provides a guide for exploratory design work as well as a blueprint for research questions and hypotheses that can be used to generate empirical support for the proposed claims.

2. Overview of the Tangible Learning Design Framework

2.1. A Note on Design Frameworks

Design frameworks are a form of design knowledge that designers can use to create interfaces and systems that users find efficient, effective or beneficial in other dimensions of user experience. They also provide a common language for designers and researchers to discuss design knowledge, generate prototypes, formulate research questions and conceptualize empirical studies. At the most basic level, frameworks like theories, are composed of a number of concepts and the interrelations between them. Frameworks may take a number of forms that specify concepts and their relations at a variety of levels of detail. For example, concepts may be simply given as categories, dimensions or elements; in this case the framework takes on a taxonomic form and can be used as a classification tool. An example of this level of framework is Fishkin's taxonomy for TUIs that includes two dimensions: embodiment and metaphor [39]. Concepts and their interrelations may also be specified through description derived from theory or grounded in empirical studies. A descriptive framework can inform design by providing sensitizing concepts, design considerations, heuristics and the like, but it does not provide explanatory accounts of framework relations. Several examples of descriptive TUI frameworks are discussed in Section 1 [6, 34, 65, 84, 89, 98]. An explanatory framework not only provides concepts, relations and descriptions, but also specifies details about how and why certain causes create their effects. While both descriptive and explanatory frameworks can be used generatively, prescriptively or analytically, because explanatory frameworks specifically explicate the relations between concepts, they can be used to develop testable hypotheses linking learning constructs, interactional behaviors and design features. There are currently no explanatory tangible learning design frameworks; our framework is a first step at filling this gap.

2.2. Developing and Using the Tangible Learning Design Framework

The Tangible Learning Design Framework was developed through a dialectic process of analysis, reflection and critique of research from different but complementary perspectives on cognition, learning and TUIs. It draws theoretically on research from information processing, constructivist learning, embodied cognition, distributed cognition and computer supported collaborative learning (CSCL); as well as empirically from prior work taking a learning perspective on TUI design. It is also grounded in ours' and others' analysis and critique of the design of prototypes and related user studies of tangibles and other forms of natural user interfaces for learning. We formulate the framework in two parts. First, we have created a taxonomy of elements of TUI design important to consider with respect to learning. This directs designer attention to critical decisions about TUI elements and gives us a language with which to communicate about these elements. Second, we have generated a set of thirteen guidelines to inform the design of these elements and have mapped the guidelines to the design elements that they inform. Our guidelines draw on theory to generate testable explanations about how and why TUI design can influence learning processes. Where possible, we support the guidelines with empirical evidence; however, in many cases the guidelines present propositions that need to be tested. While further validation is needed, our guidelines suggest theoretically grounded explanations of how and why particular TUI design decisions are predicted to affect learning; thus the Tangible Learning Design Framework is an early form of an explanatory framework. It can be used informatively or prescriptively to improve designs, analytically to support evaluation, and generatively to help formulate research designs and hypotheses. While some of the elements and guidelines are not exclusive to TUIs and the collection does not cover every aspect of TUI design, as a set they provide a starting foundation to guide effective and efficient TUI designs for learning. We expect that as more research is conducted the guidelines will be refined and expanded.

2.3. The Importance of Learning Design in the Framework

From a global standpoint, one of the implications of taking a learning perspective on TUI design is the order in which decisions are made (see Fig. 1). While interaction designers may begin by designing a tool or by imagining a desired experience and creating a facilitating environment, educational designers generally begin a step earlier by asking the big picture question of "what do we want people to learn" (i.e. what are the *learning goals*)? They then envision what kinds of *learner experiences* will support progress towards these goals and design a *learning environment* under which they believe such experiences are likely to occur. The learning environment can have many different elements (e.g. tasks, procedures, materials, and tools) that should all work together to facilitate the enactment of the desired learner experiences, thus supporting achievement of the learning goals. From this perspective, the details of the design of a tool (such as a TUI artifact) must be conceived in concert with the other elements of the learning in environment (e.g. learning tasks and procedures) and with the objective of promoting experiences that support the learning goals. Thus, choices about the learning goals and activities in which a TUI will be used need to be considered from the very beginning of the design process. For these reasons we have included the learning activities as a design element in the Tangible Learning Design Framework.

Fig. 1 Learning design process: *learning goals* drive envisioning of supportive *learner experiences*. Elements of the *learning environment* are designed to facilitate the enactment of these experiences to help fulfill the goals.

3. Tangible Learning Design Taxonomy: The Five Design Elements

TUI learning environments can be conceptualized in terms of five interrelated elements over which the designer has control: physical objects, digital objects, actions on objects, informational relations and learning activities (see Fig. 2). While a completed user interface involves the integration of all five elements, to some extent each element must be conceived, designed and implemented individually and then integrated to create the complete system. For this reason, we conceptualize TUIs as being composed of these elements in an interrelated conceptual framework. It is important to note that the ordered presentation of the elements below is not meant to indicate a linear process of design. The focus at any given moment in the design process may be on a particular element, but the other elements provide context for these decisions and multiple iterations of the different elements in turn is almost always necessary.

3.1. Physical and Digital Objects

As shown in Figure 2, the TUI system can be thought about as consisting of two kinds of objects: physical and digital. Physical objects are the set of materials through which learners interact with the TUI system. These are material objects that exist concretely in the world and have physical properties that must be designed, including visual attributes (e.g. colour), tactile attributes (e.g. texture), and sometimes auditory attributes (e.g. tone). In addition, spatial properties of the objects such as their location, orientation and configuration must be taken into consideration.

Digital objects are virtual entities in the system that also have particular attributes (e.g. colour, location, tone). The properties of digital objects that need to be designed are similar to those of physical objects with the exclusion of tactile attributes and the addition of temporal properties (i.e. attributes that change dynamically over time). Our focus is on pure TUI systems; thus Figure 2 does not show direct interaction between the learners and the digital objects. However, in a multi-touch table or a hybrid TUI/multi-touch system, learners could also interact directly with the digital objects.

3.2. Actions on Objects and Informational Relations

The next several elements we consider have to do with the coupling of physical and digital objects through action (i.e. control) and information relation or association (i.e. representation coupling). Actions on objects are the set of input manipulations that learners can take on the physical (and in some cases digital) objects that are sensed by the system; for example, tracking the speed with which a learner changes an object's position or orientation. Effective design also requires considering the probability that these potential actions will be enacted or discovered by the user for some intended purpose [24]. Physical objects can be designed with particular affordances to influence this probability.

Informational relations are the collection of couplings between the digital objects, the physical objects and actions that can be taken on them, and references to real-world entities. While a physical object may represent something specific in the TUI, it can also carry meaning from the real world (for example referring to an everyday object, action or phenomenon). Thus, it is important to consider it as both a referent and a representation. Each information relation in the system -- a mapping of one thing to another -- must be defined, either in advance by the designer or in real time by the user. The semantic aspects of the mapping can be perceptual (e.g. a red circular physical object represents an apple and can be used to plant a digital apple tree) or behavioral (e.g. the tree is planted by stamping the red circle on the system, not by dragging it across the surface). The structure of the mapping must also be considered. For example, is the red circle linked to a particular apple tree or can it be associated with multiple ones? Is the apple tree planted near where the learner stamps the red circle or can it appear anywhere in the system?

3.3. Learning Activities

Learning activities are the context, instructions and guidance provided to learners to frame their interaction with the TUI system. For example a TUI related to building construction could be presented as a competitive game in a stand-alone activity, or a collaborative team of learners might be introduced to the TUI as a resource in a larger inquiry about architectural design. Learning activity design can influence how learners take action on the system as well as how they interact with each other (as shown by the arrows between learners in Figure 2). The inclusion of learning activities into early TUI design thinking supports better design and is one of the unique aspects of our framework compared to others (e.g. [6, 39, 65, 98]).

Physical objects, digital objects, actions, informational relations, and learning activities are the five interrelated elements of our taxonomy. In the remainder of the paper, we use theories of cognition and learning to generate guidelines that can help inform design decisions and research about these elements in TUI designs for learning.

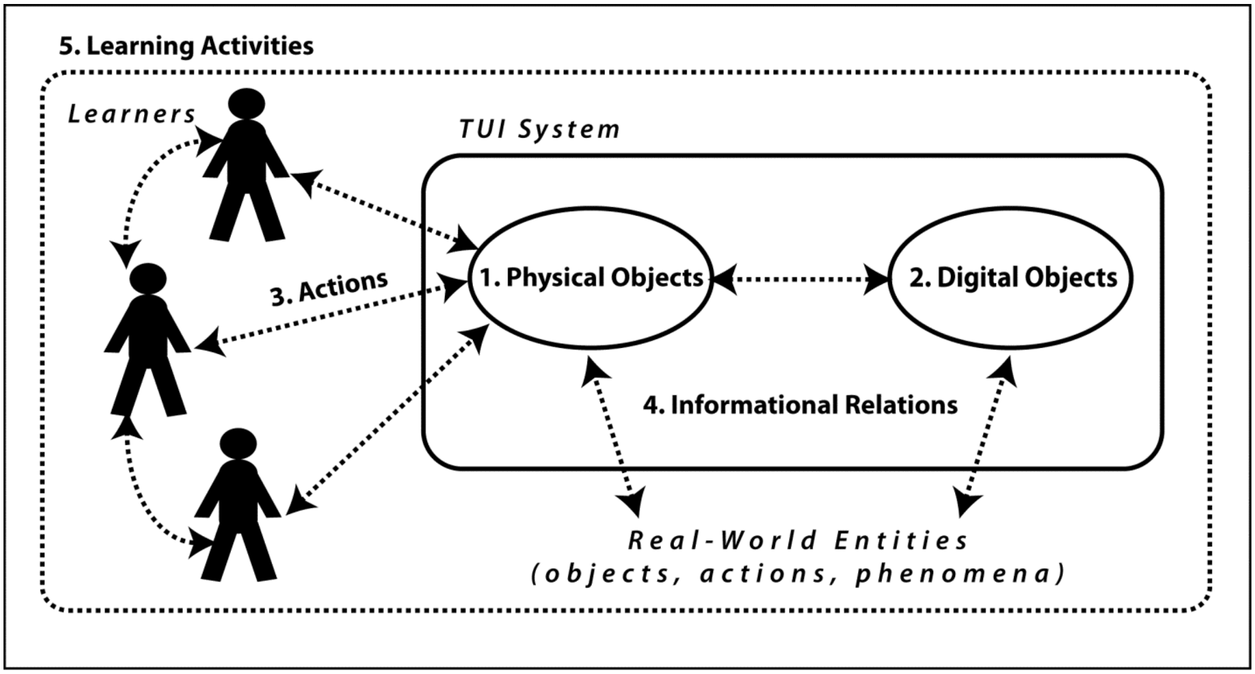

Fig. 2 Five elements of the Tangible Learning Design Taxonomy.

4. Tangible Learning Design Guidelines: Using Theory to Inform Design Decisions

There are multiple perspectives on cognition and learning, each of which can provide important insights for TUI learning design. Different perspectives on thinking and learning often drawn on epistemologically incommensurate assumptions; while some academics thus see it as untenable to productively combine them [22]; many other theorists and learning designers acknowledge the value of using multiple perspectives to inform practice [35, 43, 97]. From a pragmatic design stance we find that the different perspectives are each useful in informing decisions at different levels. An information processing perspective examines the process of how learners manage and organize information from the world to acquire memory structures to represent it. This perspective focuses on the individual and their internal mental processes. In contrast, a constructivist stance focuses on cognition and learning as a process in which people build, test, negotiate and revise viable understandings of the world. An embodied cognition stance focuses on the central role that the body has in shaping cognition and learning. A distributed cognition stance focuses on the structural and functional role of external actions, representations and artifacts in cognition and learning. These latter three perspectives all focus on the individual as embedded in a physical environment. Finally, a computer supported collaborative learning

(CSCL) perspective conceptualizes learning as a collaborative process of meaning-making and becoming a participant in the knowledge practices of a community. It focuses on the individual as embedded in a social environment. It is true that in certain circumstances, these perspectives may provide guidance that would suggest different design choices, but weighing trade-offs between competing alternatives is always a part of the design process.

The five perspectives on cognition and learning that we discuss here were chosen for their relevance and usefulness in thinking about TUI design. Each perspective contains specific theories and related empirical findings that have implications for designing TUI learning environments. In the following sections, we focus on a particular theory or group of theories within each of these five traditions, chosen for its relevance to tangible user interface design. While there is certainly other work that can also be useful in informing TUI design for learning, collectively the theories discussed here addresses critical questions related to learners' thinking, their interactions with the surrounding environment, and their exchanges with other learners; thus they provide a useful starting point for developing principled guidance for TUI learning design. The theories were analyzed to search for specific concepts and mechanisms that have been empirically validated for TUIs or in similar contexts. In some cases, empirical work supports the derivation of guidelines that may be directly applied to TUI design. In other cases, more research is needed to understand how a particular theory will apply to interaction with TUIs. While it is certainly possible (and we would encourage researchers) to bring other theories and theoretical perspectives to bear, these are the five perspectives that we have found particularly useful to inform our thinking about the design of TUI learning environments. Table 1 summarizes the thirteen design guidelines derived from these theoretical perspectives and the TUI element(s) to which they apply.

4.1. Information Processing: The Cognitive Theory of Multimedia Learning

4.1.1. The Theory

The Cognitive Theory of Multimedia Learning is grounded in the Atkinson and Shiffrin model of human cognitive architecture [16] and the theory of cognitive load [57, 105, 106]. The focus is on working memory, where information is temporarily held and processed to affect changes to long-term memory. Working memory is conceptualized as having three main components: an executive control system (responsible for selecting information and planning its processing), 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) [17, 18]. Importantly, the cognitive resources available to working memory as a whole and to each sub-component are limited [49, 73]. All learning activities impose demands on these limited cognitive resources [57, 105, 106]. While some of these demands contribute to learning (*germane* cognitive load), others distract from it (*extraneous* cognitive load) and should be minimized.

The Cognitive Theory of Multimedia Learning is a series of evidence-based design principles for reducing the extraneous cognitive load imposed by multimedia learning tools [71]. Five of these principles have particular relevance to TUI designers. The first and most basic principle is the Coherence Principle: people learn better when unnecessary content is excluded. Simply put, each and every component of the TUI learning environment design should be necessary and contribute to learning. The second is the Multimedia Principle: people learn better when words are accompanied by pictures. Next, the Temporal and Spatial Contiguity Principles state that people learn better when the related words and pictures are presented simultaneously (as opposed to sequentially) and when these pieces of information are physically proximate to each other. Research supporting these principles shows that when related pieces of information are presented separately and have to be integrated by the learner, it uses up cognitive resources that could be otherwise devoted to learning, resulting in slower or reduced learning performance [71]. Finally, the Modality Principle states that people learn better in multimedia learning environments when words are presented audibly as opposed to in textual form. This principle takes advantage of the structure of human cognitive architecture by distributing the information to be processed between the visual-spatial sketchpad and articulatory loop, resulting in an effective increase in the capacity of working memory [79].

Table 1. Summary of guidelines with reference to TUI elements to which they apply.

Guidelines	Physical Objects	Digital Objects	Actions on Objects	Informational Relations	Learning Activities
1. Distributing information across modalities can increase effective working memory capacity.	X	X			
2. Integrating spatial sources of information across and within modalities can minimize the extraneous cognitive load imposed to synthesize inputs.	X	X			
3. Using concrete representations can support interpretation of symbolic representations of abstract concepts.	X	X		X	
4. Making mappings between the form and behavior of physical and/or digital objects and real-world entities coherent can reduce extraneous cognitive load.				X	
5. Creating contextualized tasks or personal objects can support learners in forming individually meaningful goals for interacting with the TUI.	X				X
6. Using spatial, physical, temporal or relational properties can slow down interaction and trigger reflection.	X	X	X	X	X
7. Distributing parts of mental operations to actions on physical and/or digital objects can simplify and support mental skills.			X	X	
8. Leveraging image schemas in input actions can improve usability and system learnability.			X		
9. Using conceptual metaphor(s) based on image schemas to structure interaction mappings may bootstrap learning of abstract concepts.				X	
10. Designing objects that allow for spatial re-configuration can enable mutual adaptation of ideas.	X	X			
11. Creating configurations in which participants can monitor each other’s activity and gaze can support the development of shared understandings.	X	X			
12. Distributing roles, information and controls across the TUI learning environment can promote negotiation and collaboration.	X				X
13. Creating constrained or co-dependent access points schemes can compel learners to negotiate with each other.			X		

4.1.2. Implications for TUI Design

Guideline 1: Distributing information across modalities can increase effective working memory capacity. (Design of Physical and Digital Objects)

When designing the representational properties of TUI objects, designers must decide what modalities to engage and what information to communicate through each channel. Following the logic of Cognitive Load Theory and the Cognitive Theory of Multimedia Learning, TUI designers should try to leverage both visual and auditory representational forms to distribute information across the two perception channels. Specifically, when possible, words should be presented audibly as opposed to in textual form to distribute the cognitive load imposed by the TUI environment over the visual-spatial sketchpad and articulatory loop.

In the case of TUI objects, there is also a third modality (haptic) to consider. Research has shown that gestures accompanying speech can, in some cases, reduce the cognitive load on the part of the language producer or enable parallel processing of information [41]. However, another finding suggests that haptic information is blended with visual information processed by the visual-spatial sketchpad, and thus haptic information may compete with visual information for the same memory resources [56]. Preliminary research has shown no bottleneck between visual and haptic processing [96] for simple tasks, but further empirical work is needed. It is unclear whether distributing information (either redundant or complementary) to the haptic modality in TUIs can further assist in distributing cognitive load or whether the use of this modality needs to be balanced with the visual channel.

In addition, there may be situations where haptic information is particularly appropriate for the learning task (e.g. learning the three dimensional structure of molecules). In this case, it may be better to complement the haptic information using auditory information rather than visual. This can be tested by using study designs that explore the efficiency of different presentation modalities and different combinations of presentation modalities for different kinds of information. Other perspectives on learning (e.g. embodied perspective) suggest that the value in representing information haptically is not increased efficiency but that it leads to a different *quality* of understanding. This also merits further investigation.

Guideline 2: Integrating spatial sources of information across and within modalities can minimize the extraneous cognitive load imposed to synthesize inputs. (Design of Physical and Digital Objects)

The Cognitive Theory of Multimedia Learning suggests that integrating different sources of information reduces extraneous cognitive load. Thus, unless the task of integrating information sources is itself central to the learning goals, pre-integrated configurations of physical and digital objects are predicted to lead to more efficient learning. For example, TUI learning environments may have multiple objects capable of emitting sound. When sounds are made, a learner must engage in a process of searching for and associating sounds with objects. Unless this is integral to the learning goals, it imposes an extraneous cognitive load. Extraneous load can also be imposed if a learner is forced to disentangle embedded sounds from ambient ones. To avoid these kinds of extraneous load, for learning contexts all the audio content can be integrated into a single channel and presented using a "surrounding" configuration in which sound is produced near to but outside of the rest of the system (e.g. speakers placed near a tabletop) [84]. However, in some cases the process of associating sounds with objects can create germane cognitive load. In such situations separating the channels and embedding them in particular objects can be beneficial. For example, using an embedded strategy that has a learner associate animal sounds with physical representations of the animal that makes the sound can help young children learn to recognize the characteristic noises that each animal makes [64].

This guideline presents theoretical implications of the Cognitive Theory of Multimedia Learning based on research that is extensive, but conducted in traditional computer-based learning environments [71]. Further work is needed to explore and test these implications specifically in TUI learning contexts.

Guideline 3: Using concrete representations can support interpretation of symbolic representations of abstract concepts. (Design of Physical and Digital Objects and Information Relations)

Multiple representations can be designed to reduce extraneous cognitive load by using one representation to support interpretation of another [5]. For TUIs, one way to achieve this is by representing a concrete example of an abstract concept using physical objects, and providing one or more symbolic representations of the abstract concept using digital representation. For example, we might extend the distributed learning experiments of Schwartz and Martin [95] to design a TUI that supports people to learn to solve ratio or division problems using TUI objects linked to digital symbolic representations. Here the abstract concept is division. A particular division problem can be represented concretely using objects as well as symbolically using numeric notation. For example, to solve the problem of ¼ of 8, they could organize eight objects into spatially separate groups. The TUI system could respond by showing the corresponding equation in symbolic form on a display. For example, if a learner made 2 groups, then "8 ÷ 2 = 4" might be displayed; if she made 4 groups, then "8 ÷ 4 = 2" would be displayed. In this way, the physical objects serve as a concrete representation for the abstract concept of division, as well as a controller for the digital symbolic representation. Investigating how dynamic linkages between concrete and symbolic representations can help students learn abstract concepts, and exploring what kinds of teacher scaffolding support such experiences, are areas for future research. For a related example, see the description of Abrahamson's Mathematical Imagery Trainer (under Guideline 9).

Guideline 4: Making mappings between the form and behavior of physical and/or digital objects and real-world entities coherent can reduce extraneous cognitive load. (Design of Informational Relations)

Often, user interfaces make cognitive demands of a learner that do not contribute to learning. One way to minimize this extraneous load is by designing TUIs coherently (i.e. the informational relation in the digital system mirrors those in the real world). This kind of mapping requires a low amount of cognitive resources to process, freeing up more cognitive resources to devote to learning. In the ergonomics literature, coherent mappings between input actions and system responses are referred to as having stimulus-response compatibility [112]. For example, to steer a car to the right, the steering wheel is turned right. However, to steer a sailboat using a tiller attached directly to the rudder (rather than a steering wheel), turning the boat right, requires turning the tiller left. This mapping is incoherent and has to be learned, using up cognitive resources that could otherwise be used for other tasks. In some cases, a coherent mapping (e.g. front = forward for a controller) has been reinforced to such a degree that it is automated, bypassing the need for working memory processing altogether.

In contrast, in some cases it is possible to purposely use an incoherent mapping to provoke reflection on a learning goal. In this case the load added is beneficial and thus considered to be germane rather than extraneous. For example, Rogers et al. suggest that pairing a familiar action with an unfamiliar digital response in a colour mixing application encouraged learners to reflect on and develop a diversity of explanations for the phenomenon [90]. In this case, an incoherent mapping is used to create conflict and possibly promote reflection. For more strategies to trigger reflection, see Guideline 6. Similarly, Golightly and Gilmore found that a complex interface could be used to stimulate more effective problem solving than a simple one [42].

4.2. Constructivism: Goal-Directed Activity and Reflection in Meaning Making

4.2.1. The Theory

A constructivist perspective on cognition and learning conceptualizes knowledge as derived from experience, actively constructed and re-constructed by individuals through interaction with, and feedback from the world [3]. This is in contrast to epistemological views that conceptualize knowledge as something that exists in the world, independent of a knower who can transmit and acquire it. Piaget's statement that "intelligence organizes the world by organizing itself" ([80] p. 311) epitomizes a constructivist perspective. The core idea from this perspective is that learning is a process in which people are constantly constructing understanding through their interactions with the world [81, 111] and learning is driven by their goals that shape their interactions [92]. Productive learning interactions can thus be supported both by helping learners develop meaningful goals for interaction and by giving them the opportunity to create and manipulate physical materials in the world in pursuit of these goals. For example, multiple studies have shown that students learn more from traditional instructional elements such as lectures and worked-examples if they first have the opportunity to work on a related problem, thus giving them a need to know [24, 93, 94]. Potential benefits of learning through active manipulation of physical objects have been articulated and developed into pedagogical approaches by several schools of educators (e.g. [23, 28, 75, 78]). Another important feature of constructivist learning is the need for both direct interaction with the world and space to step back for reflection to reach deeper understandings. Ackermann describes this as "diving-in" and "stepping-out" [2].

4.2.2. Implications for TUI Design

Guideline 5: Creating contextualized tasks or personal objects can support learners in forming individually meaningful goals for interacting with the TUI. (Design of Physical Objects and Learning Activities)

From a constructivist perspective, learners build understanding driven by their goals for engaging in a situation. Thus if their goal is conceptualized as "completing a task," "winning a game," or simply "interacting with the TUI", they will learn different things than if they are driven by deeper goals to understand or use knowledge [72]. This presents a particular danger if the novelty of the TUI leads learners to develop goals focused only on the tool itself, rather than what they can do with it. To avoid this and support robust, extensible learning with TUIs, interactions should be framed within a learning activity that helps learners develop meaningful goals that go beyond simply interacting with the TUI.

This can be achieved by situating the learning task in which the TUI will be used in a larger context of meaning related to the world. For example, learning goals related to mathematics can be situated in the context using a TUI abacus for accounting in running a business; spatial problem solving can be embedded in a urban planning task using a TUI desk like URP [109]; and biological concepts can be contextualized in the exploration of the hybrid physical-digital Snark habitat [83]. Crucially, for learners to see a task as authentic and to develop meaningful goals around it, the task must be grounded in an authentic world (as opposed to a contrived situation) and learners need to feel that their involvement is important. When it is impossible to have learners set their own goals, a "goal adaptation" approach can be taken, which has an initial phase in which learners are supported in defining pre-set goals in terms of their own perspective and needs [33].

Another way that TUIs can help learners set meaningful goals for interaction is by enabling the use of personally meaningful objects rather than generic objects. These objects can then serve as controls or representational objects in a TUI activity [110]. By tagging learner's personal objects (e.g. with barcodes or fiducials), these objects can become key aspects of the TUI learning system. Using personal objects ensures that users already have mental models or personal links between experiences, related media and these objects [110]. For example, in the Rosebud system a child's physical toy (e.g. teddy bear) triggers the replay of one or more stories created by the child in which the toy may be a character [40]. The tangible toy is thus an index to its own stories which accumulate over time, providing a personal link between the child, the toy, stories and their history together. The toy can also be handed down, passing along its history and building new relationships between itself, its owner and the stories.

Guideline 6: Using spatial, physical, temporal or relational properties can slow down interaction and trigger reflection. (Design of Physical and Digital Objects, Actions on Objects, Informational Relations and Learning Activities)

While TUIs can support a wide range of human actions, a constructivist perspective on learning suggests that both interaction with the world and reflection are required for knowledge construction. There are several strategies that can utilize spatial, physical, temporal and relational properties of TUIs to trigger "stepping out" to support reflection. First, the spatial design afforded by TUIs may enable a learner to stop to move to another location to complete an activity. For example, in *Towards Utopia*, children must take stamps off an interactive map and over to an adjacent information station to trigger an informational narrative. This slows down their stamping activity and gives them time to reflect [14]. While this conflicts with Guideline 2 (integrating spatial sources of information can minimize extraneous cognitive load), it is an informed choice that we judged worthwhile for the pedagogical purpose of supporting reflection. This is one example of how the guidelines can support informed decision making and evaluation of design tradeoffs.

Interaction can also be slowed down through the physical size of the input space or physical objects [101]. Combined with appropriate learning design features this can enable both making space for and triggering reflection. Third, systems that respond to continuous actions can be designed to temporarily pause system response to trigger learners to stop and reflect on the effects of their actions [82]. For example, in *Futura*, a collaborative, real time sustainability game, fast paced, continuous multi-touch action is paused by world events that freeze the input space and provide content that triggers reflection [9]. Fourth, TUIs can be designed to pair everyday actions or objects with unfamiliar or unexpected system responses. This may create cognitive conflict which can serve to slow down interaction. For example, Rogers and Muller report that children's reflection and engagement were facilitated in the Hunting of the Snark game by pairing familiar input actions with unexpected output responses [89]. While these strategies do not guarantee reflection, they can slow down interaction, thereby creating time in which reflection can occur. Importantly, the learning activity can be designed to frame these temporal pauses as part of the user experience in ways that trigger reflection.

4.3. Embodied Cognition: Theories of Complementary Actions, Image Schemas and Conceptual Metaphors

4.3.1. The Theory

Theories of embodiment, originating in cognitive science (e.g. [26]) and developmental psychology (e.g. [107]) are specified at a level of detail that connects behavioral activity with underlying cognitive and interactional processes and provide a theoretical grounding for conceptualizing the value of behavioral activity in constructing understanding. Because of the diverse range of behavioral opportunities that TUIs provide, embodied theories hold particular promise for informing design. This area is also largely empirically unexplored. See [11, 13] for exceptions.

There are several ways in which theories of embodied cognition can inform the design of learners' interaction and learning with tangibles [7]. First, an individual or group of individuals can improve their cognitive strategies for solving a problem by adapting the environment through complementary strategies. Complementary actions are a strategy whereby part of a mental task or operation is dynamically distributed to action in the environment [26]. Typical organizing activities include arranging the position and orientation of objects, pointing, manipulating counters, rulers or other artifacts that can encode information through manipulation. Complementary strategies involve actions that can be either pragmatic or epistemic. Epistemic actions are those actions used to change the world in some way that makes the task easier to solve. In contrast, pragmatic actions are those actions that have a primary function of bringing the individual closer to his or her physical goal (e.g. winning the game, solving the puzzle).

Another way that people learn based on their bodily interactions with the world relates to the role that image schemas play in the development of people's thinking [7]. Image schemas, as conceptualized by proponents of embodied cognition, are mental structures that are built over time from repeated patterns of experience in the world, and reciprocally, they structure our understanding of new experiences. As such, they may be enacted when learners encounter new environments or objects. For example, we develop an in-out schema based on watching and participating in repeated experiences putting objects in and out of containers (e.g. putting our thumb in and out of our mouth, watching milk be poured into a baby bottle, taking cookies out of a box). The in-out schema is later used to understand new experiences (e.g. opening a present). Image schemas formed from our interactions with the environment may also help people structure thinking. For example, Lakens et al. have shown how people use spatial distance to think and talk about the difference between concepts [60]. Spatial distance (e.g. near-far), which is a primary image schema, acts as a scaffold for the categorization process [60]. In an experiment with two response keys, Lakens et al. found that increasing the spatial distance between the two keys (and thus participant's hands) made it easier to distinguish two concepts from different categories [60].

Image schemas also form the foundation for conceptual metaphors that are used to structure abstract concepts [54]. For example, a pathway image schema is built when a young child repeatedly experiences linear (or path-like) movement toward a desired object (e.g. mother, bottle, toy). This mental structure is then used when the learner seeks to understand other contexts involving real or metaphorical paths. For example, a learner will come to understand that goals are destinations and that destinations may be achieved through metaphorical movement along a linear pathway, for example, when thinking or saying "I have almost reached my goal." In this way, people use image schemas to understand abstract concepts through unconscious, metaphorical elaboration of image schematic knowledge structures.

4.3.2. Implications for TUI Design

Guideline 7: Distributing parts of mental operations to actions on physical and/or digital objects can simplify and support mental skills. (Design of Actions on Objects and Informational Relations)

Distributing aspects of mental operations to complementary actions can improve learners' cognitive performance. This has implications for the design of the informational relations -- the mappings between action, object and digital representation. For instance, tasks that require mental visualization (e.g. perspective change, zoom, pan, scale, rotate) may be simplified through a design in which physical actions that manipulate digital representations accordingly and thus simplify the task for learners. Using a TUI magnifying glass to zoom out or in on a digital representation on a tabletop, learners can immediately see the effect of their physical actions and compare to their imagined results. In doing so, the system supports learners to complete tasks physically or mentally as their skill level or preference dictates.

Antle et al. compared children's effectiveness, efficiency and satisfaction using TUI and GUI jigsaw puzzles, coding each child's sequence of epistemic and pragmatic complementary actions on puzzle pieces [8, 13]. They found that the physical form of the TUI puzzle pieces and spatial structure of the TUI table edges afforded more instances of problem space exploration (e.g. grouping edge pieces), contributing to mental skills development. They also found a positive correlation between successful puzzle completion and the number of times pieces were handled. In a manner similar to that reported by Goldin-Meadows [41] and in line with the theory of complementary actions, the authors suggest that it is possible that simply manipulating pieces naturally and directly with the hands reduces cognitive load, freeing up resources, such as memory, for the puzzle task.

Guideline 8: Leveraging image schemas in input actions can improve usability and system learnability. (Design of Actions on Objects)

Image schemas are mental structures based on recurring patterns of experience [54]. Primary image schemas (e.g. in-out, up-down, front-back, big-small, fast-slow, balance, linear path, near-far) develop early in life and are applied to novel situations. These schemas can be used to design input actions that users will often enact, often unconsciously, or are easy to learn because they utilize familiar schematic input actions.

Antle et al. found evidence that sensing primary image schematic actions as controls for a whole body interaction environment had usability advantages, which in turn allowed both child and adult users to focus on using the system rather than learning to use the system [12]. Similarly, Bakker et al. found usability advantages of using image schematic input actions for the design of TUI sound making objects [20, 21]. For example, the fast-slow schema was determined by sampling location data of bodies [12] or objects [21] and then calculating the rate of temporal change of location. These input sequences were then mapped to sound controls. For example, moving a tangible object quickly would speed up the tempo of sound produced. Hurtienne et al also found usability benefits of using image schemas in graphical user interface design [50].

Guideline 9: Using conceptual metaphor(s) based on image schemas to structure interaction mappings may bootstrap learning of abstract concepts. (Design of Informational Relations)

Our understanding of abstract concepts is often built on metaphorical elaboration of image schemas. For example, the image schema for in-out is metaphorically elaborated to structure our understanding of the abstract emotional concept of love when we say "He was falling *in* love with her". This image schema-concept relationship has implications for the design of the informational layer in two ways. First, the metaphorical relations between image schemas and abstract concepts can be used to structure the mapping between properties of physical objects and the meanings of digital representations. For example, the physical size of TUI objects may be linked to the importance of related digital representations (image schema: small-big; metaphor: small is unimportant and big is important; linguistic examples: "Winning the cup was a *huge* achievement." and "Please leave out the *small* details."). Second, this metaphorical relationship can also be used to structure the mapping between input actions and controls of digital objects in a fashion similar that described under Guideline 8 except that the control function is metaphorically rather than directly related to the input actions. For example, moving a tangible sound making object higher (up), causes the volume of sound to increase (image schema: up-down; metaphor: up is more; linguistic example: "Turn up the volume").

Designing informational relations structured using image schema-metaphorical concept relations builds on common enactments and metaphorical interpretations and may improve understanding and learning. Holland et al. describe Harmony Space, which is an interactive environment designed to exploit spatial metaphors for harmonic concepts. An informal study suggested that this was a promising approach for teaching novices principles of tonal harmony and harmonic based on conceptual metaphors [45]. This approach may support learners to leverage unconscious knowledge in the form of image schemas in their development of conceptual understandings rather than relying on abstract representations alone to communicate meaning [7]. For example, Antle et al. found evidence that including conceptual metaphors in input action-digital control mappings had both performance and experiential benefits for users learning about musical sound parameter (e.g. volume, pitch, tempo, rhythm) [11, 12]. Bakker et al. found a similar result [19, 20]. Antle et al. also used conceptual metaphors in the mapping of input actions to meanings of digital representations in a multimedia environment about the abstract concept of balance in social justice [99]. Users balancing and unbalancing their body's centre of gravity and position in space to control the meaning depicted by digital images of balance and imbalance in social justice (schema: balance; metaphor: justice is balance; linguistic example: "The punishment *balanced* the crime"). For example, an imbalanced body position results in the display of an image showing a homeless person juxtaposed against an opulent home. In a comparative study, the authors found little usability difference between this approach and using a simple slider or dial controller, but found that participants in the metaphor-based version were more impacted by their experience [10]. Further research is required to understand how this approach may enhance learning of abstract concepts.

Abrahamson has suggested a variation on this approach in which a tangible system is used to facilitate learners enacting a specific image schema that forms the basis for a more abstract arithmetic concept [1]. The Mathematical Imagery Trainer support learners to move their hands proportionally to each other, enacting a proportion schema, in order to control different proportion (e.g. 1:2, 1:3) visually represented as coloured proportions of the screen. He suggests that by physically enacting the image schema for proportion, learners may more readily grasp the abstract concept of proportion, represented at first visually and later symbolically in the output display.

4.4. Distributed Cognition: Theories of Physically Distributed Learning and Mutual Adaptation

4.4.1. The Theory

The theory of distributed cognition was first put forward by Hutchins in the late 1980s as a means to understand cognition as a phenomenon distributed across people and the environment in which they are located [51]. Instead of conceptualizing cognition as individual information processing, the unit of analysis is broadened. Cognitive activity is conceptualized as including individuals in a specific environment interacting with technological artefacts and using both internal and external representations to conduct some cognitive activity (e.g. ship navigation). Analysis involves understanding the way that information is represented, transformed and distributed in the cognitive system. In the late 1990s this perspective on cognition was taken up in the learning sciences as useful in conceptualizing the role of educational materials in learning [44].

Schwartz and Martin have proposed the idea of mutual adaptation as part of a theory of Physically Distributed Learning to explicate how people learn through interaction with distributed artifacts [70]. Specifically, they focus on how taking physical action on artifacts enables learners to modify their thinking through modifying the spatial structure of the world in some way [95]. For example, children with a nascent understanding of division were asked to share a bag of candy with four friends. Children were allowed to restructure the environment by organizing piles of candies into various groups until a satisfactory solution was reached (i.e. four equal groups). A second group of children solved the problem using a graphical representation (i.e. drawing pictures of the candies to be shared). Children who learned through spatial reconfiguration of the actual candies were later better able to transfer their understanding of spatial groupings to symbolic representations of division problems in arithmetic. Spatial reconfiguration of the problem space enabled learners to dynamically adapt their understandings of the laws governing the problem. Schwartz and Martin provide evidence that when people adapt both their ideas and their environment in a learning task they are better able to transfer learning to new domains [95].

4.4.2. Implications for TUI Design

Guideline 10: Designing objects that allow for spatial re-configuration can enable mutual adaptation of ideas. (Design of Physical and Digital Objects)

Understanding the mechanism and benefits of spatial re-configuration has implications for how TUIs are designed. A system that only allows (through physical or digital constraints) limited object configurations may constrain learning and transfer. If the goal is a single, particular interpretation, this approach may be beneficial. However, a system that allows multiple configurations supports learners to have the flexibility to use objects to explore and experiment in the world. In this case learners can engage in a process of sense-making to develop robust interpretations that have a greater chance to be useful in new domains [94]. For example, in the *Towards Utopia* TUI system, by using physical stamps children can change the number, location and configuration of land use activities. Digital images are used to provide feedback that encourages children to check results of each configuration until a satisfactory solution is reached [14]. Through reconfiguration that results in responsive digital feedback they can test out and adapt their ideas about the impact of land use activities on the final land state. The goal is adaptation of their ideas rather than finding a single correct end state.

Manches et al. studied the effect of allowing young children to re-configure both digital and physical representations in number tasks that involved moving individual or multiple objects [63]. They found that different representational styles (and spatial properties) influenced the adaptation of ideas, suggesting that in TUI design it is important to understand how opportunities and constraints on spatial re-configuration foster adaptation of the ideas we want learners to grasp. They suggest a strategy in which scaffolding can be used to encourage certain actions during the task (rather than at the end of the task as above). For tangible math blocks, the physicality of the objects enables spatial grouping and digital effects can be used to encourage certain actions. For example, a set of tangible blocks can be designed to help young children learn simple division. To encourage children to move half the blocks to enact division of the group into two groups, half of the group of blocks can light up [62]. Spatial reconfiguration prompted by supportive digital scaffolding during the task encourages children to enact division. As students gain proficiency at division, the scaffolding can eventually be faded (blocks only light up initially or only on demand) until the students can perform the task without the support.

4.5. Theories of Computer-Supported Collaborative Learning: Shared Attention and Positive Interdependence

4.5.1. The Theory

Theories of computer-supported collaborative learning (CSCL) [29, 58, 61, 76, 100] have much to offer TUI designers in conceptualizing how to design for multiple users in learning contexts. In the CSCL literature, collaboration is commonly defined as “a process in which individuals negotiate and share meanings” and “a coordinated, synchronous activity that is the result of a continued attempt to construct and maintain a shared conception of a problem” ([91] p. 70). Collaboration differs from cooperative activities. In the latter learners may coordinate their efforts in that the work performed is primarily individual, for example a divide-and-conquer strategy [30]. To support collaboration (rather than cooperation) it is important that learners have a shared focus around which negotiation can occur; that is, they need to be effectively supported in jointly attending to what each other are doing to ground the collaboration [27, 113]. For example, Suthers et al. found that pairs collaboratively solving science challenge problems in a digital space whose discussion tool was integrated with a visual representation of the concepts were more likely to reach the same conclusion than those whose discussion tool was in a separate space from the visual representation [103]. In addition, learners need to have a reason to negotiate with each other. True collaborative tasks create positive interdependence (for example in knowledge, tools, skills) among learners, requiring the coordinated activity of multiple people for success [59]. One way this is often instantiated in CSCL is through variations on the "jigsaw" script [15] in which each student only has access to part of the information (i.e. one piece of the puzzle) needed to solve a collaborative task [74]. However, Dillenbourg also warns of the dangers of over-scripting, and highlights the importance of clearly conceptualizing the mechanism(s) through which constraints on collaboration are expected to positively influence learning interactions [31].

Implications for TUI Design

Guideline 11: Creating configurations in which participants can monitor each other's activity and gaze can support the development of shared understandings. (Design of Physical and Digital Objects)

An important precursor to collaboration is shared attention; learners cannot meaningfully negotiate and develop common understandings if they are not attending to what each other are doing. The spatial properties of tangibles can be used to support shared attention by creating central, configurable locations for using the objects in 3D space. This encourages learners to locate themselves around a TUI in ways that afford visual access to each other and the computational artifacts, and supports better awareness of what others are doing than if learners were all on the same side of a table or a 2D display. The value of making actions visible and gaze observable in supporting collaborative meaning-making is well documented [37, 47, 104]. When learners monitor what others are doing and what aspects of the system they are attending to, they may become intrigued and decide to coordinate their efforts with another learner. Alternatively, they may notice differences in what others are doing and initiate negotiation to restore a shared understanding of the collective activity. In either case, the presence of artifacts in a shared transaction space [47] grounds the interaction by providing a referential anchor for conversation, which can be referred to by using both verbal and gestural communication channels [102, 104]. Fernaeus and Tholander provide some empirical evidence for this in a floor-and-wall TUI programming environment for children [36]. They reported that the spatial configuration afforded shared meaning making through visual access to each others' actions and locations. This in turn supported dynamic formation of subgroups, and interaction within subgroups, which fluently formed and un-formed as children collaborated on the different activities required to complete their goal.

Guideline 12: Distributing roles, information and controls across the TUI learning environment can promote negotiation and collaboration. (Design of Physical Objects and Learning Activity)

A powerful way to create positive interdependence in a collaborative learning situation is by distributing information, skills, roles, or tools among learners such that they are required to work together to be successful. [53]. This is often referred to as a "jigsaw" approach and is an example of a collaboration script or a pedagogical strategy that constrains or guides the ways in which learners collaborate [32]. In TUI systems a jigsaw script can be dually enacted through the design of both the tangible objects and the learning activity instructions. Specifically, different learners are given different sets of instructions and TUI controls to use in the activity. Marshall et al. suggest that children are more able to maintain control of tangible objects than digital ones accessed through a multi-touch tabletop [67]. This suggests a strategy of using spatial design to support private usage of physical objects and using movable digital representations for objects that are to be shared.

For example, in a tangible version of *Futura*, a digital tabletop sustainability game, learners are assigned different responsibilities (e.g. shelter, food, power) related to environmental preservation and development [9]. Each role is associated with a side of the table that gives the learner access to unique (role-specific) digital and physical objects and controls; for example, only the learner responsible for shelter can access the tools to place condos, houses and apartments on the map interface. Common objects and controls are located in the middle within the reach of all. In order to support a growing population base with enough food, energy and shelter without seriously damaging the environment, learners in the different roles need to coordinate their actions in a coherent strategy, which requires them to negotiate and collaborate.

Guideline 13: Creating constrained or co-dependent access point schemes can compel learners to negotiate with each other. (Design of Actions on Objects)

Positive interdependence is a powerful way to create a need for learners to negotiate with each other. Constrained or co-dependent access points is another way to create positive interdependence among learners using a TUI system. Access points in a TUI system are characteristics that enable the user to interact, to participate and join a group's activity [48]. While TUIs afford multi-manual input systems and thus allow several learners to actively use the system at the same time, previous non-TUI research has shown that this often results in a non-collaborative situation of parallel play [52]. This challenges whether a key feature of TUIs (the ability to have multiple simultaneous users) does in fact provide a benefit for learning with respect to collaboration.

In contrast, a constrained input system (e.g. limited number of access points) can require sharing and coordination [47], though a limited number of access point can also lead to competitive behaviors [67]. In a study comparing physical and multi-touch objects for a collaborative task, Marshall et al. found that children used more assertive and aggressive strategies in the multi-touch group because it is more difficult to protect and assert ownership over digital objects than physical objects [67]. This finding was mirrored in a study comparing tangible and multi-touch tools for a collaborative game [99]. Participants asserted ownership over tangible tools by picking them up and holding them close to their bodies. As a result, for another participant to use a tool required negotiation, which may or may not be successful depending the motivation to work together. This highlights the importance of designing sharable access points and objects in tandem with learning activities that either reward or enforce collaboration.

An intriguing third alternative for using TUIs to support negotiation is to design a multi-manual system in which the inputs are co-dependent; that is while they are sensed individually, the system responds to them collectively. Thus multiple learners each need to take a specific action in order for the system to respond in the desired way. For example in an adaptation to the role division in *Futura* described above, new housing could only be built if both the learners responsible for shelter and power used their unique tools (to create condos and powerlines) at the same time. This strategy creates a situation of positive interdependence that has the potential for supporting collaboration since it requires the coordinated action of more than one person to enact a strategy. Learners must negotiate and reconcile what they want to achieve to succeed. However, studies of interaction with multi-user tabletops in the field have suggested that even coherent groups of users may not immediately work together on collaborative applications [68]. Therefore, for this strategy to be successful, learners must begin the task together. This can be enacted through application design that requires all learners to interact to begin, or through learning activity design facilitated by a teacher or instructional materials.

This approach has already been instantiated with positive results in a non-tangible interface. The Separate Control of Shared Space (SCOSS) system gives each of a pair of learners independent mouse control over a representation of a task on half of a computer screen, but requires them to agree on their answer before they proceed [55]. In contrast to a dual-mouse, single-representation version, learning using SCOSS engaged in more rationale-based discussion and negotiation of their ideas throughout the task.

4.6. Summary of TUI Learning Design Guidelines

The previous section detailed thirteen guidelines to inform the design of the five interrelated elements of TUI learning environments. The guidelines are all grounded in theories of cognition and learning; in some cases the concepts and mechanisms they describe have been empirically validated for TUIs or in similar contexts. In other cases, more research is needed to probe the details of how a particular theory will apply to interaction with TUIs. We envision the design guidelines to be utilized in several complementary ways. In cases when they are grounded in empirical evidence, they can be used prescriptively by design practitioners to make theoretically informed choices, inform design tradeoffs, and provide evaluation constructs and measures. When empirical evidence is lacking or weak, they can be used by researchers to formulate research and generate testable hypotheses related to learning and interaction benefits of TUI designs. While the collection of guidelines does not cover every aspect of TUI design, as a set they provide a foundation to guide principled design and research of TUIs for learning. We encourage other researchers to test and probe these guidelines in empirical settings as well as bring other theories to bear to help refine and expand the set. In the following section we present just some of the many promising directions we see for future research.

5. Research Implications of the Tangible Learning Design Framework

Our analysis of the details of different theories of cognition and learning produced guidelines that can inform TUI learning design. Our analysis also revealed areas where more research is needed. This is either because the theory has not been explored in the context of TUI (i.e. hybrid digital-physical environments) that have unique affordances, or because the research findings are controversial. For example, we have identified areas where differing perspectives on learning result in conflicting guidelines. These conflicts provide rich opportunities for further research. We present a summary of five important potential research topics with the aim of supporting researchers to continue to explore the theoretical aspects of learner-tangible-interaction in areas that will have impact on TUI learning design.

Research Question 1: Are multimodal haptic and tactile interactions with TUIs beneficial, detrimental or zero sum gain?

Since haptic and tactile sensory information are thought to be processed in the visual-spatial sketchpad, a cognitive load perspective on multi-modal processing would suggest that there is no additional benefit (i.e. efficiency in terms of distributing cognitive load) in utilizing the tactile qualities of TUIs. However, an embodied perspective on cognition would suggest that all information is not equivalent and that representing information haptically or tactilely may trigger different image schemas or other sensory-motor processes that may result in a different quality of understanding. This may also differ depending on the learning task. These conjectures can be explored through controlled experiments with various learning topics where the independent variable relates to the inclusion of haptic or tactile information and the learning measures capture both efficiency and the quality of understanding and learning.

Research Question 2: Does using multiple channels and different spatial locations of sounds (e.g. ambient and embedded) hinder learning?

Cognitive Load Theory suggests that having multiple channels of sounds, for example, ambient surround sound and specific sounds embedded in individual tangible objects, will cause extraneous cognitive load, negatively impacting information processing. Similarly, embedding sounds in objects may add an unnecessary cognitive burden in identifying the source of the sound (unless this process itself is central to the learning goal). These conjectures are extensions from research done in single channel audio environments and need to be explored in the TUI context. Situations can also be created in which sound design is done to support specific learning outcomes, and immediate and longer term learning outcomes are assessed for different sound design strategies.

Research Question 3: How do different structural relations between input objects and output responses differ in their support for simplifying and supporting difficult mental operations?

The theory of complementary actions suggests that distributing difficult mental operations to closely coupled mental-physical strategies can allow learners to successfully complete challenging tasks, and in doing so develop mental abilities. The implementation of this strategy requires design decisions about the structural properties of informational mappings. For example, we need guidelines to choose how to design the links between physical objects and the digital objects they control, including choices about spatial nature of the mapping (e.g. proximate vs distal), the cardinality of mapping (e.g. one-to-one, one-to-many) and the temporal nature of the mapping (e.g. static, dynamic). We require further investigations of how best to design these mappings for specific situations. For example, Antle et al. compared children's performance solving TUI and GUI jigsaw puzzles. In the TUI version, each individual physical puzzle piece is used to control the corresponding digital puzzle piece (one-to-one, proximal, static mapping). In the GUI version, a single object (i.e. mouse) is used to acquire and manipulate all the digital puzzle pieces (one-to-many, distal, dynamic mapping). They found that the TUI design supported better performance and may enabled users to improve their mental visualization skills [13]. This finding warrants further exploration to understand what features of the physical-digital object mappings led to enhanced performance. We need guidelines for how to choose from different options for structuring the information relations between physical and digital objects and functions.

Research Question 4: Do embodied metaphor-based interaction models improve learning outcomes related to understanding and reasoning about abstract concepts?

Conceptual metaphor theory suggests that people unconsciously structure new, abstract concepts, and reason about them, utilizing existing image schemas. This process unfolds with development and learning. What remains uncertain is: (a) if these conceptual metaphors can be reliably deconstructed to reveal the image schema that structures the conceptual understanding; (b) if manipulation of digital representations can be used to support reasoning about abstract concepts; and (c) if explicitly including this metaphorical relationship in the structure of the mappings is beneficial to learning. It may be that only a small percentage of abstract concepts can be deconstructed and incorporated in ways that benefit learning. It may also be that other factors or processes involved in conceptual learning and development may influence or negate these possible benefits. These are important questions because they drive to the heart of one of the major potential advantages of TUIs for learning – the use of concrete objects to scaffold the development of abstract concepts.

Research Question 5: Do co-dependent multiple access points support productive negotiation and collaborative behaviors between learners?

The multiple access potential of TUIs may be designed to support multiple users interacting simultaneously. However, to avoid parallel independent play, learning designs can require either simultaneous or accumulation of multiple actions to trigger digital events. This can support collaborative activity since the coordinated action of more than one learner is needed to successfully enact a strategy. Research is needed to determine when such an approach influences interactions between learners (e.g. when do co-dependent access points support learners in productively negotiating with each other around what they want to achieve?), and if such interactions provide benefits to learning.

6. Conclusions

Augmented objects and environments with embedded computational controls and representations provide novel and unique interactional possibilities that can be beneficial to learning. Hybrid physical-digital user interfaces such as TUIs may be designed to facilitate specific cognitive, constructivist, embodied, distributed and social processes and mechanisms that are supportive of learning. This paper presents the Tangible Learning Design Framework, which includes a taxonomy of important elements of design and an initial set of guidelines generated from cognitive and learning theories to guide design decisions about these elements. The guidelines are associated with the design elements that they inform (see Table 1). There are more potential guidelines than space allows. However, the goal of this paper is not to be comprehensive but to present the framework and demonstrate its explanatory power. The framework also serves a generative role by suggesting research questions. We expect that as more research is conducted the guidelines will be refined and expanded and we hope other researchers will join us in this effort to push towards greater specificity in theoretically-grounded and empirically tested TUI learning design guidance.

Acknowledgements

We gratefully thank the reviewers for their valuable feedback. This project was supported, in part, by funding from SSHRC and the GRAND NCE.

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