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ORIGINAL ARTICLE

Situated play in a tangible interface and adaptive audio museum guide

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Abstract This paper explores the design issues of situated play within a museum through the study of a museum guide prototype that integrates a tangible interface, audio display, and adaptive modeling. We discuss our use of design ethnography in order to situate our interaction and to investigate the *liminal* and *engagement* qualities of a museum visit. The paper provides an overview of our case study and analysis of our user evaluation. We discuss the implications including degrees of balance in the experience design of play in interaction; the challenge in developing a discovery-based information model, and the need for a better understanding of the contextual aspects of tangible user interfaces (TUIs). We conclude that learning effectiveness and functionality can be balanced productively with playful interaction through an adaptive audio and TUI if designers balance the engagement between play and the environment, and the space between imagination and interpretation that links the audio content to the artifacts.

1 Introduction

In our adult lives play is an experience set apart from our everyday activities: Huizinga referred to play as invoking a *magic circle*, a liminal space for games [1]; Carse describes *deep play* as a profound level of ritualized engagement causing reflection on everyday experiences [2]; and psychologist Csikszentmihalyi has described *flow* as a high level of engagement, risk and challenge found in play and ritualized in sport [3]. Do we play in museums? Art historian Carol Duncan sees the museum as a ‘‘stage’’ that encourages visitors to perform rituals that are not part of their daily life [4]. Anthropologist Genevieve Bell extends this notion of extraordinary ritualized play together with learning. She describes museums as different *cultural ecologies* in which the museum visit has the qualities of *liminality* (a space and time set apart from everyday life) and *engagement* (where visitors interact to both learn and play) [5].

Guided by the notion of play in a museum experience we have considered playfulness equally with functionality and learning in the design of an adaptive museum guide. Our approach includes a tangible user interface (TUI) for its inherent playfulness and poetic simplicity, spatial audio display for the diversity of human voice and its imaginative qualities, and an integrated user modeling technique combined with semantic technologies that support exploration and discovery. We understood our interface as playful action along the lines of aesthetic interaction. By this we do not mean the type of structured play that is found in a software game on a mobile device, rather we refer to the less structured and open play that is always possible and often can be subtle and implicit like toying with a ball.

Furthermore, we aimed for our design to be situated within the setting we were designing that is to design an interface and interaction that *felt* a part of the museum.

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Toward this end we adopted the idea of museums as ecology informed by Bell's *cultural ecologies* and Nardi's and O'Day's *information ecology* [8, 42]. Bell sees museum visits as determined by the ecological interplay of space, people and design. Nardi and O'Day view organizations as organic relationships among people, practices, technology, values and locale. We utilized ecologies to situate our design and frame it ethnographically and theoretically. This approach led to us being inspired by simple physical displays and puzzles we observed in our ethnographic sessions. These observations encouraged the playful tangible object and use of puzzles in our audio content. We were also motivated by the storytelling of the museum staff and researchers that was often humorous as well as informative. We found the ecologies analytically essential in understanding how we were situating play, our interaction, and technology within the museum.

We provide here an account of the reasons and rationale of our design concept and the approach of our case-study known as *ec(h)o*. In the paper, we discuss related research to our case study followed by a discussion of our design motivations, our ecology informed design ethnography and resulting design implications. We then describe the case study, which we installed and tested at Canadian Museum of Nature in Ottawa, and analyse the TUI and aesthetic interaction aspects of our interface. We provide an overview and analysis of our evaluation and a discussion of lessons learned including several issues relevant to ubiquitous computing: the experience design of play in interaction; the balance in developing information models; and the need for a better understanding of the contextual aspects of TUIs. We conclude that based on our results of our pilot study, learning effectiveness and functionality can be balanced productively with playful interaction through an adaptive audio and TUI if designers balance the engagement between play and the environment, and the space between imagination and interpretation that links the audio content to the artifacts.

2 Relevant research

Bedersen [6] was among the first to develop an electronic museum guide prototype supporting visitor-driven interaction by utilizing portable mini-disc players and an infra-red system to allow museum visitors to explore at their own pace and sequence. Today interactive museum guides have reached significantly higher level of functionality including visitor-driven interaction, media rich delivery, context-awareness and adaptivity. We aim in our prototype system, ec(h)o to maintain a standard level of functionality with the exception of media rich delivery. While we sacrificed the ability to deliver diverse types of media we gained the opportunity to move away from a graphical user interface (GUI) and the personal digital assistant (PDA) in the hopes of creating a more playful and aesthetic interaction through a physical and embodied interface. We were also able to simplify our content approach and focus on the potential of audio to create imaginative and ludic possibilities. However, we do see possible future implementations that include images, video and dynamic text information within our TUI approach through the use of distributed visual displays within the exhibition spaces.

Previous work most relevant to our case study includes museum guide systems that utilize an adaptive approach, GUI and PDA interfaces in museum guides, and a discussion of work outside of the museum domain that utilizes audio interfaces in ubiquitous and mobile computing contexts. Equally important to our discussion are the *ludic* qualities of TUIs, and related ideas of aesthetics and play in interaction.

2.1 Adaptive museum guide systems and audio display

Adaptation and personalization approaches have been successfully applied to museums in the context of the World Wide Web [7, 8] and in handheld museum guides. ec(h)o shares many adaptive characteristics with the systems of HyperAudio, HIPS and Hippie [9–11]. Similar to ec(h)o, the systems respond to user's location and explicit user actions through the interface. HyperAudio uses a static user model set by a questionnaire completed by the visitor at start-up time and HIPS and Hippie can infer the user model dynamically from the interaction but they treat user interests as static. All systems adapt content to the user model, location and interaction history. Among the main differences with ec(h)o is that these systems depend on a PDA GUI, ec(h)o uses audio display as the only delivery channel and a tangible object as an input device. Another difference lies in how the system generates response: ec(h)o uses inference at the level of semantic descriptions of independent audio objects and exhibit. ec(h)o extends the work of the Alfaro et al. [12] by building a rich model of the concepts represented by the audio objects while HyperAudio and HIPS use partly pre-configured annotated multimedia data [13], and Hippie uses a simpler domain model. The last main difference is that ec(h)o treats user interests as dynamic, we look to evolving interests as a measure of sustainable interaction and go one step further by ensuring a high degree of diversity of interests is available. These differences exist in order to create an experience of discovery in which visitor's are given the latitude to explore new and previously unconsidered related topics of interests.

Prior to the evolution of adaptive and user modeling approaches in museum guide systems, there had been a strong trajectory of use of the PDA GUI. Typically, hypertext is combined with images, video and audio [14–17]. A good example of this is the *MEG* system [18]. It was created for the Experience Music Project in Seattle. It allows visitors 20 h of audio and video on demand. Visitors make their selections either by use of the keyboard within the PDA device or by pointing the device at transmitters located adjacent to artifacts. For further interaction with the information, visitors are dependent on the GUI, which is a typical browser and hierarchical menu format. There are clear functionality advantages in the PDA GUI approach including the organization and accessibility of large amounts of data, a user interface that is familiar since it resembles a personal computer (PC), multimodal input from pointing to text to voice, and multimedia delivery. Yet researchers such as Hans Tap have identified a tension in relationships between computer systems that rely on desktop computers as the basis for interaction and the artifacts, physical environment and everyday activities of most people [19]. He uses the term *desktop gravitation* to describe how desktop computers force people to move to the desk to carry out their work. We ask the question whether we should carry around our desks in order to experience such things as museums—in what might be described as a *world-behind-a-desk* approach to mobile computing? Furthermore, a PDA is essentially a productivity tool for business, not a device that lends itself easily to playful interaction.

Aoki and Woodruff [14] have argued that in interactive guidebooks, designers are challenged to find the balance between burdening the visitor with the functions of selection, information management and contextualization. The PDA GUI approach comes at a cognitive and experiential cost. It requires the full visual attention of the visitor such that it becomes a competing element with the physical environment rather than a valued and integrated addition to that environment. Museum systems have mostly maintained the PDA GUI approach despite the shifts in other domains to other approaches that better address the experience design issues most prominent in social, cultural and leisure activities. The play constraints of these devices are too great for the level of interaction that goes beyond playing a software game on a mobile device. For example, in the area of games and ubiquitous computing, Björk and his colleagues have identified the need to develop past end-user devices such as mobile phones, PDAs and game consoles [20]. They argue that we need to better understand how ‘‘computational services’’ augment games situated in real environments. The same can be said for museum visits.

Non-visual interfaces, particularly audio display interfaces have been shown to be effective in improving interaction and integration within existing physical contexts. For example, Brewster and Pirhonen [21, 22] have explored the combination of gesture and audio display that allows for complicated interaction with mobile devices while people are in motion. The *Audio Aura* project [23] explores how to better connect human activity in the physical world with virtual information through use of audio display. Audio is seen as an immersive display that can enrich the physical world and human activity while being more integrated with the surrounding environment. In addition, audio tends to create interpretive space or *room for imagination* as many have claimed radio affords over television. In the HIPS project, different voices and delivery styles were used to create an ‘‘empathetic effect’’ between the user and the artifacts they engaged [24]. We have adopted a similar approach to our use of audio content. Audio augmented reality systems combined with TUIs often create very playful and resonant interaction experiences [25]. In fact, the distinction between augmented reality and TUIs can be blurry indeed [26].

2.2 The poetics and play of TUIs

Tangible user interfaces like no other user interface concept is inherently playful, imaginative and poetic. In addition, the concept has *immediacy* due to its physicality. Ishii's and Ullmer's notion of *coupling bits and atoms* was informed by earlier work in graspable interfaces [27] and real-world interface props [28]. ec(h)o's TUI draws on this notion by coupling an everyday and graspable object, a wooden cube with digital navigation and information. Ishii was inspired by the aesthetics and rich affordances of scientific instruments [26] and the transparency of a well-worn ping-pong paddle [29]. Simple physical display devices and wooden puzzles at the natural history museum where we conducted ethnography sessions inspired us as well.

In 1992, Bishop's Marble Answering Machine [30] was an early embodiment of the immediate and playful qualities of TUIs. The prototype uses marbles to represent messages on the machine. A person replays the message by picking up the marble and placing it in an indentation in the machine. Jerimijenko's Live Wire is a strikingly minimal and whimsically simple demonstration of digital bits transformed into physical atoms [31]. Jeremijenko dangled a plastic wire from a motor attached to the ceiling. The motor accelerates or decelerates based on traffic across the Ethernet network. Ishii's PingPongPlus [29] explores the intertwining of athletic play with imaginative play. The ping-pong table becomes an interactive surface, the ball movement is tracked and projections on the table of water ripples, moving spots, and schools of fish among other images react to where the ball hits the table. ambientROOM [26] is a collection of tangible interfaces integrated in an office environment in order to enhance and exploit the user's peripheral awareness, for example a *phicon* (physical icon) moves and rotates on a desk mirroring the actions of a nearby hamster. More recent work, such as Andersen's Clownsparkles [32], engage children explicitly in exploratory play and emergent learning through sensor-augmented everyday objects (dresses, hats, costumes, and purses) and audio display. The work explores the role of TUIs in an open-ended game of children's dress-up. Andersen's work reveals how theatrical settings provide an *emotional framework* that scaffolds the qualitative experience of the interaction. While ec(h)o is more constrained in its play, the everyday wooden cube provides such a scaffold to a physically playful experience of interaction.

2.3 Aesthetics of interaction

Researchers in human–computer interaction (HCI) have recently explored beyond the goals of usefulness and usability to include enjoyment [33], emotions [34, 35], ambiguity [36], and ludic design [37]. Nowhere is this need more evident than in the richly interpretive and social environments of museums [24, 38]. Our emphasis is on the qualities of interaction that result in play that facilitates discovery. While we address this on an informational level in regard to our use of audio content and information retrieval, we aimed to equally explore the embodied and situated aspects of interaction or aesthetic interaction as expressed by Djajadiningrat [39] and Petersen [40].

Djajadiningrat argues for a ''perceptual-motor-centered'' approach to tangible interfaces [39]. He is less sympathetic toward the cognitive view of interaction in what he terms the ''semantic approach'' where objects communicate action through metaphor. Rather, he argues for a ''direct approach'' for its ''sensory richness and action-potential'' of the objects to carry meaning through interaction. He describes this notion of meaning in interaction as *aesthetics of interaction* whereby the ''beauty of interaction'' as opposed to the beauty of the artifact or interface, tempt the user to engage as well as ''persevere'' in their engagement [39]. He describes three factors as having a role in aesthetic interaction: the *interaction pattern* of timing, rhythm, and flow between the user and the object; the *richness of motor actions* found in the potential space of actions and skill development; and *freedom of interaction* in which a myriad of interaction paths coexist.

Petersen et al. [40] description of aesthetic interaction shares the embodied aspects described above as well as the sense of aesthetic potential that is realized through the action or engagement. They bring to the concept the philosophical view of Pragmatism that aims to situate aesthetic interaction within everyday experiences and the surrounding environment. For example, Petersen developed a playful interaction approach as part of the WorkSPACE project [41] utilizing a ball that is thrown against a floor projection of documents and work materials as a way of manipulating and exploring the information. Inherent to the ball are kinesthetic challenges, affordances and the situated relationship with the environment. These aspects are realized in action with the object. The aim of the interaction approach is to create new views of the work material through the playful actions of aiming, throwing and bouncing.

3 Design motivations

We were strongly influenced by the awareness of museums as complex and dynamic spaces. Vom Lehn et al. [42] describe museum experiences as *multivariate* that is they cannot be assessed by a single factor such as exhibit design, signage, or time spent in front of an artifact. Instead, the museum experience is subject to multiple influences and results in multiple outcomes. Given this understanding, we endeavored to consider how our design both *intervenes* in and *integrates* with the complex museum experience. The ecological models of *cultural ecologies* and *information ecologies* provided us with frameworks for contextual analysis. This approach allowed us to look further into the design process past the interface for guidance into how our design decisions were integral to the ecology or ecology inhabitants, thus supporting us in developing more appropriate design responses. We provide here a summary of the ecological concepts and a discussion of their use in our ethnographic sessions. For further discussion of the role of ecologies in museums we refer readers to [43].

3.1 Museums as ecologies

Bell sees the museum visit as a ritual determined by space, people and design [5]. She decomposes the visiting ritual into three observational categories: space, visitors, and interactions and rituals. Different types of museums have different ecologies, for example Bell describes different attributes in each of the observational categories between art museums and science museums. These ecologies are seen to be distinct and supportive of very different kinds of museum visits. Bell also describes interaction concepts that are common to all museum ecologies. We have drawn on two of these concepts in developing our approach, *liminality* and *engagement*:

- *Liminality* defines museums as places that embody an experience apart from everyday life. Positive museum experiences are transformative, spiritual, and even moving. A museum visitor should be inclined to pause and reflect, thus liminality can be seen to permit a deeper engagement.
- *Engagement* is a key concept for museums as people go to museums to learn, however this engagement is often packaged in an entertaining way; museums are a balance between learning and entertainment spaces.

Nardi and O'Day draw on activity theory [44, 45] and field studies to develop their concept of *information ecologies*. The concept they describe strives for a more systematic view of organizations based on the relationships among people, practices, technology, values and locale. For example, a library is an ecology for accessing information. It is a space with books, magazines, tapes, films, computers, databases and librarians *organically* organized to find information. Nardi and O'Day utilize the concept of ecology in order to depict the complex relationship among elements and influences of which technology is only one part. Constituent elements of information ecologies include a *system*, *diversity*, *co-evolution*, *locality*, and *keystone species*. Two of these elements were essential in supporting our design:

- *Locality* can be described as participants within the ecology giving identity and a place for things. For example, the *habitation* of technology provides us with a set of relationships within the ecology, to whom a machine belongs determines the family of relationships connected to the technology. In addition, we all have special knowledge about our own local ecologies that is inaccessible to anyone outside thus giving us local influence on change.
- *Keystone species* are present in healthy ecologies; their presence is critical to the survival of the ecology itself. Often such species take the role of mediators who bridge institutional boundaries and translate across disciplines. For example, introduction of new technologies in an ecology is often reliant on mediators who shape tools to fit local circumstances.

3.2 Design implications of our design ethnography

Our observations that fall within Bell's categorization of *interaction and ritual* emphasized that our system should be open to multiple forms of input such as movement and physical interaction with the displays, and responsive to different learning styles. In many respects, our prototype became a virtual extension of the exhibition space and acted as an augmentation to the physical interactives and other learning materials.

The displays and installations revealed diverse forms of interaction: microscopes with adjustable slide wheels that could be turned to explore different specimens; wooden puzzles which, once completed, would fall apart at the pull of a handle, creating a loud crashing sound that captured the attention of others (see Fig. 1); a collecting game called *The Rat Pack Challenge* which tasked visitors to search the room and discern collectable artifacts from non-collectable ones; discovery drawers filled with objects like fossils, fur pelts, and minerals which visitors could touch and inspect at close range (see Fig. 2); push button audio and video installations; scale models and artist recreations of

Fig. 1 A wooden puzzle interactive in the *Finders Keepers* exhibition

Fig. 2 A discovery drawer in the *Finders Keepers* exhibition

dinosaurs that people could walk up to and touch; terrariums and aquariums filled with living specimens; magazines, coloring books, and a small library of natural history artifacts that were lent to students.

Bell notes that an attribute of science museum ecologies is to support the fact that people learn in a variety of ways. Alternative approaches to learning turned up throughout our observations, such as the interactive puzzles, quizzes, and games that require visitors to explore and think about the artifacts being displayed.

The design implication here is that the observed activities support a highly tactile approach that includes holding, manipulating and being highly interactive with your hands. A TUI would situate itself well among these puzzles, games and physical displays. Another design implication is the use of puzzles and riddles as modes of interaction and content delivery. Visitors are not spoon-fed factual information in the form of didactics, rather they engage in play and discovery to learn about the artifacts and the broader concepts that tie the artifacts together thematically.

Nardi's and O'day's *information ecology* also guided design decisions. For example, the stories and information we heard in our interactions with staff and researchers at the museum were examples of the ecology concepts, *locality* and *keystone species*. This led to a novel approach to content design and development we have described in detail in another paper [46]. We observed numerous informal yet engaging delivery of specialized knowledge on behalf of the museum researchers. The majority of these types of exchanges happened as we toured the collections and storage facility. Stories connected to artifacts ranged from anecdotes on where the artifact was found and how cold it was at the time or how difficult the terrain was, stories of the difficulties of mold-making on site or humorous tales of transportation and objects temporarily getting lost, to what the objects tell us or how their meaning has changed. Often these were first hand accounts and discussed in the most informal and wide-ranging manner. Factual or thesis driven accounts of artifacts were mixed with anecdotal and humorous tales related to the discovery, processing or research of the actual artifact. This experience deeply struck us since our shared perception of the public exhibition display space was quite the opposite. Not unlike many exhibitions, the artifacts and contextualizing information appeared static and lifeless, the puzzles and games notwithstanding. In *locality* terms, it was evident to us that once the artifacts were connected to people, the understanding of these artifacts became deeply connected to all aspects of the ecology and came out in the form of storytelling that covered activities related to the artifact, conservation, storage, research and display technologies, meaning and values associated with the artifacts.

A resulting design outcome was to bring this degree of liveliness to the artifacts on display. We aimed to model our information delivery and audio experience on the informal storytelling we had experienced. We aimed to create a virtual cocktail party of natural history scientists that accompanied the visitor through the museum.

For our purposes, both ecological frameworks served our goals despite their strong differences. Bell's *cultural ecologies* formally linked different actions and attributes of the museum visitor into a coherent description. As a descriptive tool it validated our assumptions and provided a clearer link between what we observed and the design implications. It was therefore generative much like Nardi and O'Day's *information ecologies* framework. Both guided us in specific design decisions, namely the high degree of physical interaction that suggested a TUI; the wide use of puzzles, riddles and games as modes of learning which led to our use of a riddle-like approach to our audio content; and the localized and informal storytelling on behalf of the museum staff and researchers that inspired us to structure our audio experience like a virtual cocktail party. As we set out to approach an adaptive museum guide from an experience design perspective, we explored situated play in the museum and uncovered specific qualities of *liminality* and *engagement* rooted in the museum within which we were designing.

4 Case study

The design motivations and ethnography findings led us to a design that was minimal, playful and supported exploration. Our approach includes a TUI for its inherent playfulness and poetic simplicity, spatial audio display for the potential diversity of human voice and its imaginative qualities, and an integrated user modeling technique combined with semantic technologies that supported exploration. Our aim is to improve the visitor engagement by considering playfulness equally with functionality and learning. We adopted what can be described as a rich and discovery-based approach to interaction. While arguably other interface approaches could have been utilized in conjunction with the integrated modeling technique, such as a simple push-button device for input or a mobile text display device for output, such a strategy would be incongruent with our experience design goals.

4.1 Visitor scenario

In order to better understand the system we developed, we describe below a typical visitor scenario. The scenario refers to an exhibition about the history and practice of collecting natural history artifacts:

Visitors to the Finders Keepers exhibition can use the ec(h)o system as an interactive guide to the exhibition. Visitors using ec(h)o begin by choosing three cards from a set of cards displayed on a table. Each card describes a concept of interest related to the exhibition. The cards include topics such as ''aesthetics'', ''parasites'', ''scientific technique'' and ''diversity''. A visitor chooses the cards ''collecting things,'' ''bigness,'' and ''fauna biology.'' She gives the cards to an attendant who then gives the visitor a wooden cube that has three colored sides, a rounded bottom for resting on her palm and a wrist leash so the cube can hang from her wrist without her holding it. She is also given a pair of headphones connected to a small, light pouch to be slung over her shoulder. The pouch contains a wireless receiver for audio and a digital tag for position tracking.

Our visitor moves through the exhibition space. Her movement creates her own dynamic soundscape of ambient sounds. As she passes a collection of animal bones she hears sounds that suggest the animal's habitat. The immersive ambient sounds provide an audio context for the collection of objects nearby.

As she comes closer to a display exhibiting several artifacts from an archaeological site of the Siglit people, the soundscape fades quietly and the visitor is presented with three audio prefaces in sequence. The first is heard on her left side in a female voice that is jokingly chastising: ''Don't chew on that bone!'' This is followed by a brief pause and then a second preface is heard in the center in a young male voice that excitedly exclaims: ''Talk about a varied diet!'' Lastly, a third preface is heard on her right side in a matter-of-fact young female voice: ''First dump...then organize.'' The audio prefaces are like teasers that correspond to audio objects of greater informational depth.

The visitor chooses the audio preface on the left by holding up the wooden cube in her hand and rotating it to the left. This gesture selects and activates an audio object and she hears a chime confirming the selection. The audio object is linked to the audio preface of the scolding voice warning against chewing on a bone. The corresponding audio object delivered in the same female voice yet in a relaxed tone, is about the degree of tool making on the part of the Siglit people: ''Artifact #13 speaks to the active tool making. Here you can actually see the marks from the knives where the bone has been cut. Other indicators include chew marks...experts are generally able to distinguish between rodent chew marks and carnivore chew marks.''

After listening to the audio object, the visitor is presented with a new and related audio preface on her left, and the same prefaces are heard again in the center and to her right. The audio prefaces and objects presented are selected by the system based on the visitor's movements in the exhibition space, previous audio objects selected, and her current topic preferences.

4.2 Interaction design

Our interaction model relies on a turn-taking approach based on the metaphorical structure of a conversation.[1] *Turn taking* allows us to structure the listening and selection actions of the visitors. *Prefaces* and *telling* let us design the audio object in two parts: *prefaces* act as multiple-choice indices for the more detailed *telling* of the audio object. *Responses* and *disengagement* provided a selection and silent function for the system. The TUI provided input for a *response* – our equivalent of a nod. No *response* from the visitor was interpreted as *disengagement*.

The audio objects are semantically tagged to a range of topics. At the beginning of each interaction cycle, three audio objects are selected based on ranking using several criteria such as current levels of user interest, location, interaction history, etc. The topics of objects are not explicit to the visitor; rather the content logic is kept in the background.

In regard to the design process, many of the design choices were made through a series of participatory

[1] The idea of using conversation analysis concepts as a structural metaphor for non-speech interfaces is not unique in HCI, see for example: Norman M.A., and Thoma P.J., ''Informing HCI design through conversational analysis,'' International Journal, Man–Machine Studies (35) 1991, 235–250.

design workshops and scenarios, details of which are discussed in another paper [47]. For example, an asymmetrically shaped wooden cube resulted from these workshops, as did the use of the conversation metaphor, navigation and audio interface. In addition, we prototyped the exhibition environment and system in our labs in order to design the interactive zones, audio display and interaction with the exhibit displays.

4.2.1 Tangible object

The tangible interface object is an asymmetrically shaped wooden cube with three adjacent colored sides. The visitor holds the cube out in front of them in order to make a selection. The visitor makes a selection by rotating the cube so that the selected colored side faces directly upward (see Fig. 3).

The cube was carefully designed to ensure proper orientation and ease of use. The ‘‘bottom’’ of the cube has a convex curve to fit comfortably in the palm of the hand and a wrist leash is attached to an adjacent side to the curved bottom suggesting the default position of being upright in the palm and at a specified orientation to the body (see Fig. 4). The leash allows visitors to dangle the cube, freeing the hand, when not in use. The opposite side of the bottom of the cube is colored and shows an icon denoting a pair of headphones with both channels active. The sides to the left and right are each uniquely colored and display icons showing active left and right channels of the headphones, respectively. The cube is made of balsa wood. It is therefore very light (approximately 100 g or 3.5 ounces) mitigating tiredness from carrying the object.

Fig. 3 The *ec(h)o* cube

The input of the selection is done through video sensing. The ergonomic design of the cube and biomechanics of arm and wrist movement form a physical constraint that ensures that the selected cube face is almost always held up parallel to the camera lens above and so highly readable. We experienced no difficulties with this approach.

4.2.2 Audio display

The audio display has two components, a soundscape and paired *prefaces* and *audio objects*. The soundscape is discussed along with navigation in Sect. 4.2.3. In the latter component, we used a simple spatial audio structure in order to cognitively differentiate between objects. Switching between the stereo channels created localization: we used the left channel audio for the left, right channel audio for the right, and both channels for the center. It is an *egocentric* [22] spatial structure that allowed the three *prefaces* to be distinguishable and an underlying content categorization structure to exist. The spatialization was mapped to the tangible interface for selection. In addition, we provided simple chimes to confirm that a selection had been made.

The *prefaces* were written to create a sense of surprise, discovery and above all play, especially in contrast to the informational audio objects. In order to create this sense we utilized diverse forms of puns, riddles and word play, for example:

- *Ambiguous word play*: ‘‘Sea urchins for sand dollars’’ (preface); ‘‘Other then the morphology, the sea urchin and the sand dollar are very similar species’’ (abridged audio object);
- *Simple pun*: ‘‘Its like putting your foot in your mouth’’ (preface); ‘‘The word gastropod comes from two different roots: *gastro* for stomach, and *pod* for foot’’ (audio object);
- *Literary pun*: ‘‘Dung beetles play ball!’’ (preface); ‘‘Dung beetles turn dung into balls and are equipped with their forehead and legs to push these balls for some distance’’ (abridged audio object);
- *Turn of phrase*: ‘‘An inch or two give or take a foot’’ (preface); ‘‘Dung beetle nests are usually underground, and can range from a few inches to a few feet deep’’ (audio object);
- *Definition pun*: ‘‘There’s a cat in the garden!’’ (preface); ‘‘Specimen #129 is a John Macoun sample, it is known as a pussy toe because the plant flower and fruit represent a cat’s foot’’ (audio object);

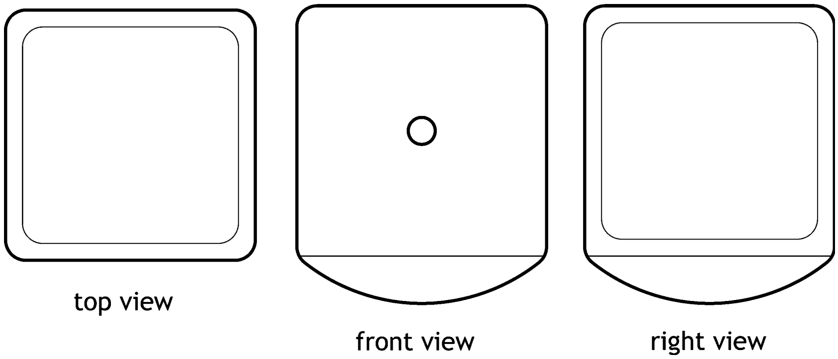


Fig. 4 A plan drawing of the tangible object revealing the *curved bottom* that suggest resting in the palm of the visitor's hand

- *Riddles*: "What is always naked and thinks on its feet?" (preface); "Where gastropods are shelled critters with stomachs that sit on a primary foot, cephalopods are bare critters with heads that sit on a primary foot" (audio object);
- *Understatement*: "Longer than you would want to know" (preface); "Tapeworms come in varying lengths and sizes. Interestingly, the longest recorded tapeworms have been those that live in humans" (audio object);
- *Contradiction*: "Ice age dentistry" (preface); "This deformed tooth is a very interesting case. It was the first recognized pathological problem in an ice age animal" (audio object).

The audio recordings of the *prefaces* and *audio objects* used a diverse set of voices that were informal in tonality and style. This added to the conversational feel and created an imaginary scene of a virtual cocktail party of natural historians and scientists that followed you through the museum. As we discussed in Sect. 3.1, we identified the natural history scientists as our *keystone species*. We organized sessions of recorded walkthroughs of the exhibition asking each scientist to provide commentary [46]. These sessions became the basis for the discrete audio objects that were categorized by topics and relationship to artifacts on display.

4.2.3 Navigation

We structured navigation at a *macro* level, where visitors move throughout the exhibition space in between artifact displays, and a *micro* level, where visitors are within a specified interactive zone in close proximity to an artifact display.

On the macro level the input is the visitor's movement, which creates an ambient soundscape through the audio display related to artifacts nearby. We divided the exhibition space into interactive zones and mapped concepts of interest to each zone and display (in regard to the user model we distinguish between concepts represented in the artifacts and concepts that can be associated with the artifacts based on user's interests, we refer to the former as *visual concepts*, see [48]). The concepts are translated into environmental sounds such as the sound of an animal habitat, and sound of animals such as the flapping of crane's wings. The visitor navigates the exhibit exploring it on a thematic level through the ambient sounds that are dynamically created. If a set of *visual concepts* strongly matches the visitor's interest, the related audio is acoustically more prominent. Figures 5 and 6 depict how the visitor's movement in the exhibition space creates the soundscape. Darkened areas within the superimposed map of the exhibition space represent different *visual concepts* translated into sound triggered by the proximity of the visitor. In Fig. 5, two dark areas are highlighted. The slightly darker area represents nearer proximity of the visitor to one set of concepts over another signaling that while the audio is composed from both zones, the nearer zone is more prominent. In Fig. 6, the highlighted zone (red in a color version of the figure) represents a strong match between the visitor's current concepts of interests and the nearby *visual concepts* and would therefore be acoustically prominent.

Fig. 5 Still frame depicting the prominence of sounds in a soundscape reflecting what's on display based in the visitor's proximity

Fig. 6 Still frame depicting the prominence of sounds in a soundscape reflecting a strong match between the visitor's interests and what is on display in the visitor's proximity

On the micro level, visitors are in an interactive zone in front of a display of artifacts. The audio display here consists of *prefaces* and *audio objects* related to the artifacts they are viewing and their own evolving interests as represented within the user model. The navigation at this level matched the minimal functionality of the tangible object. The structure is very simple given the limited choices of three options. The navigation is as follows (see Fig. 7): A visitor is played three *prefaces*, one to his left, another to his center and the third to his right. He selects the *preface* on his right side and listens to the linked audio object. On the subsequent turn the visitor hears the same two *prefaces* he did not select, and again he hears them to his left and to his center. Since he previously chose the *preface* to his right he now hears a new *preface* in that location. If the visitor then selects the center *preface*, on the subsequent turn only that *preface* is replaced by a new *preface* in the center position. If a *preface* has been replayed three times without being selected, it is replaced by a *preface* and audio object of the next highest ranking topic according to the user model.

We came to refer to this navigation approach as the "1-2-4" model since the number sequence represents the idea that on a subsequent interaction, the third *preface* would be replaced by a *fourth* preface if the third one was previously chosen. The first and second *prefaces* would be heard again. Since each spatial location consistently represents a topic of interest, the belief here is that within this limited structure we could provide persistent opportunities to pursue an interest by repeating unselected *prefaces*, only removing them after a number of repetitions. At the same time we provide further in depth choices within a given interest by *refreshing* a location with related *prefaces* and *audio objects*.

Turn	Prefaces played			Preface/audio object selected
	left	center	right	
1	1	2	3	3
2	1	2	4	2
3	1	5	4	

Fig. 7 "1-2-4" navigation model

4.3 User model

The adaptive and user model approach in ec(h)o is not the focus of this paper, we refer readers to another paper that discusses our approach in considerable depth [48]. Our approach is characterized by the use of an integrated modeling technique, supported by an ontologies and rule-based system for information retrieval. We believe that this unique approach supports a TUI that relies on limited explicit input and substantial implicit input, while at the same time the semantic web approach allows for rich and coherent information output within an audio display that is adaptive to the interactor's dynamic exploration and discovery within the museum environment. The user model dynamically integrates movement interaction and visitor content selection into initial pre-selected preferences. Based on this dynamic model we could infer potential interests and offer a corresponding range of content choices. In addition, the use of semantic technologies allowed for coherent and context responsive information retrieval.

5 Analysis of the interface and interaction

In order to understand the situated nature of the interface we provide an analysis utilizing the TUI frameworks of Shaer's TAC paradigm [49] and Fishkin's taxonomy [50]. Over the years various frameworks have been proposed to better define TUIs. Holmquist et al. [51] proposed defining concepts of containers, tools, and tokens. Ullmer and Ishii [52] proposed a framework known as the MCRit and later the Token + Constraint System [53] that highlighted the integration of representation and control in TUIs. Shaer and others have extended MCRit to propose their token and constraints (TAC) paradigm [49].

The TAC paradigm defines TUIs across three concepts: token, constraint and variable. A token represents digital information or a computational function, a

Table 1 ec(h)o specifications using the TAC paradigm [49]

TAC	Representation		Behavior		
	Token	Constraints	Variable	Action	Observed feedback
1	Cube	Cube and Hand	Preface	Hold up	Audio object heard in the center
				Rotate left	Audio object heard on the left
				Rotate right	Audio object heard on the right
				Keep down	System is silent
2	Body	Interactive zone (display area)	Preface	Enter	Soundscape fades and prefaces are heard on the left, right and in the center
				Exit	Soundscape is heard
3	Body	Exhibition space	Soundscape	Movement	Soundscape changes

constraint limits the token's behavior, and a variable is digital information that is either statically or dynamically represented by tokens. Shaer defines several categories within TAC in which among other things, TACs can be composed together. We have specified ec(h)o using the TAC paradigm in Table 1. For example in the first TAC, the cube is a token, and the constraint is the cube together with hand dexterity. The variable is the *preface*, and the behaviors of the cube are specified as well. ec(h)o's TUI would be in the token + constraint category since the wooden cube is a token and physically sets its own constraints on its behavior.[2] Further in Table 1, we have added two additional TACs, 2 and 3 that include the visitor's body as a token and two aspects of the architectural space as constraints. While we have specified ec(h)o within the TAC paradigm it seems to have strayed well beyond a *purely* TUI when considering the visitor as a token and the architecture as a constraint.

Fishkin's taxonomy is a two-dimensional space across the axes of *embodiment* and *metaphor* [50]. Embodiment characterizes the degree to which ''the state of computation'' is perceived to be in or near the tangible object. Fishkin provides us with four levels of embodiment: *distant* representing the computer effect is distant to the tangible object; *environmental* representing the computer effect is in the environment surrounding the user; *nearby* representing the computer effect as being proximate to the object; and *full* representing the computer effect is within the object. Fishkin uses metaphor to depict the degree to which the system response to user's action is analogous to the real-world response of similar actions. Further, Fishkin divides metaphor into *noun metaphors*, referring to the shape of the object, and *verb metaphors*, referring to the motion of an object. Metaphor has five levels: *none* representing an abstract relation between the device and response; *noun* representing morphological likeness to a real-world response; *verb* representing an analogous action to a real-world response; *noun* + *verb* representing the combination of the two previous levels; *full* representing an intrinsic connection between real-world response and the object which requires no metaphorical relationship.

In Fig. 8, we have applied Fishkin's taxonomy to ec(h)o. Embodiment would be considered ''environmental'' since the computational state would be perceived as surrounding the visitor given the three-dimensional audio display output. In regard to metaphor, the ec(h)o TUI would be a ''noun and verb'' since the wooden cube is reminiscent of the wooden puzzle games in the museum and the motion of the cube determines the spatiality of the audio as turning left in the real-world would allow the person to hear on the left. If we consider the visitor's movement the embodiment factor would still be environmental and we'd have to consider the visitor's body as being ''full'' in Fishkin's use of metaphor. In regard to understanding the entire system we'd have to plot ec(h)o

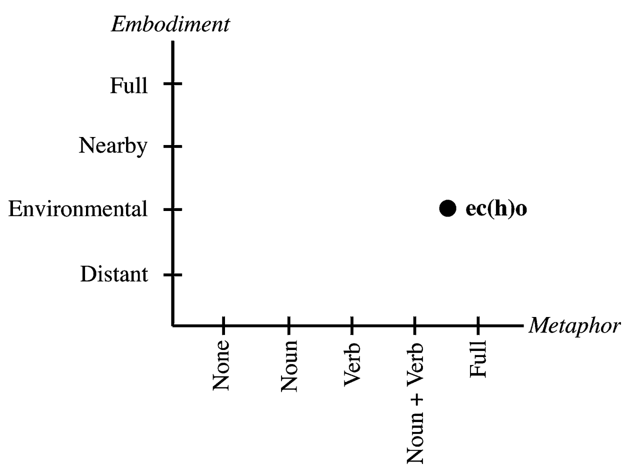


Fig. 8 ec(h)o plotted in Fishkin's tangible user interface (*TUI*) taxonomy [50]

[2] Its worthwhile to note that the TAC paradigm does not account for very minimal tangibles such as ec(h)o and Live Wire in which tokens and constraints are not related components but are integrated into one component alone such as a cube or wire.

between ‘‘noun + verb’’ and ‘‘full’’ on the metaphor axis. While Fishkin’s taxonomy addresses context beyond the tangible object rather well, again the inclusion of people themselves as a TUI seems beyond the scope of the taxonomy despite its application here.

The interaction with the tangible object in ec(h)o is characterized as a verb under Fishkin’s taxonomy and an action in the case of Shaer yet movements have complex non-linear qualities that elude simple categorization. In Sect. 4.2.2 we discussed examples of the types of word play, puns and riddles we used in our audio to encourage play and discovery. The tangible interface aimed for a complementary physical play, which as we discussed is open and often can be subtle and implicit like toying with a ball in your hand. We designed the tangible object such that it had suggested actions like resting in a palm or pivoting on a wrist yet we knew we could not design the actions directly rather only suggest possibilities, what Djajadiningrat refers to as the *action-potential* of physical objects [39]. Further, the physicality of the objects meets our bodies in often unique or wide ranging kinesthetic combinations in which optimal efficiency gives way to play and experimentation.

In what are simple actions of holding and rotating the cube we observed a diverse set of interaction techniques when selecting *prefaces*. We identified at least five basic techniques:

- *Hold and rotate*, one hand holds the cube resting on the palm while the other hand rotates it in place (see Fig. 9a, b);
- *Hold, rotate and cover*, one hand holds the cube resting on the palm while the other hand or both hands rotate the cube. The topside is uncovered until the selection is made and then the topside is covered again until its time to make another selection[3] (see Fig. 9c, d);
- *Cradle and hide*, two hands rotate and cradle the cube, after selection is made the colored side is rotated and hidden against the visitor’s body (see Fig. 9e);
- *Rotate wrist*, one hand holds the cube between fingers and thumb, and rotates the wrists to make a selection (see Fig. 9f, g);
- *Rotate with fingers*, one hand holds the cube and rotates it by rolling with the fingers and thumb (see Fig. 9h).

It is important to note that we observed combinations and variations of these techniques, as well as individual experimentation with the different approaches. As one might expect we also observed a range of methods for holding the cube when not selecting prefaces or walking through the exhibition such as cradling it in hands, holding it at one’s side or behind one’s back, dangling it from the wrist, or holding its leash to gently sway it from side to side. This sense of play extended to participant’s movements through the exhibition space. In the interviews, participants commented on how they returned to zones to see if the system would indeed not repeat audio objects already heard. In addition to moving from zone to zone participants appeared to experiment with their movements entering and exiting zones altering the soundscape (for example, see the number of location changes in a short period of participants 3 and 6 in Table 2 in Sect. 7).

We provide these details of interaction to describe the degree of play and variety afforded by the interface as opposed to a *single path* of interaction—all of these approaches worked equally well. Djajadiningrat points out that aesthetic interaction is where ‘‘there is room’’ for a myriad of types, combinations and sequences of actions [39]. This experiential space is created in the embodied action between physical objects and our bodies. In Sect. 2.3 we discussed the example of the ball as a form of *pragmatic aesthetics* in Petersen et al [40]. A wooden cube, like a ball is a very familiar object that has a history of use in games and play that can be open-ended and exploratory. As Petersen observed, the ball promotes playfulness and promises a different type of potential than a tool. Rather then the promise of efficiency and accuracy, the ball and in our case the cube promises discovery and exploration.

6 Implementation

Our prototype for testing consisted of four main components: position tracking, vision sensing, audio engine, and reasoning engine. Two main types of events trigger the communication between the components: visitor’s movement through the exhibition space and selection of audio objects. The high level architecture is shown in Fig. 10. The knowledge models and ontologies refer to the semantic web approach to information retrieval which is not pertinent to the discussion here [54].

The prototype was installed and tested in the *Finders Keepers* exhibition at the Canadian Museum of Nature. The exhibition theme was collecting natural

[3] Technically there is no requirement to cover the cube color after a selection has been made since the recognition in the vision system is ‘‘gated’’ meaning once it recognizes a color it does not look for a new color until the next interaction cycle.

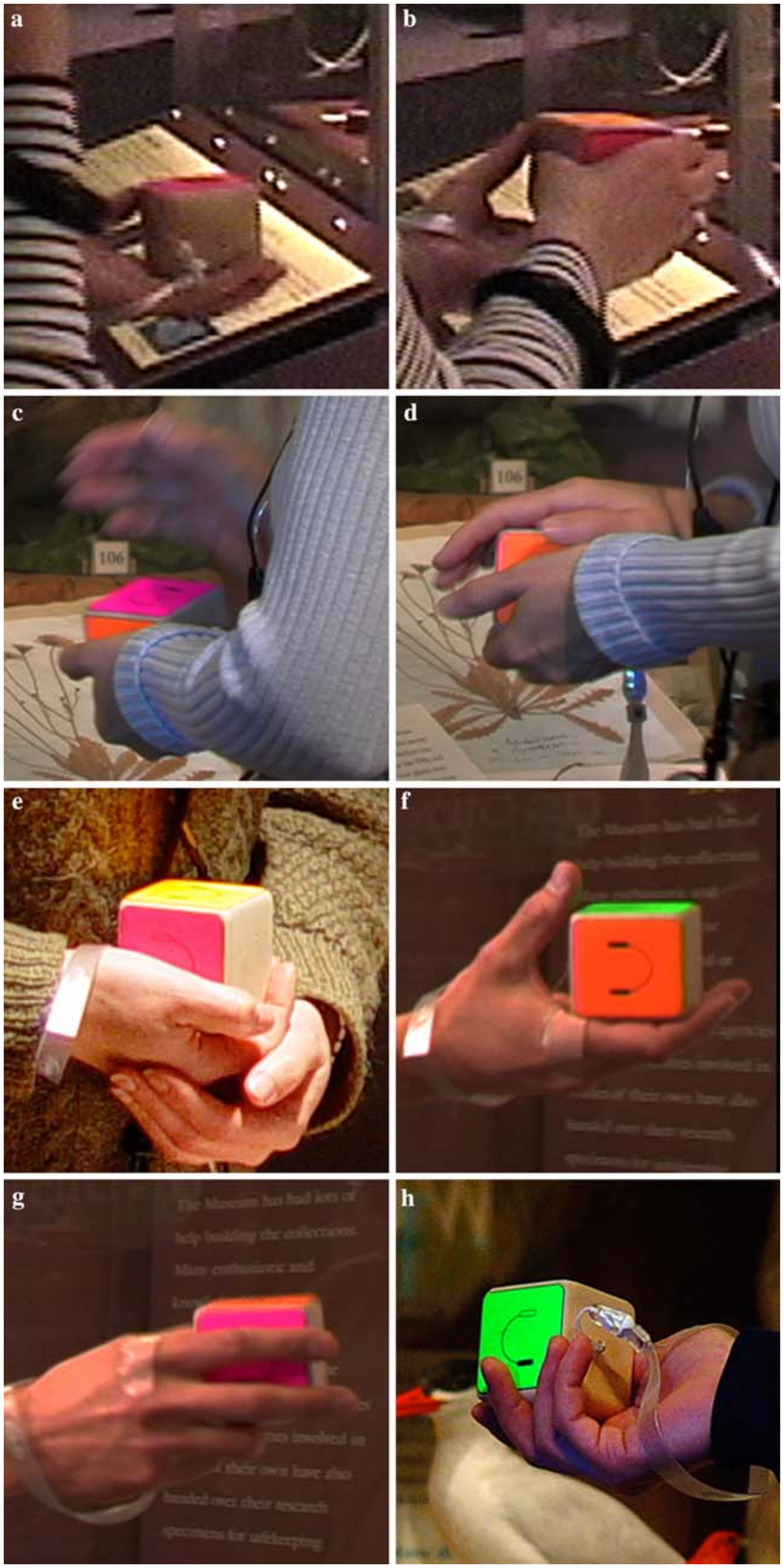


Fig. 9 a–h Different interaction techniques for selecting *prefaces*: **a, b** Hold and rotate; **c, d** Hold, rotate and cover; **e** Cradle and hide; **f, g** Rotate wrist; **h** Rotate with fingers

Table 2 Test session characteristics

Participant	Length	No. of cycles	No. of selections	No. of locations
Participant 1	10:36	27	19	8
Participant 2	6:19	11	7	4
Participant 3	8:56	22	12	10
Participant 4	9:53	21	16	5
Participant 5	9:18	22	17	5
Participant 6	5:01	16	7	9
Expert 1	15:03	32	23	9
Expert 2	17:58	36	29	7

history artifacts in Canada. While theoretically we could have installed the system throughout the exhibition we created only three zones of interaction due to our limited installation times between the open hours of the museum. We produced over 600 reusable audio objects and annotated them with the ontological information. The average length of an audio object is approximately 15 seconds. The shortest is 5 s and the longest 31 s. The prefaces typically are 3 s in duration.

Position tracking We used a combined radio frequency identification (RFID) and optical position tracking system developed by Precision Systems (http://www.precision-sys.com). Optical tags were attached to the tops of the headphones. Visitors carried an active RFID tag in a pouch. We installed cameras over the interactive zones and one in the central area of the space. This was adequate for tracking the visitor location throughout the sessions.

Audio engine We developed a multi-channel editor, mixer and server in the Max/MSP™ environment to function as the audio engine. This engine created dynamic soundscapes and delivered unique channels of stereo audio to individual users. The audio was delivered wirelessly over FM transmitters that provided a stereo signal. Each visitor carried a small inexpensive digital receiver in a pouch.

Vision sensing A vision sensing system supported the selection of audio objects via the tangible interface. We developed a system in Max/MSP based on the "eyes" system (http://www.squishedeyeballs.com). Cameras were installed over each interactive area.

Reasoning engine The reasoning engine receives all the input and directs output based on inferences based on a rule system and user model. Information retrieval actually employed a semantic web approach that allowed us to select the audio objects based on their semantic properties and how they relate to the museum artifacts, exhibits, individual user interests and user's interaction history. The system was implemented using the JESS inference engine with the DAMLJessKB extension that converted DAML + OIL ontologies to Jess facts. The reasoning module was connected with other modules through the user datagram protocol (UDP) socket connections [55].

7 Evaluation

The exhibition, 'Finders and Keepers' contains seven exhibits, five of which are booth-type exhibits, each with several dozens of artifacts organized around topics (see Fig. 11). Two exhibits are open exhibits with larger artifacts such as a mastodon skeleton (see

Fig. 11 An example of a "booth-type" display in the exhibition Finders Keepers

Fig. 10 *ec(h)o* high level architecture

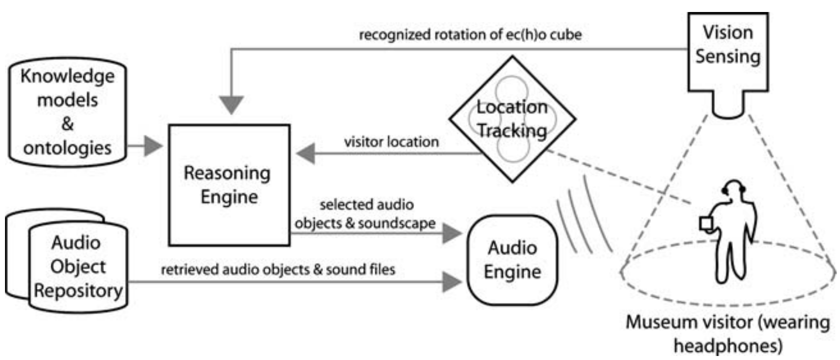


Fig. 12). For the exhibition we created three interactive zones: two in booth-type exhibits and one in an open space exhibit.

The formal user evaluation effort involved sessions with six participants and two expert reviewers. The participants had previous experience with interactive museum systems such as docent tours (three participants), interactive kiosks (3), audiotape systems (4), film and video (5), seated and ride-based systems (2) and PDA systems (2). The test group included two men and four women, from 25 to 53 years old. The experts included a senior researcher and senior interaction designer from the museum. Both were familiar with the exhibit and its underlying concepts. In addition to an extended discussion with the expert reviewers they provided us a written evaluation of the system.

Table 2 shows the characteristics of each user session: the total length of the interaction, number of interaction cycles, number of selected and listened to audio objects, and number of location changes.

Our evaluation is based on Miller and Funk's [56] use of traditional 'validation' and 'verification' approaches in evaluating ubiquitous computing systems. Our verification efforts focused on user experience and the perception of the system. Our validation efforts focused on the user model and system response components. Since user experience is more relevant to our discussion in this paper we provide here a short summary of the validation results that have been discussed in detail in [48].

7.1 Summary of user model and performance evaluation

The validation of the ec(h)o components, namely user model and object selection, showed that these

Fig. 12 An example of an ''open exhibit'' display in the exhibition Finders Keepers

performed at the required level of accuracy and flexibility. In regard to the experience design goals of play and discovery, our integrated modeling approach implemented two techniques to facilitate wider exploration and the discovery of new topics of interests and the ability to make new connections among topics and artifacts. The first being the aim of keeping interests balanced such that a given topic or set of topics does not dominate and prevent exploration of new topics, for this we used a spring model to proportionately moderate levels of interest. We felt it was important that the user model learns to ''forget older interests'' so that newer ones can be invoked. The second technique is to maintain a high level of variability of primary and secondary interests among the objects presented. This affords greater opportunity for the user to evolve his or her interest through a reflection on content as discussed above (see Sect. 6.3). The results of a separate laboratory tests showed that these techniques contribute to the goal of establishing dynamics in the user model that support exploration and discovery of new interests through moderating evolution in the user interests, maintaining significant influence of changing context (when a visitor moves to another exhibit), and protecting against the domination of a few concepts that would choke off exploration.

We introduced the evaluation of system response or in our case, object selection based on interaction criteria of *variety*, the richness of choices for further interaction at each interaction step; *sustained focus*, ability of the system to sustain the focus on particular interests; and *evolution*, ability of the system to follow shifting user interests during interaction with the system. We can conclude that the system offers the highly variable objects when user changes the location and the variety increases as the user continues the interaction in a particular location. The high variety during the object selection steps is supported while the system maintains the focus on the concepts of interest as expressed in the user model. The low value of evolution during the object selection stage indicates the continual change in topics offered corresponding to the modest changes in the user model. This behavior matches our expectations. Several ranking criteria are combined to select audio objects offered in the next step. It is the weight with which these criteria contribute to the object ranking that determines the combination of the concepts of interest in the objects offered. To achieve different behavior from the system the relative weight of contributing criteria would have to be altered.

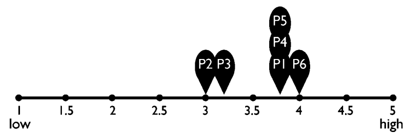
7.2 Evaluation of user experience

We evaluated user experience through observation, a questionnaire, and a semi-structured interview. The questionnaire included 63 questions that assessed user experience related to the overall reaction to the system, the user interface, learning how to use the system, perceptions of the system's performance, the experience of the content, and degree of navigation and control. Majority of the questions in the questionnaire were on a Likert scale yet it provided for open-ended written comments. Throughout the questionnaire, and especially during the semi-structured interviews we looked for an overall qualitative assessment of the experience based on Bell's ecological components of *liminality* and *engagement* [5]. For a summary of the questionnaire results see Fig. 13.

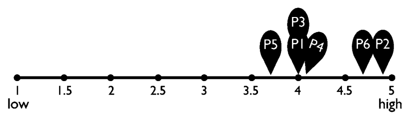
Overall, participants found the system enjoyable and stimulating, perhaps in part due to its novelty. The general sense of satisfaction was split between those participants who liked the playful approach and those who did not. While our sample was small we noted a clear age difference in that the ''younger'' participants rated satisfaction higher based on their liking of the playful approach (this was confirmed in the semi-structured interviews).

Among the factors that stood out as most positive for the participants was that the cube and audio

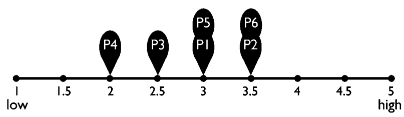
Fig. 13 Summary of the questionnaire results on user experience ($n = 6$; 63 questions on Likert scale of 1–5 (five being best)



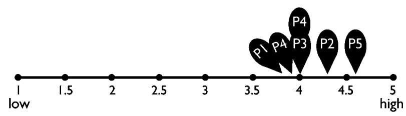
Overall reaction: 5 ratings including "terrible-wonderful; difficult-easy" averaged for each participant. Overall average rating is 3.6 with a standard deviation of 0.40.



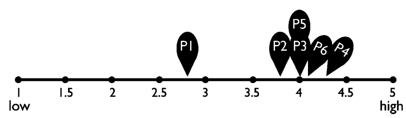
Tangible user interface: 7 ratings including "uncomfortable-comfortable; difficult-easy to manipulate; annoying-enjoyable" averaged for each participant. Overall average rating is 4.24 with a standard deviation of 0.45.



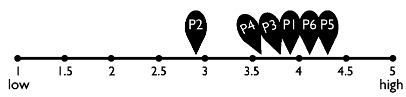
Headset: 2 ratings including "uncomfortable-comfortable" averaged for each participant. Overall average rating is 2.92 with a standard deviation of 0.59.



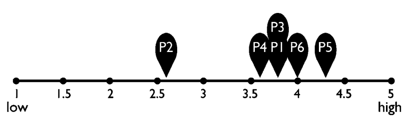
Learning Curve for the system: 8 ratings including "difficult-easy to get started; risky-safe to explore features; unclear-clear feedback" averaged for each participant. Overall average rating is 4.07 with a standard deviation of 0.31.



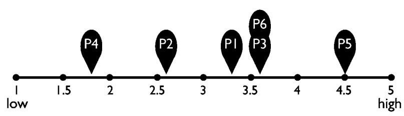
Perception of system performance: 8 ratings including "slow-fast system response; never-always reliable" averaged for each participant. Overall average rating is 3.83 with a standard deviation of 0.56.



Quality of the content: 15 ratings including "uninformative-informative; generalized-customized for me; rigid-playful; predictable-surprising" averaged for each participant. Overall average rating is 3.78 with a standard deviation of 0.47.



Quality of the audio experience: 9 ratings including "confusing-clear; mechanical-human; wasteful-valuable" averaged for each participant. Overall average rating is 3.67 with a standard deviation of 0.60.



Navigation and control: 8 ratings including "never-always able to navigate efficiently; always-never found myself lost in the system; always-never found myself uncertain of the system state" averaged for each participant. Overall average rating is 3.23 with a standard deviation of 0.95.

delivery were seen as playful. The open-ended written comments and semi-structured interviews made this point clear as well. The TUI was well received especially in terms of ergonomics and ease of use. This was not a surprise to us since our early testing and participatory design sessions provided us with considerable feedback, especially on ease of use and enjoyment. We went through several iterations and form factors of the wooden cube and tested it against different hand sizes. This may have also resulted in the fact that learning to use the interface and navigation were rated highly and participants felt the system had a low learning curve and that it was easy to get started:

Umm, I found it was really easy. Sometimes I got so engaged in listening to what they were saying that I forgot in which orientation I was holding the cube. And I found that I would have to occasionally look down. But the way it was designed with the round part to go in your palm... it was really easy to quickly reorient myself to how I was holding that cube. (Participant 5)

It should be stated that we provided a short tutorial on the system at the beginning of each evaluation but nevertheless this feedback is encouraging. Interestingly, the audio content was perceived to be both accurate and clear. The issue of trust and delivery style is an area to further investigate. Since we collected the information directly from scientists and staff at the museum rather than a more generic source we wonder if this contributed in part to this result [46]. These results lead us to believe that the system meets or satisfies many of the current advances of museum guide systems.

The questionnaire did point out challenges and areas for further research. Some things we expected such as the headphones were uncomfortable, yet to such a degree that we are currently rethinking the tradeoff between personalized spatial audio and use of headphones. Other results point to a threshold in the balance between levels of abstraction and local information. Since visitors had difficulties at time connecting what they were listening to and what was in front of them (in part this was an inherent challenge in the exhibition since the display cases had dozens to over a hundred artifacts, see Fig. 10a, b). In many respects this contributes to our finding that the ontological approach did not provide a clear enough contextual link between the artifacts and the audio information. In addition, we see both a threshold point in play versus focused attention on the exhibit in that the question relating to the content asking if it was "distractive-synergistic" scored 2.83. This raises the issue of balance in play and the possibility to shift attention away from the environment rather than play as a means of further exploring the environment.

In an open-ended question in the questionnaire and through the interviews we explored the issues of liminal play and engagement. The results here are quite clear that play was a critical experiential factor in using the system. It was often remarked how the experience was similar to a game:

> *The whole system to me felt a lot like a game. I mean I got lost in it, I found myself spending a lot of time in a particular area then I normally would. And just the challenge of waiting to hear what was next, what the little choice of three was going to be. Yeah... So I found it over all engaging, it was fun, and it was very game-like.* (Participant 4)

The playfulness did in most instances suggest a quality of engagement that led to learning even through diverse types of museum visits from the visitor who browses through quickly but is still looking to be engaged to the repeat visitor who experiences the audio information differently each time:

> *I learned a lot and well you know I am a scientist here, and I think anybody going through, even people who are in a real rush, are going to pick up some interesting facts going through. And... I mean, that was good, the text was great and was short enough that somebody in a rush is still going to catch the whole thing.* (Participant 1)

As mentioned earlier, there is a threshold between play in support of the exhibit on display and play with the system that can be an end in itself and even a distraction. For example, one user's enthusiasm for the game-like quality led her to at times pay more attention to the interaction with the system than the exhibition. In addition, people respond to play differently and can be argued to belong to different types of players [57]. One participant would have preferred a more serious and "non-playful" approach.

The prefaces were playful, but the text was not at all, you know, that contrast between them.... but I find it was too playful and I think maybe, either you, or maybe you could give people the choice between you know choosing a playful or a non-playful version." (Participant 2)

In addition, participants' observations on the *liminality* of the experience manifested in comments suggesting that play was more natural for children rather than themselves, however as expressed below, they soon overcame this issue:

At first it felt a little bit strange, especially holding this cube that looked like a children's toy, and I felt a little bit awkward about doing that, but I got over that pretty quickly. (Participant 5)

It was quite chatty, which was kind of fun. I kind of felt like 'Oh, I bet like a twelve year old would really like this'. (Participant 3)

8 Discussion

In this paper we've explored situated play in a tangible and adaptive audio museum guide. Our approach in ec(h)o was to create a coherent space for play and discovery across all components of the design including reasoning, audio delivery and interface. The space suggests actions and meaning but maintains an openness and interpretation that requires playful interaction on the part of the user in order to realize the *action-potential* or relevancy of the information. While we see that the results of our pilot study support the notion that learning effectiveness and functionality can be balanced productively with playful interaction, we see further research and some caution when dealing with the space of playful and interpretive interaction. With the practicalities of design in mind we see issues of balance in between play and the environment, and the space between interpretation and information that links the audio content to the artifacts. Theoretically we have questions on the degree to which we best understand the contextual and situated aspects of TUIs.

8.1 Design issues

The balance of playful intervention When is a good thing too much? In our case, playfulness does not directly lead to satisfaction. In our results, playfulness was identified positively in all aspects of the interface yet overall satisfaction was split between those participants who enjoyed *playing* and those who did not. As we reported, one participant explicitly asked for a non-playful version. However, we did not expect our approach or any approach to museum interaction to be universally accepted. We actually find the question of too much play to be of more interest. There is a need to find the balance between play in support of the exhibit and play with the system that can be a distraction and even an end in itself. Otherwise, designers run the risk of users engrossed in playing with the system at the expense of interacting with their surroundings, as one participant commented happened to her periodically. This is not the same issue as the one we raised about PDAs demanding full attention for that is an inherent design and cognitive relationship given the GUI nature of the device. Playful interaction lends itself well to integrating with the context and in many cases depends on it, as in bouncing a ball off the floor or wall. While we achieved a reasonable balance and are generally on the right track with our approach, we feel more is required for a better understanding of how to design *situated* TUIs in regard to play.

Balancing the richness of ambiguity & the richness of information When is a good thing too little? At times participants had difficulties connecting what they were listening to and what was in front of them. It is possible that the system did not always provide a coherent story, a resulting tradeoff of our aims of open discovery. Nevertheless, a much richer model of discourse and storytelling could be an option to pursue, for example a richer world model for location as Goßmann and Specht describe [58]. Visitors in museums clearly invest in connections with concrete artifacts while ec(h)o experimented with the idea of connections between artifacts and audio objects at the higher ontological level. The results indicate that a much richer model is needed or the hypothesis of linking objects at higher abstract ontological levels is not the best approach for ubiquitous context-aware applications or it has to be combined with other approaches.

Puns, riddles or icons What is ten pixels square, black and white all over and not funny? We discussed the range of puns, riddles and word play we used for the *prefaces* that served as indices for navigation choices. In comparison, we performed preliminary testing with other approaches like *earcons* [59] and the more traditional *question and answer* structure. The *earcon* design was perceived as too confusing and abstract. It was simply too difficult to encode the range of concepts of interests and themes into communicable *earcons* that could be remembered by the user. The *question and answer* design was viewed as static and unrelenting after only a few turns. We feel the early efforts of our word play approach are promising. The use of word challenges as either indices or user instructions has interesting potential in interaction design.

8.2 Situating TUIs

The concept of TUIs is deceptively simple. We manipulate the world through physical atoms with overwhelming ubiquity. This includes manipulating the world of digital bits since Fishkin argues a keyboard can be considered a tangible interface. A possible criticism of his taxonomy is that it may be too broad and inclusive to be useful yet in our view this approach widens the concept to expose boundaries [50]. We found this approach very useful for the fact that it considers the contextualization of TUIs. As we encountered in our analysis, it also opens interesting questions such as the nature of the human interactor and the role of embodied interaction in a tangible interface. At the moment however, we are most interested in the contextualization issues of TUIs.

In Fig. 14 we plotted TUIs that we cited and described in our discussion of related works (see Sects. 2.1, 2.2, 2.3).

We consider these projects to be contextual in that the environment beyond the immediate interface elements affects the interaction or meaning of the interaction, or as in ec(h)o or Live Wire [31], the works are situated in an identifiable setting. Live Wire mirrors the connection between network activity within the immediate office space and network traffic originating on the network outside of the office such as email. Despite the differences in ambientROOM [26] and WorkSPACE [41] they are both office environments and thus context specific. ambientROOM is the most complex of the projects here and in fact represents a number of different TUIs connected only by their shared context. In respect to contextual TUIs, a state of "full" embodiment is not a desirable quality. Utilizing Ishii's notion of "foreground" and "background" activity, the "foreground" activity comes at the cost of awareness of "background" bits or activity. The contextualized realm is the awareness of the activity and setting around you. The state of "full" metaphor is interesting in that without "full"

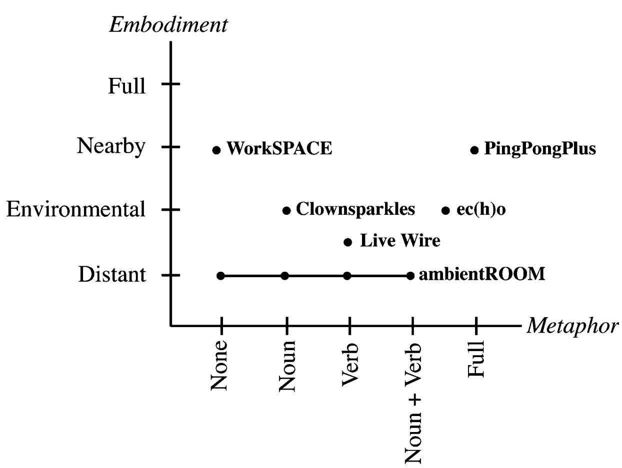


Fig. 14 *Situated* tangible user interfaces plotted in Fishkin's TUI taxonomy [50]

embodiment, the fullness seems to come from the active presence of the human body. In PingPongPlus [26] it is difficult to consider the ping-pong paddle as active without an arm and body attached to it moving it to hit the ball. According to Ishii, the paddle "can co-evolve with a user by changing its physical form and being united with the human hand," and paddles are a "transparent physical extensions of our body" [26] The traces of the body presence are left on a well-used paddle in the form of thumb and finger marks. We have already discussed the notion of the museum visitor in ec(h)o as a "full" metaphor tangible interface (see Sect. 5).

This is important since Fishkin concludes his discussion of his taxonomy by identifying that the domain of TUIs is evolving toward TUIs converging on "full" embodiment and "full" metaphor. He cites "Sketchpad" [60] as an example of a "full" metaphor and "Illuminating Clay" [61] as an example of "full" embodiment. We strongly feel this overlooks the situational value of the taxonomy and risks overlooking developments in *situated* TUIs.

9 Conclusion

ec(h)o is an augmented audio reality system for museum visitors that utilizes a tangible interface. We developed and tested the prototype at the Canadian Museum of Nature in Ottawa. In ec(h)o we tested the feasibility of audio display and a TUI for ubiquitous computing systems – one that encourages an experience of play and engagement. In this paper we have presented relevant work in the domains of adaptive museum guides and audio displays, ludic approaches to TUIs, and aesthetic interaction. We provided an overview of our design motivations rooted in ethnography and concepts of ecologies that together led to our approaches in audio delivery and tangible interface. We described the components of our prototype and gave an analysis of our interface utilizing TUI frameworks that revealed the embodied and contextual nature of our design. We also analyzed the interaction revealing the aesthetic qualities of the interaction pattern between the object and the visitor, and the myriad of interaction paths. We also described our implementation and evaluation design.

The findings of this project are positive while also calling for more research in several areas. We conclude that based on our results from our pilot study learning effectiveness and functionality can be balanced productively with playful interaction through an adaptive audio and TUI if designers balance the engagement between play and awareness of the environment, and balance the richness of ambiguity with the richness of information that links the audio content to the artifacts. We see further research in the role of puns, riddles and word play in interaction design, and we especially see the need to further develop theoretical frameworks for TUIs that reveal and explain the *situated* nature of the many projects that adopt a tangible and aesthetic interaction approach.

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