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Ontology-Based User Modeling in an Augmented Audio Reality System for Museums*

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Abstract. Ubiquitous computing is a challenging area that allows us to further our understanding and techniques of context-aware and adaptive systems. Among the challenges is the general problem of capturing the larger context in interaction from the perspective of user modeling and human–computer interaction (HCI). The imperative to address this issue is great considering the emergence of ubiquitous and mobile computing environments. This paper provides an account of our addressing the specific problem of supporting functionality as well as the experience design issues related to museum visits through user modeling in combination with an audio augmented reality and tangible user interface system. This paper details our deployment and evaluation of ec(h)o – an augmented audio reality system for museums. We explore the possibility of supporting a context-aware adaptive system by linking environment, interaction object and users at an abstract semantic level instead of at the content level. From the user modeling perspective ec(h)o is a knowledge-based recommender system. In this paper we present our findings from user testing and how our approach works well with an audio and tangible user interface within a ubiquitous computing system. We conclude by showing where further research is needed.

Key words. audio augmented reality, context-aware, museum guide, ontologies, semantic technologies, tangible user interface, testing, ubiquitous computing, user evaluations user modeling

1. Introduction

Fundamental to human–computer interaction (HCI) is the design of interactive systems that support people's goals and respond to individual backgrounds. In ubiquitous computing it is equally important to consider the influence of context on people's interactions and experiences. The intent is, as Fischer argues "to say the 'right' thing at the 'right' time in the 'right' way" (Fischer, 2001). A critical factor in ubiquitous computing is that what is perceived as "right" is largely mediated by the context within which the users find themselves.

In the area of user–adapted interaction, user modeling has attempted to address many issues related to HCI. Fischer provides a clear account of the successes and

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future challenges of user modeling in HCI (Fischer, 2001). Among these challenges is the general problem of capturing the larger context in interaction (see Fischer, 2001, pp. 80–81). The imperative to address this issue is great considering the emergence of ubiquitous and mobile computing environments. This paper provides an account of addressing the specific problem of supporting functionality as well as the experience design issues related to museum visits through user modeling in combination with an audio augmented reality and tangible user interface system. We developed and tested a museum guide prototype, known as *ec(h)o* in order to research interaction design, user modeling, and adaptive information retrieval approaches that respond to the richness of a museum visit and the museum context.

Our aim is to support the limited input common to tangible user interfaces while maintaining rich and adaptive information output via a three-dimensional audio display. We believe an integrated modeling technique that is weighted toward modeling of implicit communication works well with a tangible user interface in creating a playful and discovery-rich experience. We believe this approach combined with ontologies and a rule-based system for information retrieval provides a richness of information that is responsive to the context and unique aspects of the museum visitor's interaction.

Our findings are both encouraging and cautionary. First, we found that it is possible to build a highly flexible and accurate user model and recommender system built on information collected from user interaction. This approach supported a user experience of liminal play and engagement. The ontologies and rule-based approach proved to be a strong combination. However, the ontological approach did not provide a clear enough contextual links between the artifacts and audio information and either more extensive knowledge engineering is needed or our approach has to be combined with stronger narration or discourse models.

In this paper we first review the general problem of context, our intended approach, and provide theoretical and related research as background. Following that we provide an account of our design and rationale for the prototype and its implementation. We give a detailed report of our evaluation and findings. We conclude with a brief analysis of our findings and discussion of future issues and research direction.

2. The Challenge of Capturing the Larger Context

Many HCI theorists and researchers identify issues of "context" as putting a strain on the traditional theories of HCI (Bodker, 1990; Dourish, 2004; Gay and Hembrooke, 2004; Nardi, 1995). As Nardi puts it, "we are beginning to feel a theoretical pinch, however – a sense that cognitive science is too restrictive a paradigm for finding out what we would like to know" (Nardi, 1995, p. 13).

For example, a visit to a museum reveals an everyday yet complex interaction situation. The factors within museum experiences are social, cultural, historical,

76 and psychological. The influences on the experience vary from the actions and pre-
77 vious knowledge of the visitor, visitor's learning style, and the dynamics of others
78 around them including friends, family and strangers. Naturally, the experience is
79 also affected by the presence of the artifacts and collections, which are products of
80 institutional history, curatorship, exhibition design, and architecture. The time of
81 day, duration of visit, room temperature and so on all have an impact. The expe-
82 rience can be characterized as *multivariate*, that is, it cannot be assessed by a sin-
83 gle factor such as exhibit design, signage, or time spent in front of an artifact (vom
84 Lehn, et al., 2001). Instead, the museum experience is subject to multiple influences
85 and results in multiple outcomes (Leinhardt and Crowley, 1998). Many similar sit-
86 uations have been discussed in design research such as how we work (Ehn, 1989),
87 seek information (Nardi and O'Day, 1999), learn (Gay and Hembrooke, 2004), and
88 live in our homes (Bell and Kaye, 2002; Tolmie et al., 2002).
89   In response to the issue of context, ethnographic and scenario-driven methods
90 have begun to take hold in HCI practice (Carroll, 2000, 2002; Suchman, 1987). An
91 emerging set of "context-based" theories for HCI has adapted ideas from an even
92 wider spectrum of psychological, social, political and philosophical theories based
93 on understanding human activity. For example, Nardi, Bødker, Gay and others
94 (Bodker, 1990; Gay and Hembrooke, 2004; Nardi, 1995) have advocated on behalf
95 of activity theory[1] . Dourish (2001, 2004) argues in his concept of embodied inter-
96 action that activity and context are dynamically linked – or "mutually constituent"
97 (Dourish, 2004, p.14).
98   Suchman (1987) argues that the nature of interaction between systems and peo-
99 ple require the same richly interpretive work required in human interaction, yet
100 with fundamentally different available resources. For example, humans make use
101 of non-verbal and inferential resources that can handle ambiguity and result in
102 intelligible actions. This is not the case for computers. Fischer argues this raises
103 two challenges: "(1) How can we capture the larger (often unarticulated) context
104 of what users are doing (especially beyond the direct interaction with the computer
105 system)? (2) How can we increase the 'richness of resources' available for computer
106 programs attempting user modeling to understand (what they are told about their
107 users) and to infer from what they are observing their users doing (inside the com-
108 putational environment and outside)" (Fischer, 2001). In addition, Fischer cites
109 Weiser and Bobrow (Bobrow, 1991; Weiser, 1993) in arguing that ubiquitous com-
110 puting (and ultimately tangible user interfaces) aims to address the context issue
111 by eliminating the separation between computational artifacts and physical objects,
112 thus creating computational environments that require new approaches to interface
113 and display.

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[1]A theory developed by psychologists in the early 1920s (Vygotsky, 1925/1982), as a research tool and an alternative framework for understanding human activity as it relates to individual consciousness.

3. Background and Related Research

This research ties together several distinct domains that we will briefly review. These include adaptive museum guides, non-graphical user interfaces, user modeling, and semantic technologies.

3.1. ADAPTIVE MUSEUM GUIDE SYSTEMS

It is difficult to directly compare ec(h)o with other museum systems since our approach employs a unique form of interaction. However, ec(h)o shares many characteristics with the adaptive systems of HyperAudio, HIPS and Hippie (Benelli et al., 1999; Oppermann and Specht, 2000; Petrelli et al., 2001). Similar to ec(h)o the systems respond to a user's location and explicit user input. HyperAudio uses a static user model set by a questionnaire completed by the visitor at start-up time. HIPS and Hippie infer the user model dynamically from the interaction but they treat user interests as static. All systems adapt content based on the user model, location and interaction history. There are however many key differences between ec(h)o and these systems. HyperAudio, HIPS and Hippie depend on a personal digital assistant (PDA) graphical user interface (GUI), for example Hippie's audio interface is dependant on the GUI in such instances as *earcons* (Oppermann and Specht, 2000). ec(h)o uses an audio display as the only delivery channel, and a tangible user interface for input. 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. (2003) by building a rich model of the concepts represented by the audio objects while HyperAudio and HIPS use partly pre-configured annotated multimedia data (Not and Zancanaro, 2000), and Hippie uses a simpler domain model. The last key difference is that ec(h)o treats user interests as dynamic, we look to evolving interests as a measure of sustainable interaction.

A museum guide that is conceptually more closely related to ec(h)o is the LISTEN project (Eckel, 2001), it is the follow-up to the Hippie system (Goßmann and Specht, 2002). It provides a personalized immersive audio environment delivered through wireless headphones. The LISTEN system is driven by the directional location tracking of the museum visitors and delivers "three-dimensional sound emitted from virtual sound sources placed in the environment" (Terrenghi and Zimmermann, 2004). The sound sequences are pre-processed by curators and artists. They are selected for the visitor based on a user-specified type. ec(h)o's user model changes dynamically based on the interaction. Its approach to the style of audio delivery and interaction model are also different. However, it is difficult to thoroughly compare LISTEN with ec(h)o as comprehensive evaluation results have not been reported beyond preliminary findings (Terrenghi and Zimmermann, 2004).

3.2. NON-GRAPHICAL USER INTERFACES

Prior to the evolution of adaptive and user modeling approaches in museum guide systems, there has been a strong trajectory of use of the PDA graphical user interface. Typically, hypertext is combined with images, video and audio (Aoki et al., 2002; Aoki and Woodruff, 2000; Proctor and Tellis, 2003; Semper and Spasojevic, 2002). Aoki and Woodruff have argued that in electronic guidebooks, designers are challenged to find the balance between burdening the visitor with the functions of selection, information management and contextualization (Aoki and Woodruff, 2000). The PDA graphical user interface approach comes at a cognitive and experiential cost. It requires the full visual attention of the visitor such that it is a competing element with the physical environment rather than a valued addition to that environment. Aside from projects like LISTEN, museum systems have mostly maintained the PDA graphical user interface 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.

Non-visual and non-graphical user interfaces, particularly audio display interfaces have been shown to be effective in improving interaction and integration with existing physical contexts. For example, Brewster and Pirhonen (Brewster et al., 2003; Pirhonen et al., 2002) 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 (Mynatt et al., 1998) 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. Audio augmented reality systems combined with tangible user interfaces often create very playful and resonant interaction experiences (Hummels and Helm, 2004). In fact, the distinction between augmented reality and tangible user interfaces can be blurry indeed (Ishii and Ullmer, 1997).

Tangible user interfaces like no other user interface concept is inherently playful, imaginative and even poetic. In addition, the concept has *immediacy* due to its physicality. Ishii and Ullmer's notion of *coupling bits and atoms* was informed by earlier work in graspable interfaces (Fitzmaurice et al., 1995) and real-world interface props (Hinckley et al., 1994). ec(h)o's tangible user interface draws on this notion by coupling an everyday and graspable object, a wooden cube with digital navigation and information (Ishii and Ullmer, 1997). Ishii was inspired by the aesthetics and rich affordances of scientific instruments (Ishii and Ullmer, 1997) and the transparency of a well-worn ping-pong paddle (Ishii et al., 1999). 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 (Crampton-Smith, 1995) was an early embodiment of the immediate and playful qualities of tangible user

195 interfaces. The prototype uses marbles to represent messages on the machine. A
196 person replays the message by picking up the marble and placing it in an inden-
197 tation on the machine. Ishii's PingPongPlus (Ishii et al., 1999) explores the inter-
198 twining of athletic play with imaginative play. The ping-pong table becomes an
199 interactive surface. The ball movement is tracked and projections on the table of
200 water ripples, moving spots, and schools of fish among other images react wherever
201 the ball hits the table. While ec(h)o is more constrained in its play, the everyday
202 wooden cube provides entry to a qualitatively diverse experience of interaction.
203   Over the years, various frameworks and interaction models have been proposed
204 to better define tangible user interfaces. Holmquist and others (Holmquist et al.,
205 1999) proposed defining concepts of containers, tools, and tokens. Ullmer and Ishii
206 (Ullmer and Ishii, 2001; Ullmer, 2002; Ullmer et al., 2005) proposed a framework
207 known as the MCRit that highlighted the integration of representation and con-
208 trol in tangible user interfaces. Shaer and others have extended MCRit to propose
209 their Token and Constraints (TAC) paradigm (Shaer, 2004). Most relevant to our
210 approach is Fishkin's proposed taxonomy which is situated and contextual in its
211 thinking (Fishkin, 2004). Fishkin's taxonomy is a two-dimensional space across the
212 axes of *embodiment* and *metaphor*. Embodiment characterizes the degree to which
213 "the state of computation" is perceived to be in or near the tangible object. Met-
214 aphor in this sense is the degree to which the system's response to a user's action
215 is analogous to a real-world response to a similar action. Further, Fishkin divides
216 metaphor into *noun metaphors*, referring to the shape of the object, and *verb met-
217 aphors*, referring to the motion of an object. For example, in ec(h)o, according to
218 Fishkin's taxonomy embodiment would be considered "environmental" since the
219 computational state would be perceived as surrounding the visitor given the three-
220 dimensional audio display. In regard to metaphor, ec(h)o would be a "noun and
221 verb" since the wooden cube is reminiscent of the wooden puzzle games in the
222 museum and the motion of the cube determines the spatiality of the audio as
223 turning left in the real-world would allow the person to hear on the left.

224 3.3. USER MODELING

225 'Knowledge-based HCI' (Fischer, 2001) explores the possibility of implicit com-
226 munication channels between a human and a computer. These channels capture
227 the idea of shared knowledge about problem domains, communication processes,
228 and agents involved with communicating parties. This notion is very close to the
229 goals of user modeling (Wahlster and Kobsa, 1989). Several researchers worked on
230 the incorporation of user modeling in order to improve the collaborative nature
231 of human–computer systems (for examples see Fischer, 2001). In our research we
232 expand the role of user modeling into the realms of audio augmented reality and
233 tangible user interfaces.
234   In the context of our work, the user model performs the function of a recom-
235 mender system (Resnick and Varian, 1997). "Recommender systems represent user

236   preferences for the purpose of suggesting items to purchase or examine" (Burke,
237   2002). Several types of recommendation techniques have been developed: collabo-
238   rative, content-based, demographic, utility-based, and knowledge-based. Often the
239   researchers combine several techniques to achieve maximum effect. Burke (2002)
240   compares the recommendation techniques from the perspective of their ability
241   to deal with the 'ramp-up' problem (Konstan et al., 1998): an introduction of
242   new users and new items. In this regard, knowledge-based recommenders perform
243   favorably. This is an important feature for ubiquitous computing environments that
244   often manifest the 'walk-up-and-use' characteristic. Knowledge recommender sys-
245   tems require three types of knowledge (Burke, 2002): catalog knowledge or knowl-
246   edge about objects to be recommended, functional knowledge of mapping between
247   user needs and objects, and user knowledge. In the case of ubiquitous comput-
248   ing applications the functional knowledge must include the knowledge of the envi-
249   ronment since context-awareness is a key requirement of ubiquitous computing
250   systems. The knowledge of the user can be specific to the domain of recommen-
251   dation; or can expand to general user modeling.

252   From a user modeling perspective, ec(h)o is a knowledge-based recommender
253   system. Similar to Towle and Quin's (2000) proposal, we build explicit models
254   of users and explicit models of objects. However, in ec(h)o the models are not
255   built around specific content but rather ec(h)o uses ontologies at a higher level of
256   abstraction. Users, objects, and environment are annotated with these ontologies.
257   Another significant feature where ec(h)o differs from other knowledge-based rec-
258   ommender systems (for example Entrée, Burke, 2002), is that it does not solicit
259   user's feedback about the quality of recommendations.

260   In addition to user modeling, capturing user interests is a central research focus
261   of several disciplines such as information retrieval and information filtering. Most
262   such systems are based on document retrieval where a document's content is ana-
263   lyzed and explicit user feedback is solicited in order to learn or infer user inter-
264   ests. In our approach, there is no direct feedback from the user. Our prototype
265   can be categorized as a personalized system, as it observes user's behavior and
266   makes generalizations and predictions about the user based on their interactions
267   (Fink and Kobsa, 2002; Seo and Zhang, 2000). Our approach to observation of
268   user behavior is unobtrusive, similar to approaches to monitoring user browsing
269   patterns (Lieberman, 1995; Mladenic, 1996) or user mouse movement and scrolling
270   behavior (Goecks and Shavlik, 2000).

271   3.4. SEMANTIC TECHNOLOGIES

272   Modeling is an integral part of the user modeling by definition. Several types
273   of models are used ranging from simple categories through statistical models,
274   Bayesian networks to formal knowledge models as known in symbolic artificial
275   intelligence (Wahlster and Kobsa, 1989). It is these latter models that potentially
276   benefit the most from semantic web research.

277   The semantic web initiative (Berners-Lee et al., 2001) aims to achieve a vision
278 of creating a web of meaning. It argues for a set of technologies and techniques
279 that integrates artificial intelligence into the core of the World Wide Web. The cor-
280 nerstone of semantic web is ontologies (Chandrasekaran, et al., 1991) that provide
281 a mechanism for modeling domains of interest. The formalization is essential for
282 reasoning (Post and Sage, 1990) about the domain. Ontologies and reasoning are
283 basic semantic web technologies that are useful not only in traditional web appli-
284 cation domains such as knowledge management, data integration and exchange,
285 or agent coordination but are extensively used in other domains for representa-
286 tion purposes. For example, Baus and colleagues (2002) use ontologies to model
287 the environment in a mobile navigation system. In the Story Fountain system
288 (Mulholland et al., 2004), ontologies are used to describe stories and the domain
289 in which they relate. In order to determine the appropriate domain, reasoning is
290 employed for the selection and organization of resources from which the stories are
291 built.
292   A main advantage of ontologies, as the concept has developed within semantic
293 web research is the ability to cross-link different domains (Noy and Hafner, 1997).
294 In the area of user interaction this provides us with a clear formalism to connect
295 knowledge about the user, environment, and user aims.
296   An obstacle in connecting and sharing data, is that often the knowledge cap-
297 tured within an application is at too low a level of abstraction; it is too domain
298 specific. Ontologies provide a mechanism for building several layers of abstraction
299 into the model (Noy and Hafner, 1997).
300   The assumption we are testing in our approach is that we can use ontologies
301 and semantic web techniques to build interactive systems that successfully operate
302 at higher levels of abstraction. Such a design can be shared across multiple applica-
303 tions. Furthermore, only low-level application-specific logic has to be developed for
304 a new application. Our approach tests this assumption in the context of an audio
305 augmented reality system with a tangible user interface.

306 ## 4. Design and Rationale

307 The aims of our design were to develop a ubiquitous computing museum guide
308 that supports *liminal* and engaging play in its user experience; investigates user
309 modeling limited by implicit input from users' actions; and delivers a wide breadth
310 of information associated with artifacts on exhibit via audio display that is
311 responsive to users' changing interests. In short, we aimed to investigate less
312 explored avenues in current museum guide systems research including play, embod-
313 ied interaction, and highly associative as well as contextualized content delivery.
314   In the last decade, advances in audio museum guides include visitor–driven
315 interaction, access to large collections of supplementary information for museum
316 artifacts, and the development of adaptive and context-aware systems. Many of
317 these advances have come on the heels of innovations in mobile computing

318 including computer processing capabilities, data storage, connectivity and size. This
319 has culminated in the growing use of PDA devices combined with sensor systems
320 for use as interactive museum guides (Proctor and Tellis, 2003). Yet, outside the
321 domain of museums, for example in the area of games and ubiquitous computing,
322 Björk and his colleagues have identified the need to develop past end-user devices
323 such as mobile phones, personal digital assistants and game consoles (Bjork et al.,
324 2002). They argue that we need to better understand how "computational services"
325 augment games situated in real environments. Our design ethnography observa-
326 tions confirmed that museum interactives such as computer kiosks were less used
327 than physical and play-based interactives (Wakkary and Evernden, 2005). In addi-
328 tion, Proctor (Proctor and Tellis, 2003) has found that in museum use PDAs cre-
329 ate expectations of a multimedia experience that lessens the relationship between
330 the visitor and the artifacts. As examples, visitors tend to want more of every-
331 thing yet they quickly lose interest in audio/visual and interactive clips; the visual
332 screen made the moments in-between interactions problematic since if the screen
333 became blank, visitors thought the devices were broken, yet they did not want the
334 screen on all the time since it distracted them from the exhibition. The main point
335 of these findings is that the focus of the visitor is on the experience of the device
336 rather than the experience of the museum.

337   The anthropologist Genevieve Bell has described museums in terms of *cultural
338 ecologies* (Bell, 2002). Bell sees the museum visit as a ritual determined by space,
339 people and design. She decomposes the visiting ritual into three observational cat-
340 egories: space, visitors, and interactions and rituals. Different types of museums
341 have different ecologies, for example Bell describes different attributes in each of
342 the observational categories between art museums and science museums. These ecol-
343 ogies are seen to be distinct and supportive of different kinds of museum visits. Bell
344 also describes concepts that are common to all museum ecologies. We have drawn
345 on and extended two of these concepts in developing our approach, *liminality* and
346 *engagement*.

347   Liminality defines museums as places that embody an experience apart from
348 everyday life. Positive museum experiences are transformative, spiritual, and even
349 moving. A museum visitor should be inclined to pause and reflect, thus liminali-
350 ty can be seen to permit a deeper engagement. Engagement is a key concept for
351 museums as people go to museums to learn, however this engagement is often
352 packaged in an entertaining way; museums are a balance between learning and
353 entertainment spaces. It is easy to see how liminality and engagement include ludic
354 experiences in which play and discovery are encouraged. In our adult lives, play
355 is an experience set apart from our everyday activities: Huizinga refers to play
356 as invoking a "magic circle", a liminal space for games (Huizinga, 1964); Carse
357 describes "deep play" as a profound level of ritualized engagement causing reflec-
358 tion on everyday experiences (Carse, 1987); and psychologist Csikszentmihalyi has
359 described "flow" as a high level of engagement, risk and challenge found in play
360 (Csikszentmihalyi, 1990).

361   Our aims led us to a design that was inherently minimal and playful. In order
362 to move past the limitations of device-centered approach we developed a tangible
363 interface supported by an audio display, and a user model and adaptive informa-
364 tion retrieval system. The tangible interface creates a playful transition between the
365 physical space and the virtual information space of the audio. The audio display
366 creates a virtual context that allowed us to create new layers of engaging experien-
367 tial spaces such as ambient sounds and conversational information delivery.
368   Given the limited input and output of our interface, we chose a user model
369 approach to act as a mediator for the visitor. The user model dynamically inte-
370 grates movement interaction and visitor content selection into initial pre-selected
371 preferences. Based on this dynamic model we could infer potential interests and
372 offer a corresponding range of content choices even as visitors' interests shifted
373 over time. In addition, the use of semantic technologies allowed for coherent and
374 context responsive information retrieval.
375   While arguably other interface approaches could have been utilized in conjunc-
376 tion with the integrated modeling technique, such as a simple push-button device
377 for input or a mobile text display device for output, such a strategy would be
378 incongruent with our experience design goals. Nevertheless, we designed our user
379 modeling and semantic technologies technique such that it could be easily modi-
380 fied for other interfaces and applications.
381   The project was informed by ideas of ecologies, like Bell's *cultural ecologies* and
382 prominently used audio. This combination led us to the name ec(h)o, which is
383 intended to signify the words *eco*, an abbreviation for the word "ecology", and
384 *echo*, denoting the acoustic aspects of the project.

385 4.1. VISITOR SCENARIO

386 In order for us to better describe the system we developed, we provide below a
387 typical visitor scenario. It should be noted that the scenario describes aspects of
388 the project that are not the focus of discussion in this paper such as soundscapes.
389 The scenario refers to an exhibition about the history and practice of collecting
390 natural history artifacts in Canada at the Canadian Museum of Nature in Ottawa:

391   *Visitors to the Finders Keepers exhibition can use the ec(h)o system as an interactive*
392   *guide to the exhibition. Visitors using ec(h)o begin by choosing three cards from a set of*
393   *cards displayed on a table. Each card describes a concept of interest related to the exhibi-*
394   *tion. The cards include topics such as "aesthetics", "parasites", "scientific technique" and*
395   *"diversity". A visitor chooses the cards "collecting things," "bigness," and "fauna biology."*
396   *She gives the cards to an attendant who then gives the visitor a shaped wooden cube that*
397   *has three colored sides, a rounded bottom for resting on her palm and a wrist leash so*
398   *the cube can hang from her wrist without her holding it. She is also given a pair of head-*
399   *phones connected to a small, light pouch to be slung over her shoulder. The pouch contains*
400   *a wireless receiver for audio and a digital tag for position tracking (see Figure 1).*
401   *Our visitor moves through the exhibition space. Her movement creates her own*
402   *dynamic soundscape of ambient sounds. As she passes a collection of animal bones she*

Figure 1. A Museum visitor testing the ech(o) system.

403 *hears sounds that suggest the animal's habitat. The immersive ambient sounds provide*
404 *an audio context for the collection of objects nearby.*
405   *As she comes closer to a display exhibiting several artifacts from an archaeologi-*
406 *cal site of the Siglit people, the soundscape fades quietly and the visitor is presented*
407 *with three audio prefaces in sequence. The first is heard on her left side in a female*
408 *voice that is jokingly chastising: "Don't chew on that bone!" This is followed by a brief*
409 *pause and then a second preface is heard in the center in a young male voice that*
410 *excitedly exclaims: "Talk about a varied diet!" Lastly, a third preface is heard on her*
411 *right side in a matter-of-fact young female voice: "First dump . . . then organize." The*
412 *audio prefaces are like teasers that correspond to audio objects of greater informational*
413 *depth.*
414   *The visitor chooses the audio preface on the left by holding up the wooden cube*
415 *in her hand and rotating it to the left. This gesture selects and activates an audio*
416 *object that is linked to the audio preface of the scolding voice warning against chew-*
417 *ing on a bone. The corresponding audio object delivered in the same female voice yet*
418 *in a relaxed tone, is about the degree of tool making on the part of the Siglit people:*
419 *"Artifact #13 speaks to the active tool making. Here you can actually see the marks*
420 *from the knives where the bone has been cut. Other indicators include chew marks . . .*
421 *experts are generally able to distinguish between rodent chew marks and carnivore chew*
422 *marks."*
423   *After listening to the audio object, the visitor is presented with a new and related*
424 *audio preface on her left, and the same prefaces are heard again in the center and to*
425 *her right. The audio prefaces and objects presented are selected by the system based*
426 *on the visitor's movements in the exhibition space, previous audio objects selected, and*
427 *her current topic preferences.*

428 4.2. INTERACTION MODEL

429 Our interaction model relies on a turn-taking approach generally based on
430 the structure of a conversation[2]. We designed our audio objects in two parts,

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[2]We use the term "conversation" in the context of the use of conversation analysis to inform HCI design. The idea of using conversation analysis concepts as a structural metaphor for non-speech interfaces is not unique in HCI, see for example (Norman and Thomas, 1990).

431 *prefaces* and *audio objects*: *prefaces* act as multiple-choice indices for the more
432 detailed *telling* of the audio object. The tangible user interface provides input for
433 a response to the delivery of *prefaces*.

434   The implementation went as follows: *ec(h)o* offers the visitor three short audio
435 pieces as *prefaces*. The system is in effect offering three turn-taking possibilities for
436 the visitor. Switching between the stereo channels created localization: we used the
437 left channel audio for the left, right channel audio for the right, and both channels
438 for the center. It is a simple *egocentric* (Brewster et al., 2003) spatial structure that
439 allows the three *prefaces* to be distinguishable and an underlying content categori-
440 zation structure to exist. The spatialization was mapped to the tangible user inter-
441 face for selection. The visitor *responds* by rotating the wooden cube in his hand
442 and thus selecting a *preface*. The system delivers the audio object related to the
443 *preface*. After the delivery of the object, the system again offers three *prefaces*. The
444 visitor's response is expressed through the gesture selection with the wooden cube.
445 Additionally, the system may be met by no response, because the visitor does not
446 wish to engage the system. The system will then enter into a silent mode. The
447 visitor may also have moved away and the system will then initiate a soundscape.

448   The *prefaces* were written to create a sense of surprise and discovery. The audio
449 recordings used a diverse set of voices that were informal in tonality and style.
450 This added to the conversational feel and created an imaginary scene of a virtual
451 cocktail party of natural historians and scientists that followed you through the
452 museum. The audio objects were developed through interviews with museum staff
453 and researchers (Wakkary et al., 2004).

454   A topic of interest is conceptually represented by each preface or spatial loca-
455 tion. The structure is very simple given the limited choices of three options. The
456 navigation is as follows: a visitor is played three *prefaces,* one to his left, another
457 to his center and the third to his right. He selects the *preface* on his right side
458 and listens to the linked audio object. On the subsequent turn the visitor hears the
459 same two *prefaces* he did not select, and again he hears them to his left and to his
460 center. Since he previously chose the *preface* to his right he now hears a new *pref-
461 ace* in that location. If the visitor then selects the center *preface,* on the subsequent
462 turn only that *preface* is replaced by a new *preface* in the center position. If a *pref-
463 ace* has been replayed three times without being selected, it is replaced by a *preface*
464 linked to an audio object of a completely new topic.

465   The audio objects are semantically tagged to a range of topics. At the begin-
466 ning of each interaction cycle, three audio objects are selected based on ranking
467 using several criteria such as current levels of user interest, location, interaction
468 history, etc (see Section 4.4.2). The topics of each object are not explicit to the vis-
469 itor; rather the consistency and content logic are kept in the background.

470   In regard to the design process, many of the design choices were made through
471 a series of participatory design workshops and scenarios, details of which have
472 been written in another paper (Wakkary, 2005, in press). For example, the tan-
473 gible user interface and its implementation as an asymmetrically shaped wooden

474 cube resulted from these workshops. We also recreated the exhibition environment
475 in our labs; this aided us in the design the interactive zones and audio display.

476 4.3. USER MODEL

477 At the core of the ec(h)o's reasoning module is a user model (Wahlster and Kobsa,
478 1989) that is continually updated as the user moves through the exhibition space
479 and selects audio objects.
480   Figure 2 shows an interaction schema of the user model with other modules.
481 There are two main update sources in the system. First, as the user moves through
482 the exhibition the speed of the movement and/or stops in relation to different arti-
483 facts provides updates to the user model. The user type is computed based on the
484 speed and uniformity of the user movement. The slowing down and rest points in
485 front of an artifact are interpreted as an interest in concepts represented by the
486 artifact.
487   The second source of updates to the user model considers a user's direct inter-
488 action when selecting an audio object. In the model this correlates to an increased
489 interest on behalf of the visitor in concepts presented by the audio object and this
490 is reflected in the user's interaction history.

491 4.3.1. *User Model Components*

492 *Interaction history* is a record of how the user interacts with the augmented
493 museum environment. Two types of events are stored in the interaction history: the
494 user's movement and user's selection of objects. The user path through the museum
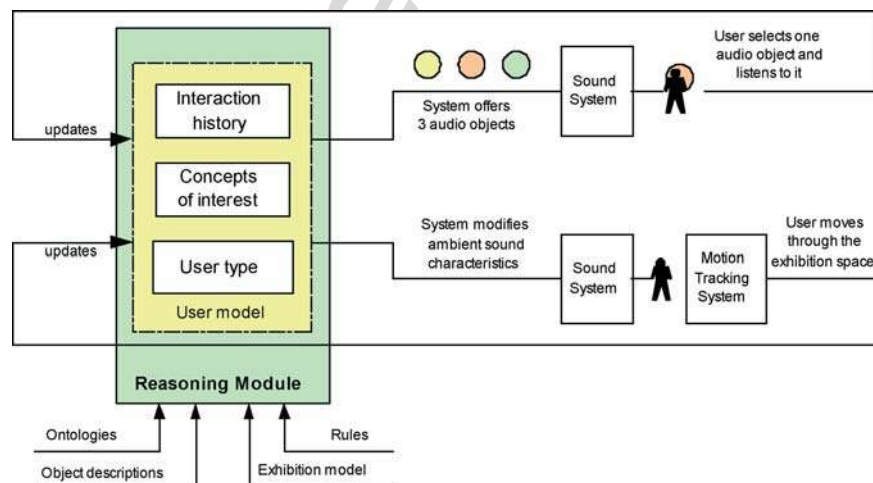

Figure 2. Interaction of usermodel with other modules.

495 is stored as discrete time-space points of locations on the path. A second type of
496 information stored in interaction history is the user's selections of audio objects.
497   *User type* in the museum context is well studied in museum studies (Dean,
498 1994) and is used in several systems personalizing the user experience (Serrell,
499 1996; Sparacino, 2002). In the case of ec(h)o, several categorizations were used,
500 for example one user may review almost every artifact on her path, and another
501 user may be more selective and choose artifacts that have only certain concepts.
502 Our categorization of user types is based on Sparacino's work (Sparacino, 2002).
503 It classifies users into three main categories. These categories were validated by our
504 site studies and interviews with staff at various museums:

505 • The avaricious visitor wants to know and see as much as possible. He is
506   almost sequential, and does not rush;
507 • The selective visitor explores artifacts that represent certain concepts and is
508   interested in only those concepts;
509 • The busy visitor does not want to spend much time on a single artifact prefer-
510   ring to stroll through the museum in order to get a general idea of the exhi-
511   bition.

512 In ec(h)o, the user type category is not static but is updated every minute. The
513 rules for the type specification consider the location data accumulated within the
514 longer time interval and concepts of previously selected audio objects.
515   *User interests* are represented as a set of weighted concepts from the 'concept
516 ontology'[3] (described in Section 4.4). In ec(h)o, each artifact and exhibition is
517 annotated with a set of concepts from the same ontology. The audio objects pres-
518 ent a set of particular concepts as well. In each interaction step the system updates
519 the user interests in response to two update channels described above. The update
520 process is described in detail in Section 5.5.
521   The interaction of the user with artifacts and audio objects is stored in the
522 interaction history that together with the user types are used to infer the user's
523 interests. Several aspects of the update process are parameterized. We discuss the
524 user model parameters and the user model update process in Section 4.5 after we
525 introduce the model for representing content and context in the next section.

526 4.4. INFERENCE-BASED AUDIO OBJECT RETRIEVAL

527 The audio object retrieval process is performed by the rules that encode multiple
528 object selection criteria. The rules match semantic descriptions of the objects and
529 the museum environment with user information maintained by the user model.

---

[3]We use term 'interest' or 'user's interest' when referring to the user model. We use the term 'con-
cept(s) of interest' when referring to the concepts when used to annotate the objects or before they
were used to modify the level of corresponding interests in the user model. The relation of the inter-
est in the user model to the concepts in the concept ontology is crucial as it links user model to
the model representing content and context as described in the subsequent section.

530   The content model is based on the semantic description of all the properties of
531 the audio objects and the museum environment that could help us to select visitor
532 and context relevant audio objects. Our ontological model builds significantly on
533 the standard Conceptual Reference Model (CRM) for heritage content developed
534 by CIDOC (Crofts et al., 2003). The CRM provides definitions and a formal struc-
535 ture for describing the implicit and explicit concepts and relationships used in the
536 cultural heritage domain. We have also developed several ontologies specifically for
537 the purpose of ec(h)o.

538 4.4.1. *Ontologies for Describing Content and Context*

539 The content of the audio object is not described directly but annotated with three
540 entities: concepts of interest, topics, and themes. The *concepts of interest*[4] describe
541 the domains that are expressed by the audio objects such as 'evolution', 'behav-
542 ior', 'lifestyle', 'diversity', and 'habitat'. We realized that it would be impossible to
543 model the content at the actual descriptive level of objects, science and events, so
544 we opted for higher levels of abstraction that in turn provide a unifying degree
545 of formalization for all audio objects in the collection. The starting point for our
546 concept ontology was a set of concepts used by the museum curators at the time
547 of designing the exhibit. We have further extended this initial ontology with con-
548 cepts identified through analysis of the content of audio objects used in ec(h)o and
549 through interviews with museum researchers (Wakkary et al., 2004). As a result the
550 concept ontology has a flat structure with 39 identified concepts[5]. These concepts
551 are mapped to the Dewey Decimal Classification (represented as an ontology),
552 which indirectly gives our concept ontology a hierarchical structure that can be
553 used for drawing inferences.
554   The concepts play a significant role in the system in linking audio objects and
555 museum artifacts with user interests. The user model (described in the section
556 above) captures a level of user interest in each concept. The audio object retrieval
557 mechanism uses those levels to determine the most appropriate audio objects for
558 the next interaction turn. Similarly, the exhibits are annotated with the concepts
559 that are visually represented in the exhibit (so called *visual concepts*). When a vis-
560 itor slows down or stops in the exhibit those visual concepts are used to update
561 the user model.
562   A *topic* is a higher-level category for describing several objects within the same
563 exhibit. Objects annotated with different concepts of interest can still have the
564 same topic. *Themes* are defined as entities that are represented across several exhi-
565 bitions and are supported by one or more topics; for example, the theme of
566 'bigness' can include topics such as 'invertebrates' and 'marine biology'.

---

[4] The concepts of interests represent interests as used by the user model introduced in Section 4.3.
[5] As a result the concrete user model can contain up to 39 interests. However, this is very unlikely
as a result of the implemented user model update process described in Section 4.5.
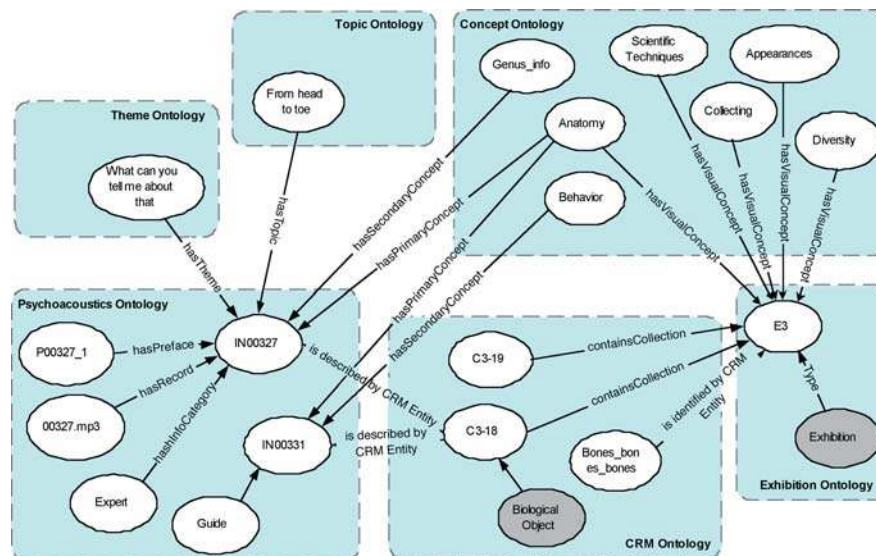
Figure 3. ec(h)o content ontologies.

567   We have used *CRM* to describe the museum exhibits and artifacts. CRM pro-
568 vides a comprehensive model for describing physical entities, temporal entities and
569 places. We have used CRM to model events and places related to the objects and
570 narratives captured in the audio objects.
571   Figure 3 shows an example how audio objects ('IN00327' and 'IN00331') are
572 represented in ec(h)o. Both objects exist as independent entities and are related
573 through several ontological relations. The audio object 'IN00327' is annotated with
574 the concepts of interest 'Anatomy' and 'Genus Info.' 'IN00327' has a topic 'From
575 Head to Toe' and supports the theme 'What Can You Tell Me About That'. The
576 audio object 'IN00331' is annotated with the concepts of interest 'Anatomy' and
577 'Behavior' but is a 'Guide' object (some relations for 'IN00331' were omitted from
578 the picture). The 'Guide' objects differ from the 'Expert' objects by being directly
579 related or referring directly to the artifacts in the exhibition, while the content
580 of 'Expert' objects describes more general knowledge and is reusable in different
581 contexts.
582   Both objects 'IN00327' and 'IN00331' describe the same museum artifact 'C3-
583 18' representing a 'common dolphin skull' artifact in the exhibition 'E3'. The 'C3-
584 18' is an instance of a 'Biological object' class in the CRM and has many proper-
585 ties that link it to other artifacts in the exhibition (not shown in the picture). The
586 exhibit instance 'E3,' from the exhibit ontology holds the information about the
587 artifacts in the particular exhibit. In addition, 'E3' is annotated with visual con-
588 cepts 'Collecting', 'Anatomy', 'Scientific Techniques', 'Diversity' and 'Appearances'
589 that are represented visually in this particular exhibit.

590 Both topics and themes are common tools used by the curators when design-
591 ing a museum exhibition. In ec(h)o, we use topics and themes in the audio object
592 selection process to support fluency of the interaction between the user and the
593 system. We use CRM referents of place and time period of the artifacts for the
594 selection of the corresponding background sounds appropriate for the presented
595 audio objects.

596 4.4.2. *The Audio Object Selection Process*

597 The audio object selection is based on the ranking of objects. Multiple criteria
598 contribute to the ranking and the audio object with highest ranking is selected.
599 The ranking criteria reflect the dynamic nature of the interaction that is repre-
600 sented by a level of current user interests, previously listened to audio objects and
601 exhibits visited. The system is not intended to be a guide system but rather to
602 enrich the experience of the exhibit and artifacts.
603 The ranking criteria are listed in Table I. Criterion 1 contributes to audio
604 objects by further describing previously described artifacts while criterion 2 con-
605 tributes to the ranking of guide audio objects if a previous audio object was also
606 a guide audio object or the user entered a new exhibit[6]. Criteria 3–5 provide for
607 the continuity in the interaction by contributing to the audio objects that elaborate
608 on the same concepts within the same topic and theme. The contribution of crite-
609 rion 6 is scaled with the current levels of user interests (which change after each
610 interaction step).
611 The selection process is parameterized and the contribution of each criterion is
612 weighted by its relative importance. Instead of doing extensive testing for weight
613 values the weights were established in consultation with an expert in interactive
614 narrative and storytelling. Table I shows the relative weight distribution for rank-
615 ing criteria. The only criterion, which we have tested for a range of values, is the
616 contribution between matching concepts of interest in the user model and match-
617 ing audio object descriptions (Criterion 6, see Section 7 for evaluation and testing
618 results). The remaining values were kept stable. The 'From', 'ec(h)o', and 'To' col-
619 umns show the absolute values for the weights and '%' column show the relative
620 contribution to the overall ranking[7]. The 'From' column shows the absolute values
621 for the weights when interests in the user model contributed to the object rank-
622 ing, at a minimum of 13% and 'To' column shows the weight values when interests
contributed, up to a maximum of 48%.

---

[6]Guide objects provide for quick orientation in an exhibit with multiple artifacts by directly referring
to those artifacts.
[7]The objects score in all criteria, otherwise the percentage contribution is shifted towards the
matched criteria. Also, it should be noted that while criteria 1–5 always contribute their full weight
the contribution from the criterion 6 varies. The value of criterion 6 shown in the table is the user
level of interest in the audio object represented at the maximum level.

Table I. Weight distribution for object ranking

Criteria	From	%	ec(h)o	%	To	%
1. Describing artifact previously referred to by the audio object	10	22	10	16	10	13
2. Object is a 'guide' type of audio object describing an artifact	6	13	6	10	6	8
3. Continuing in previous topic	8	18	8	13	8	11
4. Continuing in previous theme	8	18	8	13	8	11
5. Continuing description of concepts in previous audio object	7	16	7	11	7	9
6. Concepts in the object match user interest	5.6	13	22	36	36	48

The middle column labeled 'ec(h)o' shows the actual values used in the final demonstration. The distribution of ranking contributions in the 'ec(h)o' column is used for audio object selection while a visitor remains within the same exhibit. When users change exhibits only the criteria 2, 3, 4, and 6 are used with the relative distribution of 14, 18, 18, and 50%[8] respectively.

The criteria are implemented in the form of forward chaining rules in which the condition part matches semantic characteristics of each audio object with the interaction history and user interests. If the characteristics of the audio object satisfy the condition, the rule is fired and the ranking for the object is increased. Several rules can be fired for the same audio object. After all rules for the matching audio objects are fired and contributed to ranking, the object with the highest ranking is selected.

For example, the rule below represents criterion 1 in Table I. The rule adds ratings to the audio object that describes the same artifact as the object being replaced. The rule checks whether candidate object `?in2` describes the same artifact `?a` as previous object `?in1`. Next, we make sure that `?in2` is not an exhibition object but an actual artifact within the exhibition. The `PropertyValue` is a fact representing semantic descriptions in the form of triples (obtained from the ontologies via transformation when loaded into the inference engine). For brevity, we have also used XML entity descriptions to refer to the namespaces of the ontologies.

---

[8]It should be noted that the levels of interests in the user model are updated with visual concepts in the new exhibit *before* they are used to calculate the ranking. As a result the influence of the context of the new exhibit (in addition to 14% for guide objects) is strongly represented in a 50% contribution from the user model.

```
(defrule artifact2artifact- - -1
  (user-group (user ?u) (group 1))
  (replace (user ?u) (context ?e) (object ?in1) (context ?e)
           (sequence ?seq) (time-chosen ?t))
  (test (neq ?in1 nil))
  (in-context ?a ?e)
  (PropertyValue &psch;#describes ?in1 ?a)
  (PropertyValue &psch;#describes ?in2 ?a)
  (not (PropertyValue &rdf;#type ?a &crm;#exhibition))
  (not (replaced (user ?u) (next-object ?in2) ))
=>
  (call ?*object-ratings* addRating ?u ?in1 ?in2 ?
           *artifact-rating* ?t))
```

643 For more details about representation and information retrieval aspects in ec(h)o
644 see (Hatala et al., 2004) and (Hatala et al., 2005).

645 4.5. USER MODEL UPDATE PROCESS

646 The rule-based user model provides a generic structure that enables the system
647 developer to consider several inputs that influence user interests. In addition, the
648 model allows the developer to tune the relative influence of each input using a set
649 of parameters. In ec(h)o, we interpreted two aspects of the user interaction with
650 the system and environment: user movement and audio object selection. Each of
651 these actions has a different effect on the model of user interests.
652   *Influence of initial interest selection.* A new user starts with a blank user model.
653 In order to bootstrap the model we ask each visitor to indicate initial interests.
654 Prior to entering the exhibition space the user selects a set of cards represent-
655 ing concepts of interest that best match their interests (see Section 4.1 Visitor
656 Scenario). An operator enters the chosen concepts of interest into the user model
657 as user's initial interests[9] and from that point the system evolves the user model
658 through the two update channels described below. The parameter controlling the
659 initial interests' weight can be set by the developer.
660   *Influence of object selection on user interest.* In ec(h)o each audio object is
661 described by two concepts of interest: primary and secondary. When a user selects
662 an audio object its primary and secondary concepts of interest are used to update
663 the corresponding user's interests if they were already present in the user model, or
664 adds them to the user model if they were not previously included in the model. As
665 a result, the model is *dynamic* and the number of interests in the model can vary

---

[9]In a fully implemented system the same could be achieved automatically by asking the user to select a set of initial interests using a computer kiosk system.

666 depending on each user's individual interaction with the system. The model enables
667 the developer to specify the parameters of how much the primary and secondary
668 concepts of interest in the selected audio object increase the level of corresponding
669 interests in the user model.

670 *Influence of location change (context)*. The second type of input in ec(h)o is
671 user movement. Each exhibit in ec(h)o is annotated with concepts that are visually
672 represented in the exhibit (visual concepts, Section 4.4.1). For example, an exhibit
673 with photos of pioneer explorers is annotated with a concept of 'History of Col-
674 lecting'. When a user stops in a particular location (exhibit), the system interprets
675 this as interest in the visual concept. The user model updates or adds the visual
676 concepts as interests to the model. A set of parameters controls the influence of
677 the visual concepts on the model.

678   The user model uses a spring model to keep interests balanced. The level of
679 interest is represented by the real number and can range[10] from 0 to 10. The sum
680 of all interests never exceeds the value of 30. In the model we consider only posi-
681 tive influences from the user interaction that directly increase the level of some of
682 the interests. When this increase causes an imbalance (the sum is above 30), the
683 implemented spring model proportionally decreases values of other interests. This
684 mechanism supports a highly dynamic nature of the user model and guarantees
685 that only a certain number of interests can have a high value. Another charac-
686 teristic of this mechanism is that it forces the system to 'forget' the 'older' inter-
687 ests in favor of recently invoked interests. When the interest value drops below a
688 set threshold during the update process the interest is removed from the model
689 altogether.

5. Implementation

691 Figure 4 shows the architecture of the ec(h)o system. ec(h)o was implemented and
692 tested in a public exhibition space at Canadian Museum of Nature in Ottawa in
693 March 2004. The system used a combined Radio Frequency Identification (RFID)
694 and optical sensing for position tracking. The system tracked the "x, y" coordi-
695 nates of each visitor approximately every 1.6 s with a spatial resolution of 0.3 m.
696 In terms of hardware, the position tracking system used a separate array of video
697 cameras but all sensing data was integrated.

698   In addition, we used the "eyes" vision system[11] to allow for quicker refresh
699 rates. The vision module included color video cameras connected to desktop com-
700 puters to cover specified interactive zones. A camera positioned on the ceiling

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[10]The range of the values for individual interests and their total was selected to achieve a desired
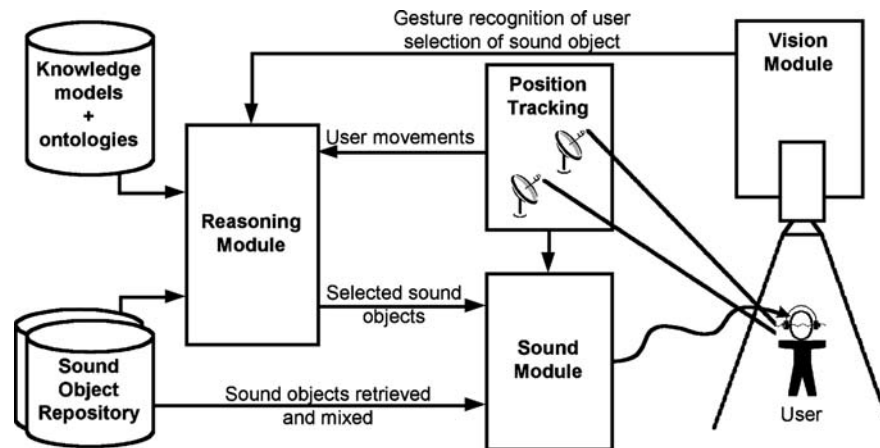proportion between object ranking criteria (see Section 4.4.2).
[11]http://www.squishedeyeballs.com

Figure 4. ec(h)o architecture.

701 above the artifacts was used to detect the rotation of the cube by visitors within
702 one camera zone[12] in combination with the positioning system.
703   The sound module consists of a sound-file playback and mixing system driven
704 by the position-tracking module. User position information is provided by the
705 position tracking system and used to dynamically mix the soundscapes the user
706 is immersed in. The sound module uses a custom-designed software mixing sys-
707 tem implemented on a single computer. We have developed an authoring environ-
708 ment for mapping sounds to the physical topology of an exhibition. The delivery
709 of the audio objects is through a stereo audio interface using FM radio trans-
710 mission to portable FM receivers. In our testing environment the system served
711 four simultaneous users. The system scales simply by adding more FM transmit-
712 ters. The vision and audio delivery systems were developed in our lab using the
713 Max/MSP environment.
714   The reasoning module was fully implemented with all features described in the
715 previous sections. The real-time nature of the ec(h)o environment was the driving
716 force for the selection of an implementation platform that supported the reason-
717 ing engine. As shown in Figure 5, the Jess inference engine is at the center of the
718 reasoning module. We have used DAMLJessKB to load DAML+OIL ontologies
719 into Jess (for details see Kopena and Regli, 2003). DAMLJessKB uses Jena tool-
720 kit to convert ontologies into RDF triples that are converted to Jess facts. When
721 converted ontologies are loaded into Jess, the rules representing DAML+OIL
722 semantics infer the missing relations in the RDF graph. This happens at start-
723 up time and prepares the system to respond to the input in a real-time fash-
724 ion. In the development version we embedded the reasoning engine in the Tomcat

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[12]The zone for the camera depends on the height of the mount and height of the hand handling
the cube. For example, the zone diameter for the camera mounted at 4 m can be as wide as 15 m
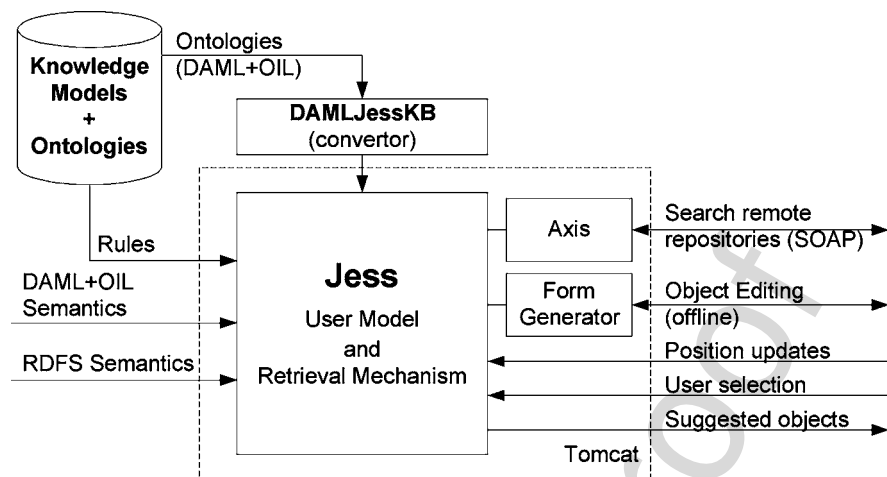with a wide angle lens.

Figure 5. Implementation schema of the reasoning module.

725   environment in order to facilitate online editing of knowledge models as shown
726   in Figure 5. However, for the final deployment we used the reasoning engine
727   as a standalone application for performance reasons. All communication with
728   the reasoning engine was accomplished through User Datagram Protocol (UDP)
729   connections.

730   The user model that forms the significant part of the reasoning engine was
731   implemented[13] using a combination of rules and specific Jess extensions via Java
732   classes to support computation tasks such as object ranking and the spring model
733   calculations used to compute the user interests.

734   We produced over 600 reusable audio objects at a low level of granularity
735   and annotated them with the ontological information. The average length of each
736   audio object is approximately 15 s. The shortest length is 5 s and the longest 31 s.
737   The prefaces typically last 3 s. A majority of informational and narrative audio
738   objects originated from the interviews with researchers and staff from the Cana-
739   dian Museum of Nature in Ottawa. We subsequently scripted the objects and used
740   actors for the recordings. For details on the content development (see Wakkary
741   et al., 2004).

742   ## 6. Evaluation

743   Evaluation of ubiquitous computing systems is extremely complex as these systems
744   'bridge the physical and online worlds' and require seamless navigation between
745   the two, without imposing significant cognitive load on the user (Spasojevic and
746   Kindberg, 2001). There is no agreed upon framework for evaluation of such

---

[13]The only part of the user model that was not continually updated in the final prototype was the
user type as the size of the final exhibition did not provide enough supporting data for inferring
this information.

747 systems as known in other domains such as information retrieval (trec.nist.gov) or
748 Robocup (robocup.org). Although Burnet and Rainsford (Burnett and Rainsford,
749 2001) argue for a hybrid approach combining quantitative and qualitative evalu-
750 ations situated in a well-defined environment, such as a 'smart room' (Pentland,
751 1996), many projects use ad-hoc evaluation approaches borrowed from other better
752 established domains. These typically include an analysis of log files for various
753 events and user activities, observing user behavior and conducting user interviews.
754 The small number of test users is also an issue in that it does not allow one
755 to make strong conclusions. For example, the evaluation of the deployment of
756 mobile computing systems in the Exploratorium museum project provided 'exis-
757 tence proofs' for certain reactions and phenomena based on a mix of log files,
758 observations and interviews with a small number of users rather than statistical
759 evidence (Fleck et al., 2002).

760 We have found Miller and Funk's (2001) view of the problem of evaluation of
761 ubiquitous computing systems from the traditional 'validation' and 'verification'
762 perspective very useful. In regard to validation, we evaluate whether the system
763 performs the functions it was built for based on the requirements specification.
764 Verification tests the system against the reality-checking of user evaluation to see
765 whether the system provides the envisioned benefits.

766 Following Miller and Funk's approach allowed us to focus our evaluation on
767 areas where we researched novel approaches in adaptive ubiquitous systems. We
768 also avoided the evaluation of aspects of the system that are not well defined or
769 understood. Below we describe three *validation* steps for two main components of
770 the ec(h)o system, the user model and system response:

771 1. User model updates: the user and environment models are updated with respect
772 to model modifiers that represent observed user actions in the environment. The
773 user model update mechanism interprets the meaning of the actions as con-
774 veyed by the model modifiers to adjust modeled user characteristics, i.e. in our
775 case, the level of user interests. In the user model validation we measure how
776 well the model changes user interests with respect to the input and interaction
777 criteria set for ec(h)o.
778 2. System response: the second validation we performed evaluates how the system
779 selects audio objects based on the user characteristics with respect to the inter-
780 action criteria.
781 3. User interaction: in this validation step we evaluated user interaction. We eval-
782 uated the audio objects characteristics the user selected against the interaction
783 criteria.

784 In the system *verification* we obtained qualitative data that measured user expe-
785 rience. We developed questionnaires and performed interviews focusing on user's
786 perception and satisfaction with the system from the perspective of our key
787 research questions.

6.1. VALIDATION OF THE USER MODEL FLEXIBILITY

As mentioned in Section 4.5 the rule-based user model provides a generic structure that enables the system developer to consider several inputs that influence the level of user interests in the user model. These inputs influence initial interest selection, object selection, and location change. In addition, the model allows the developer to tune the relative influence of each input using a set of parameters. The spring model implemented in the user model keeps the rest of the model balanced with the maximum values of each interest capped at a value of 10 and the sum of all interest values at 30.

Each of these actions has a different effect on the user interests. In order to achieve a well-balanced user model we designed a series of tests that evaluated how the rules responded to each type of user action. The second series of tests was designed to balance the relative influence of each type of action in the context of typical user interaction. Both tests were performed in a laboratory setting and they used variations of previously observed user interaction.

We performed a series of tests in which we tested the different combinations of parameters for the maximum interest value (maximum-concept), audio object selection contribution (primary-concept and inferred secondary-concept), location change contribution (visual-concept), and initial user interests (initial-concept). Table II shows the range of values for each parameter tested.

The goal of this test was to find a combination of parameters that would establish the dynamics in the user model with the following characteristics: moderate evolution in user interests when listening to audio objects, significant influence of changing context (visual concepts in exhibits), and protecting the user model from the domination[14] of a few concepts. Similarly, in the initiation stage we were looking for the balance between concepts initially selected by a new user and how these are combined with visual concepts when a user enters the first exhibit. It should be noted that the user model is only one component used in the ranking of audio objects; there are other factors that significantly influence object selection and overall interaction (as shown in Section 4.4.2).

Table II. Values of tested parameters

Parameter	Tested values
Initial-concept	5, 7, 10
Primary-concept	0.7, 1, 1.5, 2
Visual-concept	1, 2, 3
Maximum-concept	8, 10, 12

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[14] As a result this would prohibit exploration of other concepts of interest and lock the user into a few concepts.
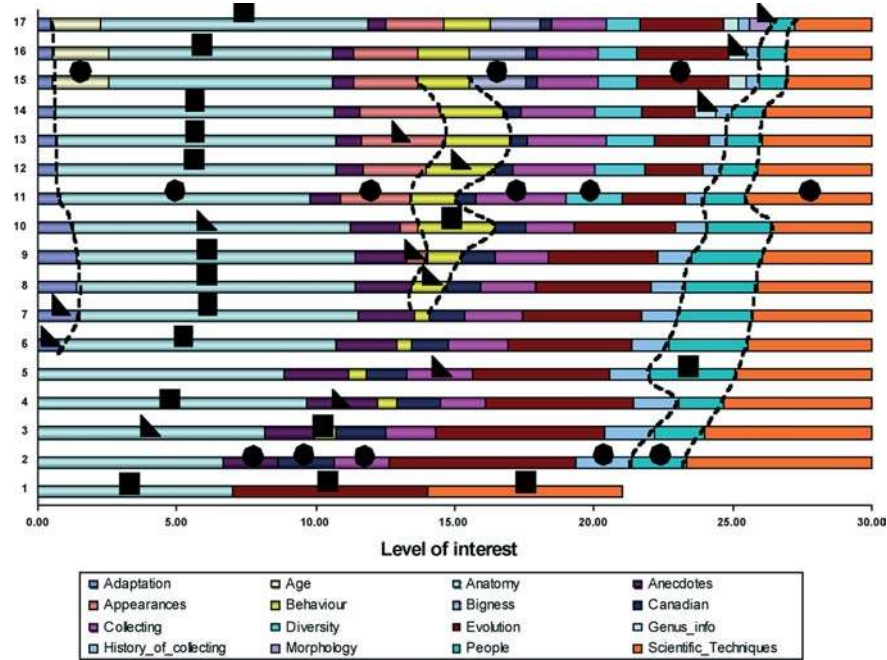
Figure 6. User model dynamics with response to user interaction with the exhibit and listening to the audio objects.

In order to simulate user interaction input we used a fixed sequence of steps that were captured from the users interacting with an earlier version of ec(ho) in our lab. We evaluated all the combinations of parameters by analyzing the graphical representations of the user model as shown in Figure 6. The figure shows the sequence of steps and evolution of interests in each step. In the first step the user selects three concepts as his or her initial concepts of interest. The circle icon indicates concepts introduced to the model by the visual concepts in the exhibit in which the user enters (Step 2, 11, and 15). In the rest of the steps the user selected audio objects. The square icon indicates a primary concept of interest and a triangle icon denotes a secondary concept of interest in the selected audio object. Figure 6 demonstrates some of the significant features of our user model. A broken line on the left shows how a concept of interest ('Adaptation') introduced to the model via listening to audio objects is being continually reduced as other concepts of interest are increasing in value. The dynamics is highlighted for the other two concepts of interest ('Behavior' in the middle and 'People' on the right). The same applies to the initial concept of interest ('Scientific techniques' furthest to the right) that is not selected and its value is reduced continuously. Figure 6 also shows how the value for a concept of interest ('Anatomy') is not increasing once it has reached the maximum value.

837   The user model proved to be very flexible and responsive to the parameter val-
838 ues and allowed us to control the dynamics of the interest levels. The combina-
839 tion of parameters that supported the dynamics of the user model closest to our
840 goals was seven for the initial-concept, 1.5 for the primary-concept, two for the
841 visual-concept, and 10 for the maximum-concept. These values supported the con-
842 tribution of the user model at the level of 36% of the overall ranking of the audio
843 objects (column 'ec(h)o' in Table I). We kept these values fixed for the rest of the
844 evaluation.

845   The selected combination of parameter values is specific to our ec(h)o appli-
846 cation and not individual users. It is likely that other applications would require
847 different dynamics. Our model is rule-based and designed to be highly flexible. This
848 not only allows us to modify the values of the parameters that suit the application
849 but also to introduce new parameters into the model as needed.

850 ## 6.2. USER EXPERIMENT SETUP

851 We installed the ec(h)o system in an existing exhibition about collecting called
852 'Finders and Keepers'. The exhibition contains seven exhibits, five of which are
853 booth-type exhibits, each with several dozens of artifacts organized around topics.
854 Two exhibits are open exhibits with larger artifacts such as a mastodon skeleton.
855 For the exhibition, we created three interactive zones: two in booth-type exhibits
856 and one in an open space exhibit.

857   The formal user evaluation included six participants. The participants had previ-
858 ous experience with interactive museum systems such as docent tours (three partic-
859 ipants), interactive kiosks (3), audiotape systems (4), film and video (5), seated and
860 ride-based systems (2) and personal digital assistant systems (2). The test group
861 included two men and four women, aged 25–53-years old.

862   The testing session for each user started with a brief introduction on the pur-
863 pose and testing procedure. Participants had an opportunity to interact with the
864 system while one of the researchers accompanied them to explain how to use it.
865 We logged all the interactions of this tutorial phase but as this was a "coached"
866 session we did not include this data in our final evaluation. After this short train-
867 ing session the users had an opportunity to ask questions and seek clarification.
868 Next, participants engaged the system as a typical museum visitor would. Users
869 began by selecting their initial concepts of interest and they were then left alone
870 to freely explore the exhibition. We logged all interactions with the system and
871 used this data for the evaluation of the system described in the following sec-
872 tions. After the main testing session, the users were asked to complete a question-
873 naire. Finally, we conducted and videotaped a semi-structured interview with each
874 participant.

875   In addition to the six users we tested the system with two expert reviewers.
876 These experts included a senior researcher and senior interaction designer from

Table III. Test session characteristics

User ID	Length	#Steps	#Selections	#Locations
User1	10:36	27	19	8
User2	6:19	11	7	4
User3*	8:56	22	12	10
User4	9:53	21	16	5
User5	9:18	22	17	5
User6*	5:01	16	7	9
Expert1	15:03	32	23	9
Expert2	17:58	36	29	7

the museum. Both were familiar with the exhibit and its underlying concepts. The experts tested the system for an extended period of time with specific focus on the depth of the content and meaningfulness of the interaction. After each of the expert testing sessions we discussed the issues the experts wanted to clarify. Finally, they provided an extensive written report on the system performance.

Table III shows the characteristics of each user session: the total length of the interaction, number of interaction steps, number of selected and listened to audio objects, and number of location changes. As can be seen from Table III the number of location changes for User3 and User6 are exceptionally high. After examining the log files we found that the system repeatedly registered the single event of entering the same exhibit. This may have been caused by either the user moving along the exhibit boundary or by an error in the position-tracking module[15] . As explained in the previous section, this event caused the user model to be updated with the concepts represented by the exhibit (visual concepts), which skewed the object selection process towards those concepts. Therefore we did not include these two users in our evaluation data.

6.3. VALIDATION OF THE SYSTEM RESPONSE (OBJECT SELECTION)

In section 6.1 we showed how the system interprets the user actions and how user actions are used to update the user model and specifically the level of user interests. In this section we present our results of the recommender part of the system that selects audio objects to be offered to the user.

To evaluate the system response capabilities we have used interaction criteria. The level of fulfillment of interaction criteria can be observed from the audio objects offered to the user at each interaction step. To measure the system performance with respect to interaction criteria we defined three characteristics: variety, sustained focus, and evolution. These characteristics measure semantic relationships between offered audio objects with respect to concepts these audio objects represent.

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[15]It is possible that participants were exploring the soundscape feature that is played when users leave an interactive zone and stops playing when users enter a zone. This starting and stopping of the soundscape would result from weaving along the boundary of an interactive zone.

905 In ec(h)o, at each interaction step three objects are offered O_{s1}, O_{s2}, and O_{s3}.
906 Each object is annotated with a primary and secondary concept of interest it rep-
907 resents P_{s1}, P_{s2}, P_{s3} and S_{s1}, S_{s2}, S_{s3} respectively. If we define two sets $P_s = \{p|$
908 unique interests in $\{P_{s1}, P_{s2}, P_{s3}\}\}$, $S_s = \{s|s$ is unique interest in $\{S_{s1}, S_{s2}, S_{s3}\}\}$,
909 and $\|M\|$ denotes the number of elements in the set M then we can define three
910 criteria as follows:

Variety – describes the richness of choices for further interaction at each inter-
action step. The variability is a basic mean to put users in control of selecting
topics of further interaction. It also compensates for an inherent inaccuracy of user
interest modeling by providing multiple alternatives. Formally, we define variety in
interaction step s as Var_s

$$Var_s = c_1^*\|P_s\| + c_2^*\|S_s - P_s\}\|$$

911 where we set $c_1 = 1$ and $c_2 = 0.5$. In case of ec(h)o Var_s can range from $\langle 0, 4.5\rangle$
912 so we scaled it to $\langle 0, 1\rangle$ for a clearer comparison.

Sustained focus – An ability of the system to sustain the focus on particular
interests. Mono-topical systems provide a maximum degree of sustained focus but
do not follow shifting user's interests. On the other side of the spectrum are sys-
tems selecting topics randomly where the sustained focus cannot be reasonably
evaluated.

$$Sust_{s+1} = c_1^*\|P_{s+1} \cap P_s\| + c_2^*\|P_{s+1} \cap S_s\| + c_2^*\|S_{s+1} \cap P_s\| + c_3^*\|S_{s+1} \cap S_s\|$$

913 where we set $c_1 = 1$, $c_2 = 0.5$ and $c_3 = 0.25$. In case of ec(o) $Sust_{s+1}$ can range
914 from $<0, 6.75>$ so we scaled it to $\langle 0, 1\rangle$ for a clearer comparison.

Evolution – An ability of the system to follow shifting user interests during
interaction with the system. Adaptive systems have an ability to continually shift
the focus of the interaction by continuously monitoring user's interaction. We have
defined evolution as the weighted number of new concepts introduced between two
steps in the interaction.

$$Evolv_{s+1} = c_1^*\|P_{s+1} - (P_s \cup S_s)\| + c_2^*\|S_{s+1} - (P_s \cup S_s)\|$$

915 where we set $c_1 = 1$ and $c_2 = 0.5$. In case of ec(h)o $Evolv_{s+1}$ can range from
916 $\langle 0, 4.5\rangle$ so we scaled it to $\langle 0, 1\rangle$ for a clearer comparison.

917 Table IV shows the values of the proposed evaluation characteristics when
918 applied to the mockup data. The rows labeled as primary and secondary concepts
919 represent concepts of interest for three hypothetical audio objects offered to the
920 user. The values in columns 1–10 were chosen to show how different combinations
921 of concepts affect the three measurements. As defined above, variety is measured
922 for each interaction step and has a value of 0 if all concepts are identical (e.g. col-
923 umn 1) and a value of 1 if all values are unique (e.g. column 11). The sustained
924 focus in a particular interaction step is based on the values in this step and the
925 previous step. The sustained focus measures how many concepts from the previous

Table IV. Behaviour of sustained focus, evolution and variety

	1	2	3	4	5	6	7	8	9	10	11	12	13
Primary concept 1	a	a	b	b	b	c	c	d	f	g	i	i	i
Primary concept 2	a	a	b	b	b	c	c	d	f	g	j	j	q
Primary concept 3	a	a	b	b	b	c	c	d	f	g	k	l	r
Secondary concept 1	a	a	b	c	c	b	d	e	d	h	l	i	q
Secondary concept 2	a	a	b	c	c	b	d	e	d	h	m	m	r
Secondary concept 3	a	a	b	c	c	b	d	e	d	h	n	p	p
Sustained Focus		1.00	0.00	0.67	0.56	0.44	0.44	0.22	0.22	0.00	0.00	0.48	0.26
Evolution		0.00	1.00	0.33	0.00	0.00	0.33	0.33	0.67	1.00	1.00	0.11	0.67
Variety	0.00	0.00	0.00	0.14	0.14	0.14	0.14	0.14	0.14	0.14	1.00	0.86	0.71

step are repeated in the next step. This information is weighted differently for primary and secondary concepts being repeated as either primary or secondary concepts (columns 7, 8, and 9 demonstrate this clearly). The evolution is also computed from the current and previous interaction step and it captures how many new concepts were introduced at the primary and secondary levels. It is not a mere complement of the sustained focus as can be seen from columns 6, 7, 8, and 9. Finally, the last three columns in Table IV shows a more realistic distribution of concepts in offered audio objects. In column 12 concepts 'i' and 'j' are repeated as primary concepts, concept 'm' is repeated as a secondary concept and concept 'i' is repeated also as a secondary concept. In column 13 two concepts are repeated: 'i' as a primary and 'p' as a secondary concept.

We have calculated the sustained focus, evolution and variety for each user interaction. Figure 7 shows actual results for one user (graphs for other users show the same trends). The horizontal axis represents interaction acts that trigger object selection. These can be either the user entering the exhibition zone (step number is circled) or the user making a selection of an audio object. When a user enters the space three new audio objects are offered. After a user makes a selection the selected object is replaced with the new one and possibly a non-selected object is replaced if it had already been offered three times.

In Figure 7 we can observe that the system supports high variety of objects in each step without significant changes between the interaction steps. However, trend lines for sustained focus and evolution demonstrate significant changes at the steps representing a change of the exhibit zone. In these points the sustained focus factor decreases significantly indicating that objects offered in the new location represent new topics of interest from those offered in the previous location. This system behavior reflects our selection of the weights established in Section 6.1, specifically the weight for visual-concept, giving a strong influence of the context on the user model. Once the user stays in the same interaction zone the sustained focus increases reflecting continual changes in the user model. The trend changes in the evolution characteristics are caused by the same decision.
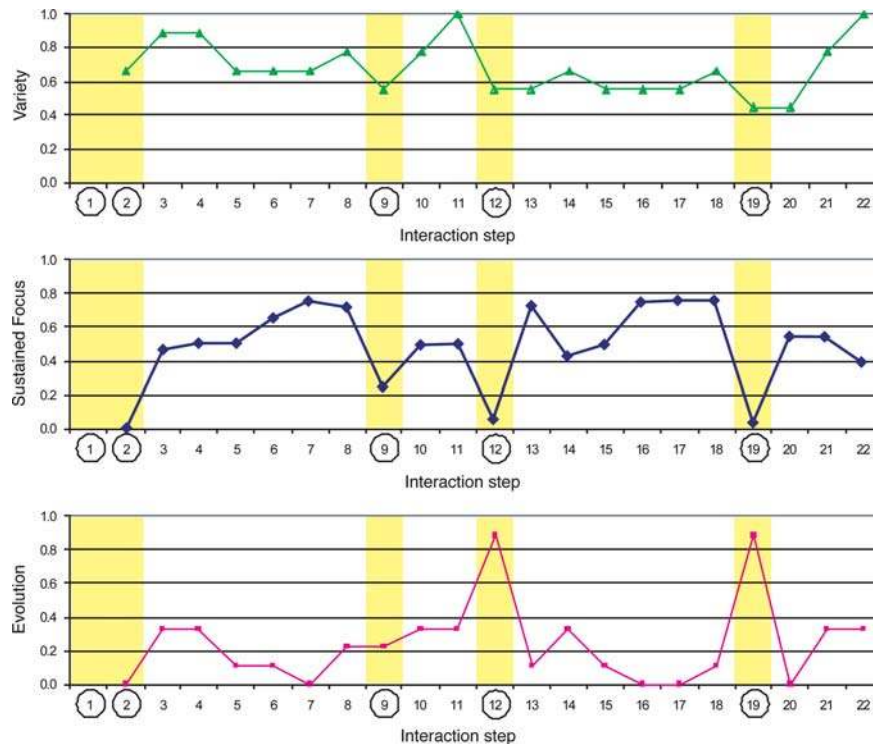
Figure 7. Variety, sustained focus and evolution for User 5.

Because the changes in the exhibit location caused such significant differences
we separated the statistical processing for the 'location-change' steps from the
'object-selection' steps. Table V shows the statistical values for all three character-
istics as obtained from seven test subjects.

Based on the values in Table V we can conclude that the system offers highly
variable objects when users change location and the variety increases as users con-
tinue 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 correspond-
ing to the modest changes in the user model.

This behavior matches our expectations. As described in Section 5.3.2, 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.

Table V. Statistical values for variety, sustained focus and evolution

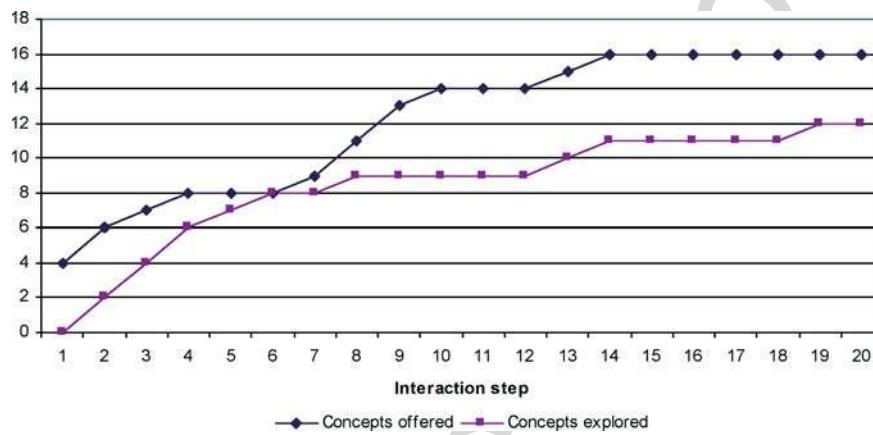|	Overall		Selection		Location	
	AVG	STD	AVG	STD	AVG	STD
Variety	0.73	0.18	0.77	0.16	0.61	0.14
Sustained focus	0.50	0.21	0.58	0.15	0.23	0.15
Evolution	0.30	0.24	0.23	0.16	0.53	0.24

Figure 8. Concepts offered and concepts selected for User 5 (cumulative).

6.4. EVALUATION OF USER INTERACTION

While in the previous section we evaluated the system's ability to respond in the manner corresponding with our interaction criteria, in this section we examine how users interacted with the system.

As presented in the previous section we have tuned the system to favor sustained focus over evolution. However, a high level of variety enabled users to 'defy' the sustained focus of the interaction by selecting audio objects with newly introduced concepts of interest. Figure 8 shows the dynamics of how the system introduced new concepts of interest and how the users explored those concepts via object selection in the course of interaction. The horizontal axis represents interaction steps and vertical axis represents a cumulative number of concepts of interest introduced and explored up to that interaction step. The grayed areas represent steps where users changed location. The zero value for the number of concepts selected in step one is due to the fact that users did not select any object before moving into another exhibit.

The graphs in Figure 8 shows that at the beginning the system introduces new concepts at a more rapid pace. At the same time the user explores objects (and concepts of interest) rapidly until a point is reached where the user explores some

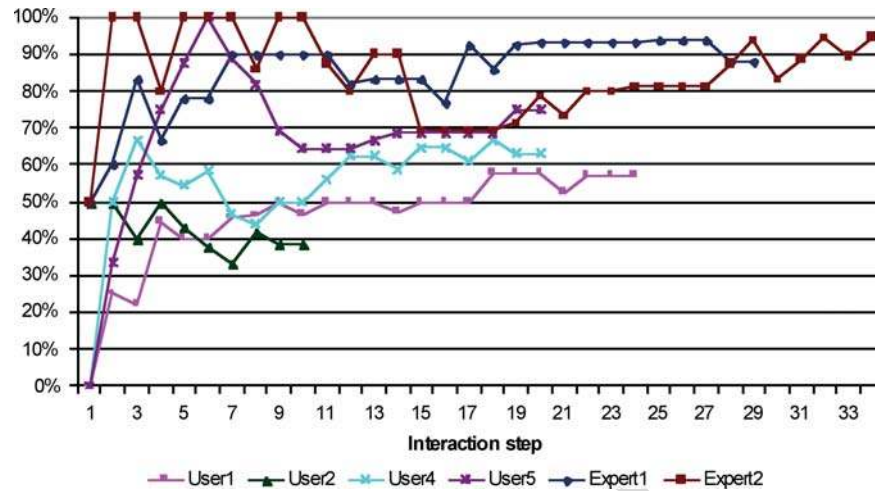*Figure 9.* Concept exploration relative to concepts introduced.

of the concepts in more depth (Steps 8–12 and 14–20). Although the absolute values differ between users we have found a similar pattern is present for all users.

Figure 9 shows the percentage of selected concepts of interest by individual users relative to the number of concepts of interest introduced via offered audio objects. The graph shows that after initial steps users quickly converge to a stable proportion of the selected concepts of interest in the range of 30–70% of concepts offered.

It is difficult to speculate whether with ongoing interaction the level of concept exploration the users reached would remain at a constant level. Theoretically, as the number of concepts of interest in our system is limited to 39 concepts, the users have an opportunity to explore all of them. On the other hand, as we can see from the available data, users tend to explore certain concepts in more detail.

6.5. VERIFICATION: EVALUATION OF USER EXPERIENCE

User experience was evaluated through observation during the sessions, a questionnaire, and a semi-structured interview. The questionnaire included sixty-three 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. The questionnaire also provided for open-ended written comments. Majority of the questions were on a Likert scale. 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* (Bell, 2002). For a summary of the questionnaire results see Table VI.

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

Categories	Average	Standard deviation
Overall reaction (five questions including "terrible-wonderful; difficult-easy".	3.60	0.78
Tangible user interface (seven questions including "uncomfortable-comfortable; difficult-easy to manipulate; annoying-enjoyable"	4.24	0.50
Headset (two questions including "comfortable-uncomfortable to wear"	2.92	0.12
Learning curve for the system (eight questions including "difficult-easy to get started; risky-safe to explore features; unclear-clear feedback)	4.07	0.36
Perception of system performance (eight questions including "slow-fast system response; never-always reliable"	3.83	0.39
Quality of the content (fifteen questions including: "uninformative-informative; generalized-customized for me; rigid-playful; predictable-surprising"	3.78	0.52
Quality of the audio experience (nine questions including "confusing-clear; mechanical-human-like; wasteful-valuable"	3.67	0.30
Navigation and control (eight questions including "never-always able to navigate in an efficient way; always-never found myself lost in the system; always-never found myself uncertain of system state	3.23	0.29

1014   Participants found the system enjoyable and stimulating, perhaps in part due to
1015 its novelty. The general sense of satisfaction was split between those participants
1016 who liked the playful approach and those who did not. While our sample was
1017 small we noted a clear age difference in that the "younger" participants rated sat-
1018 isfaction higher based on their liking of the playful approach (this was confirmed
1019 in the semi-structured interviews).
1020   Among the factors that stood out as most positive for the participants was that
1021 the cube and audio delivery were seen as playful. The open-ended written com-
1022 ments and semi-structured interviews made this point clear as well. The tangi-
1023 ble user interface was well received especially in terms of ergonomics and ease of
1024 use. This was not a surprise to us since our early testing and participatory design
1025 sessions provided us with considerable feedback, especially on ease of use and
1026 enjoyment. We went through several iterations of the wooden cube selecting the
1027 lightest wood we could find (balsa wood) and going through several form factors
1028 tested against different hand sizes. This may have also resulted in the fact that
1029 learning to use the interface and navigation were rated highly and participants felt
1030 the system had a low learning curve and so it was easy to get started. It should

1031 be stated that we provided a short tutorial on the system at the beginning of each
1032 evaluation (see Section 6.2) but nevertheless this feedback is encouraging. Inter-
1033 estingly, the audio content was perceived to be both accurate and clear. The issue
1034 of trust and delivery style is an area to further investigate. Since we collected the
1035 information directly from scientists and staff at the museum rather than a more
1036 generic source we wonder if this contributed in part to this result (Wakkary et al.,
1037 2004). These results lead us to believe that the system meets or satisfies many of
1038 the current advances of museum guide systems.

1039   The questionnaire did point out challenges and areas for further research. Some
1040 things we expected such as the headphones were uncomfortable, yet to such a
1041 degree that we are currently rethinking the tradeoff between personalized spatial
1042 audio and use of headphones. Other results point to a threshold in the balance
1043 between levels of abstraction and local information. Since visitors had difficulties
1044 at time connecting what they were listening to and what was in front of them
1045 (in part this was an inherent challenge in the exhibition since the display cases
1046 had dozens to over a hundred artifacts). In many respects this confirms our find-
1047 ing that the ontological approach did not provide a clear enough contextual link
1048 between the artifacts and the audio information. In addition, we see both a thresh-
1049 old point in play versus focused attention on the exhibit in that the question relat-
1050 ing to the content asking if it was "distractive-synergistic" scored 2.83. This raises
1051 the issue of balance in play and the possibility to shift attention away from the
1052 environment rather than play as a means of further exploring the environment.

1053   In an open-ended question in the questionnaire and through the semi-structured
1054 interviews we explored the issues of liminal play and engagement. The results here
1055 are quite clear that play was a critical experiential factor in using the system. It
1056 was often remarked how the experience was similar to a game:

1057   *"At first it felt a little bit strange, especially holding this cube that looked like a chil-*
1058   *dren's toy, and I felt a little bit awkward about doing that, but I got over that pretty*
1059   *quickly. The whole system to me felt a lot like a game. I mean I got lost in it, I found*
1060   *myself spending a lot [more] time in a particular area then I normally would. And just*
1061   *the challenge of waiting to hear what was next, what the little choice of three was*
1062   *going to be. Yeah ... So I found it over all engaging, it was fun, and it was very*
1063   *game-like."* (Participant 5)

1064 The playfulness did in most instances suggest a quality of engagement that led
1065 to learning even through diverse types of museum visits including the visitor who
1066 browses through quickly but is still looking to be engaged, to the repeat visitor
1067 who experiences the audio information differently each time:

1068   *"I learned a lot and well you know I'm a scientist here, and I think anybody going*
1069   *through, even people who are in a real rush, are going to pick up some interesting*
1070   *facts going through. And ... I mean, that was good, the text was great and was*
1071   *short enough that somebody in a rush is still going to catch the whole thing. And there*
1072   *wasn't much delay really, I mean once you showed your cube it came up pretty fast,*
1073   *and that is important with museum-goers. I think museum-goers don't stand and spend*

1074 *a bunch of time in one spot so it has to be something that comes up pretty quickly."*
1075 (Participant 4)

1076   As mentioned earlier, there is a threshold between play in support of the exhibit
1077 on display and play with the system that can be an end in itself and even a
1078 distraction. For example, one participant occasionally focused more attention on
1079 playing with the system than the exhibition due to her enthusiasm for the game-
1080 like quality. In addition, people respond to play differently and can be argued to
1081 belong to different types of players (Bartle, 1990). One participant would have pre-
1082 ferred a more serious and "non-playful" approach. In this case the playfulness and
1083 short length of the audio was seen as anecdotal rather than serious and scholarly.

7. Discussion

1084

1085   At the outset of this paper we acknowledged the challenge to capture the larger
1086 context through user modeling, particularly in ubiquitous and mobile computing
1087 applications. No doubt Fischer poses the problematic as a description of an ongo-
1088 ing research program than a question that a single project can address (Fischer,
1089 2001). Nevertheless, our strategies along this front included the sensing and infer-
1090 ence based on visitor movement, like many other systems, however, we also utilized
1091 a mixed criteria, combining ranking of concepts of interest based on direct user
1092 selection of audio objects *mixed* with visual concepts that we mapped to the con-
1093 text (see Sections 4.3.2 and 6.1). Our aim here was to allow for the possibility of
1094 new interests to form externally through the context. As it turned out, in analyzing
1095 the participants' selections of audio objects based on the interaction criterion of
1096 *evolution* (see Section 6.3), significant changes occurred less through user selection
1097 (this was always possible since we maintained high degree of variability in concepts
1098 at all times) than from visitors moving to another exhibit. The criterion of *evolu-*
1099 *tion* can be said to evaluate internal influences (user's reflection on content) and
1100 external influences (user's reflection on context). This was possible given our aim
1101 to consider user interest as dynamic and evolving based on the interaction with the
1102 environment. In fact, we earlier stated that we do not see our system as a museum
1103 guide, recommending things based on what people like or know at the outset of a
1104 visit, rather we see it as a way to provide enrichment to the ongoing experience of
1105 the exhibit and artifacts.
1106   The specific problem we stated at the outset of the paper was how to support
1107 the fuller experience design goals as well as functionality with an integrated model-
1108 ing technique and use of semantic technologies in combination with an audio aug-
1109 mented reality and tangible user interface approach.
1110   In regard to functionality, the user experience results show that ec(h)o was
1111 extremely easy to use and quick to learn, and the overall system performed well
1112 (see Section 6.5). The validation of the ec(h)o components, namely user model and

1113 object selection, showed that these performed at the required level of accuracy and
1114 flexibility. While we did not perform a comparative test with other systems, in the
1115 verification it was clear that participants had experience with many different museum
1116 based systems (see Section 6.2) and we can expect that comparisons were made with
1117 past experiences in evaluation of ease-of-use, learning curve, and performance.

1118   In regard to the experience design goals of play and discovery, we feel our
1119 integrated modeling approach implemented two techniques to facilitate wider
1120 exploration and the discovery of new topics of interests and the ability to make
1121 new connections among topics and artifacts. The first being the aim of keeping
1122 interests balanced such that a given topic or set of topics does not dominate and
1123 prevent exploration of new topics, for this we used a spring model to proportion-
1124 ately moderate levels of interest (see Section 6.1). As we stated, it is important
1125 that the user model learns to "forget older interests" so that newer ones can be
1126 invoked. The second technique is to maintain a high level of variety of primary
1127 and secondary interests among the objects presented. This affords greater oppor-
1128 tunity for the user to evolve his or her interest through a reflection on content as
1129 discussed above (see Section 6.3). These techniques contribute to the goal of estab-
1130 lishing dynamics in the user model that support exploration and discovery of new
1131 interests through moderating evolution in the user interests, maintaining significant
1132 influence of changing context (when a visitor moves to another exhibit), and pro-
1133 tecting against the domination of a few concepts that would choke off exploration.

1134   We introduced the evaluation of system response or in our case, object selection
1135 based on interaction criteria of *variety*, *sustained focus*, and *evolution*. We've found
1136 these terms useful in the discussion above and we can say that we can measure
1137 *variety*, and rationalize it together with *evolution* as dependent factors in explo-
1138 ration and discovery of new user interests through interaction. *Sustained focus* is
1139 less clear of a measure at this stage and something we will investigate in future
1140 research.

1141   There are cautions in our findings. The first is designers must strike a balance or
1142 they run the risk of users engrossed in the playing with the system at the expense
1143 of interacting with their surroundings, as one participant commented happened
1144 to her periodically. The second caution stems from the results that indicate that
1145 visitors had difficulties at times connecting what they were listening to and what
1146 was in front of them. It may be that the system did not always provide a coher-
1147 ent story, a resulting tradeoff due to its dynamic nature. Nevertheless, a much
1148 richer model of discourse and storytelling could be an option to pursue. In addi-
1149 tion, users in the museum settings are significantly connected with concrete arti-
1150 facts while ec(h)o experimented with the idea of the connection between artifacts
1151 and audio objects residing at a higher ontological level. The results indicate that
1152 either a much richer model is needed or the hypothesis of linking objects at higher
1153 abstract ontological levels is not suitable for ubiquitous context-aware applications
1154 or it has to be combined with other approaches.

8. Conclusion and Future Work

ec(h)o is an augmented audio reality system for museum visitors that was developed and tested for the Canadian Museum of Nature in Ottawa. In ec(h)o we tested the feasibility of audio display and a tangible user interface for ubiquitous computing systems – one that encourages an experience of play and engagement. The interface uses audio as the only channel to deliver short audio objects that can originate from the web. We have built several ontologies that richly described the museum environment and artifacts, audio objects and user interests. The knowledge-based recommender system builds a dynamic user model based on user choices and user movement through the exhibit and recommends audio objects to the user.

The findings of this project are positive while also calling for more research in several areas. First, we found that it is possible to build a highly flexible and accurate user model and recommender system built on information observed from user interaction that supports play and discovery as well as functionality. Ontologies and rule-based approaches proved to be a strong combination for developing such systems, yet some museum visitors are looking for more coherent stories that are highly contextualized. The ontological approach did not prove satisfactory and either more extensive knowledge engineering is needed or it has to be combined with stronger narration or discourse models. As museums are highly social places, another area that needs more research is extending the system with support for groups and group interaction.

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