SPECIAL ISSUE
Original article

doi: 10.1111/j.1365-2729.2007.00238.x

# Innovative socio-technical environments in support of distributed intelligence and lifelong learning

**G. Fischer*** & **S. Konomi*†**

*Center for LifeLong Learning and Design (L$^3$D), University of Colorado, Boulder, CO, USA
†Center for Spatial Information Science (CSIS), University of Tokyo, Meguro-Ku, Tokyo, Japan

**Abstract** Individual, unaided human abilities are constrained. Media have helped us to transcend boundaries in thinking, working, learning and collaborating by supporting *distributed intelligence*. Wireless and mobile technologies provide new opportunities for creating novel socio-technical environments and thereby empowering humans, but not without potential pitfalls. We explore these opportunities and pitfalls from a *lifelong-learning* perspective and discuss how wireless and mobile technologies can influence and change conceptual frameworks such as the relationship between planning and situated action, context awareness, human attention, distances in collaborative design activities, and the trade-off between *tools for living* and *tools for learning*. The impact of wireless and mobile technologies is illustrated with our research projects, which focus on moving *'computing off the desktop'* by *'going small, large, and everywhere'*. Specific examples include human-centred public transportation systems, collaborative design, and information sharing with smart physical objects.

**Keywords** context awareness, distributed intelligence, human attention, lifelong learning, situated action, wireless and mobile technologies.

## Introduction

A fundamental challenge for research in computer science, cognitive science, and the learning sciences is to understand thinking, learning, working and collaborating by exploiting the power of omnipotent and omniscient technology based on reliable, ubiquitous wireless and mobile computing environments (Pea 2004). New ways of thinking and new educational approaches are needed to address the design of socio-technical environments (Mumford 1987). We need to understand what tasks should be reserved for educated human minds and the collaboration among different human minds, and what tasks can and should be taken over or aided by cognitive artifacts. In such an information-rich world, the true power comes not from more information, but from information that is personally meaningful, relevant to people's concerns and relevant to the task at hand.

The impact of wireless and mobile technology (WMT) on future education cannot simply be measured as tools that facilitate existing learning practices. We need to take a deeper look into social practices in the discourse of pedagogical mobile applications (Roschelle 2003). Through the discussions on key conceptual frameworks and our experiences with three types of wireless and mobile applications, we shed light on fundamental issues that arise as WMT influences and changes the context and the goals of education

**Accepted:** 20 February 2007
**Correspondence:** Shin'ichi Konomi, Institute of Industrial Science, Ew-601, The University of Tokyo, 4-6-1, Komaba, Meguro-Ku, Tokyo 153-8505, Japan. Email: konomi@csis.u-tokyo.ac.jp

  

This paper is organized as follows: we will first discuss challenges for education of the future, followed by identifying a number of human-centric requirements for WMT. We will then describe conceptual frameworks and application systems developed at the Center for Lifelong Learning and Design ($L^3D$ 2005) addressing these challenges and requirements, and discuss their impact on learners. We will conclude by reflecting on the opportunities and pitfalls associated with WMT in education.

## Challenges for education of the future

We first discuss challenges for education of the future, focusing on issues around lifelong learning and distributed intelligence.

### Lifelong learning

Our approach to lifelong learning is grounded in a *basic assumption*: If the world of working and living relies on collaboration, creativity, definition and framing of problems, dealing with uncertainty, change and distributed cognition – then education needs to prepare students for meaningful and productive lives in such a world. Education from a lifelong learning perspective should help learners enhance their abilities to learn, engage in meaningful activities, exploit the power of media and promote new civic discourses, as a major role for new technologies is not to deliver predigested information but to provide for social debate and discussion (Bruner 1996). Lifelong learning (Gardner 1991), as it takes place outside schools differs in numerous dimensions in fundamental ways from school-based learning: (1) the learning is often self-directed and driven by interest and needs; (2) formal learning activities and environments are often less prominent compared with informal ones; (3) it takes place in tool-rich environments; and (4) it is often carried out as a collaborative activity (Fischer & Sugimoto 2006).

Wireless and mobile technologies provide a set of key features that support these dimensions of lifelong learning (Sharples 2000). In particular, mobility facilitates situated learning in authentic settings, wireless networks enable communication and collaboration across physical boundaries (Okada *et al*. 2003), and embedding the right ubiquitous computing devices in the environment allows people to exploit the power of embodied virtuality (Weiser 1991) and engage in activities and learning.

### Distributed intelligence

We need to gain a deeper understanding of how *distributed intelligence* (Pea 1993; Salomon 1993; Hollan *et al*. 2001; Fischer 2006) can make fundamental contributions to the future of education, learning, and the development and use of new media. In many traditional approaches, *human cognition* has been seen as existing solely 'inside' a person's head, and studies on cognition have often disregarded the physical and social surroundings in which cognition takes place. *Distributed intelligence* provides an effective theoretical framework for understanding what humans can achieve and how artifacts, tools, and socio-technical environments can be designed and evaluated to empower human beings and to change tasks (Norman 1993).

Distributed intelligence is a fundamental framework by which to marry the raw intellectual power of the human mind with appropriate technologies (Donald 2004). Skills related to literacy (Ong 1982) are the most important contribution. There is no doubt that information and communication technologies have created fundamental new design possibilities, but their true strengths and weaknesses need to be further explored. Figure 1 provides a graphical illustration of some of the major stepping-stones toward increasing the power of the collective human mind aided by technology.

To address these challenges, wireless and mobile technologies should not be perceived simply as add-ons to existing practices but as catalysts for fundamentally rethinking what education and learning should be and could be in the 21st century.

## Wireless and mobile technologies: understanding how usage and activity unfold

Our research efforts, which have focused on a human-centric perspective and co-evolution, have emphasized the importance of usage and activity rather than technologies. The following questions have served as guiding principles for our research efforts (Buxton 2002):

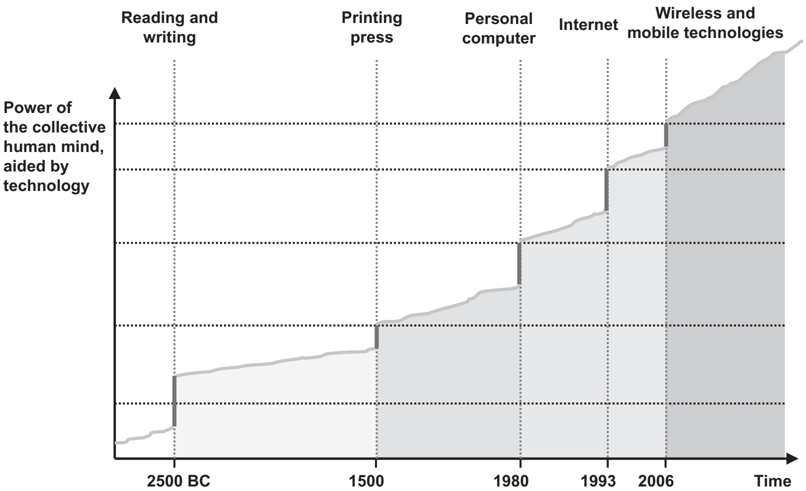


**Fig 1** Beyond the unaided individual human mind.

1. *Who* is using the computer? – learners, teachers, skilled professionals, technically sophisticated users, domain workers.
2. *What* are they doing? – moving through space, accessing information, engaging in informed participation and collaborative knowledge construction, communicating with others, participating in collaborative design activities.
3. *Where* are they doing it? – in classrooms, in their work environments.
4. *When* are they able to do it? – at any time without major preparations or set-up.
5. *Why* are they doing it? – a self-directed and self-motivated activity, an assigned task, to obtain information.
6. *How* do they do it? – in a tool-rich environment, in their heads.

Taking the co-evolution of usage and technologies into consideration, it is a key challenge to find the right answers to these questions. The rest of this section examines how usage and activity with WMT unfolds in terms of these six questions under the following four themes: (1) transcending the unaided, individual human mind, (2) planning and situated action, (3) context awareness, and (4) human attention as the scarce resource.

## Transcending the unaided, individual human mind

Our research has identified and explored a fundamental distinction about distributed intelligence and the change of tasks in a tool-rich world by identifying two major design perspectives (Pea 2004; Carmien & Fischer 2005):

- *Tools for living* (such as eyeglasses) are grounded in a *distributed intelligence* perspective, in which intelligence is mediated by tools for achieving activities that would be error prone, challenging, or impossible to achieve.
- *Tools for learning* (such as training wheels) are grounded in a '*scaffolding with fading'* perspective in which the ultimate goal is autonomous performance by people without tools.

This distinction raises the fundamental question concerning what it means to learn in the 21st century in which powerful tools are available 'anywhere at any time' for many intellectual activities – allowing people to have instant access to facts, assisting people in spelling, doing arithmetic, memorizing experiences, making sense of a large amount of information, connecting and collaborating with others, and performing numerous other intellectual activities. These tools' ubiquitous availability provides numerous benefits. However, they can also introduce challenges in relation to effective, fluent and ethical uses of the tools (Carmien 2006).

Tools for living rely on the presence of the tools at all times, and wireless and mobile technologies can therefore make them more relevant because we can in principle rely on them at all times.

### Planning and situated action

Technologies that allow for accessing and using any information, any place, at any time may eliminate the need to plan ahead for something we can make better decisions about when the event is actually taking place (Suchman 1987; Brown *et al*. 1989).

For example, train and bus schedules can nowadays be accessed on mobile phones, eliminating the need to plan and fix an itinerary *before* travelling. This and other wireless and mobile technologies (such as route planners and car guidance systems) are changing the skills needed to be a smart traveller by shifting the focus from smart planning to smart situated actions.

### Context awareness

Our research explores the unique possibilities of environments that model and represent domains, tasks, design guidelines, solutions and their rationale, and the larger context of such environments being *embedded in the physical world.*

A key requirement for context-aware environments (Dey *et al*. 2001) is the basic assumption that the 'interaction between people and computers requires essentially the same interpretive work that characterizes interaction between people' (Suchman 1987). This assumption raises the following interesting challenges:

**1** How can we model the larger context of what users are doing? Interactions with computational artifacts are often part of a larger activity, such as a complex design task, but computer systems do not 'understand' the larger activity. Context is often unarticulated and dynamic: understanding it may require consideration of what is happening beyond the direct interaction with the computer system and what emerges through learners' interactions with people and artifacts.

**2** How can we increase the richness of resources available for computer programs to understand their uses (or what they are told about their users) and to infer from what they are observing their users doing, inside the computational environment and outside (Horvitz *et al.* 1999)? We need to understand why learners are engaged in a task, in particular, if learners are engaged in a self-directed and self-motivated activity or an assigned task. Systems that embody such understanding may support or take over a current task. They may also reserve the task for educated human minds or collaboration among them.

### The scarce resource: human attention

Simon (1996) has argued that 'What information consumes is rather obvious: it consumes the attention of its recipients. Hence a wealth of information creates a poverty of attention, and a need to allocate efficiently among the overabundance of information sources that might consume it.' The challenge of future computer systems is therefore not to provide information '*any time and anywhere*', but to '*say the "right" thing at the "right" time in the "right" way to the "right" person*'.

Context awareness again is a critical factor in overcoming the problem of information overload. Without some awareness of the tasks learners are performing, and without some 'understanding' of the knowledge background of the learners with respect to these tasks, computational environments (and human collaborators) can make only limited determinations of the relevance of information.

## Research exploring distributed intelligence and lifelong learning

Over the last decade, the Center for LifeLong Learning and Design ($L^3D$ 2005) has developed a research agenda focused on distributed intelligence and lifelong learning. Our fundamental assumptions and objectives relevant to the framework of this paper are:

**1** focusing on *intelligence augmentation* rather than on artificial intelligence by empowering human beings rather than replacing them (Fischer & Nakakoji 1992; Terveen 1995);

**2** providing support not only to individuals but to groups and communities, and thereby exploiting the power of social creativity based on informed participation (Fischer *et al*. 2005);

**3** contextualizing generic systems to person- and task-specific environments to account for a 'universe of one' by supporting meta-design, customization, and end-user development (Fischer 2001);

4 pursuing *co-evolution* between (i) new media, (ii) new theories about working, learning and collaborating, and (iii) the creation of a new learning organization in a synergistic approach (Fischer 1998; Brown & Duguid 2000; Roschelle 2003).

We claim that most current uses of wireless and mobile technologies to support learning are restricted to a 'gift wrapping' approach (Fischer 1998): they are used as add-ons to existing practices rather than a catalyst for fundamentally rethinking what education and learning should be about. We are pursuing co-evolution to transcend 'gift wrapping' and 'techno determinism' in which technologies dominate learning experiences.

Based on these fundamental assumptions and objectives, we have explored *'computing off the desktop'* in three different directions (Fischer *et al*. 2004):

1 *Going small:* socio-technical environments supported by personalized, portable devices and wireless communication (Carmien *et al*. 2005) that afford information and communication between people as they move around in the world – the specific application context being the *Mobility-for-All* project (see the section *Going small:* Mobility-for-All).
2 *Going large:* large computational surfaces such as interactive tables and walls (Streitz *et al*. 2005) that allow people from diverse backgrounds to access, contribute to, and interact with information in an inherently social manner to support collaborative work among collocated people – the specific application context being the *Envisionment and Discovery Collaboratory* (*EDC*, see the section *Going large: Envisionment and Discovery Collaboratory*).
3 *Going everywhere:* smart physical objects (Sackmann *et al*. 2006) that communicate with computational environments, allow for context-aware information services, and create articulate environments – the specific application context being the *QueryLens* system (see the section *Going everywhere:* QueryLens).

Figure 2 illustrates these three directions. Differentiating between them and describing them separately does not imply that many future systems will not benefit particularly from their tight integration (Fischer *et al*. 2005). Learners engage in varieties of personal and social activities in different places and context and each approach may support a certain context better than others. At the same time, there are unique opportunities in the intersections of the three approaches.

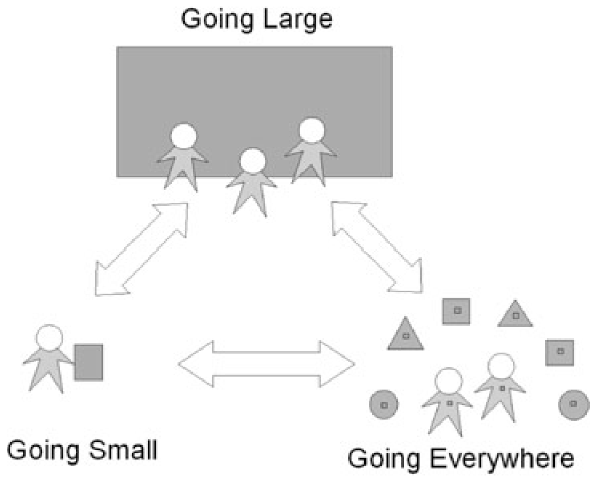

Fig 2 Going small, going large and going everywhere.

## Application systems

Wireless and mobile technologies influence how issues related to our research agenda come into play in different application domains. This section introduces three application systems that we have developed in our research centre, and discusses their implications for designing future socio-technical environments for lifelong learning with innovative wireless and mobile technologies.

### Going small: *Mobility-for-All*

To use current public transportation, it is necessary to comprehend, manipulate, and process essential navigation artifacts (i.e. maps, schedules, landmarks, labels and signs and clocks) often encoded in difficult-to-understand representations. The need to master complex navigational artifacts can be barriers to community access and independence for persons with cognitive disabilities. The *Mobility-for-All* project (Sullivan & Fischer 2003; Carmien *et al*. 2005) integrates distributed human and computational resources to eliminate this need and allow cognitively disabled

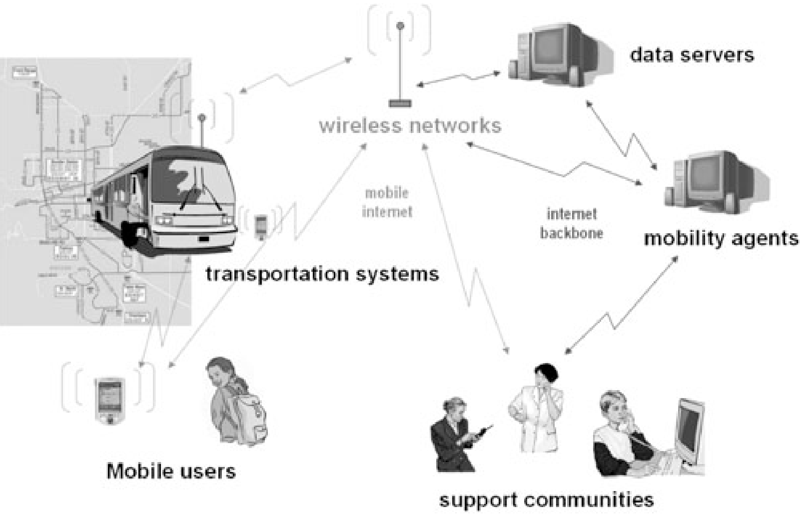


Fig 3 A socio-technical architecture to support mobile users and their support communities on transportation systems.

people to do what they normally could not easily perform or learn.

Our work is guided in large part by the distributed intelligence framework and seeks new division of roles between planning and situated action. An increasing number of travellers are now using Web-based information services to search for optimal schedules, print maps and acquire other essential knowledge needed to *plan* trips. Wireless and mobile technologies are further impacting travellers' practices by making resources and tools that used to be available only prior to travel also available during travel.

The project's design approach was inspired by observations of instructors who accompanied new students during training sessions and provided personally contextualized, 'just-in-time' instructions for what to do and where to go next. To reduce the workload on support communities, the project team considered how technologies could be designed to assist persons in their care as they travelled or learned a new route. The socio-technical architecture shown in Fig 3 was designed to address the needs of mobile users travelling to and from a group home facility in a community setting. This architecture leverages two emerging ubiquitous technologies:

1 wireless, mobile, location-aware personal digital assistants (PDAs) or cellular phones, and
2 mobile Global Positioning System (GPS) technology available as standard equipment on an increasing number of public transit vehicles.

This architecture supports the following goals:

- Direct support of the mobile user with personally relevant navigational tasks, including selecting a destination, locating the right bus, preparing to board, boarding the bus; signalling the driver where to stop, and disembarking.
- When needed, initiate or facilitate communications between the mobile user, support communities, and transportation system operators.
- Provide a 'safety net' when something 'goes wrong'.

We conducted early assessment and basic usability tests using an interactive simulation program and a PDA-based prototype (Carmien *et al*. 2005), which allowed us to test and refine our experimental method and data-gathering technique to prepare for future rounds of more robust user studies. Our experiences with the *Mobility-for-All* project illuminated the issues that arise when wireless mobile technologies change context and goals of learning.

The socio-technical architecture was designed to eliminate the need to learn the uses of existing complex artifacts (cf. *tools for living*) and empower people with different cognitive abilities by seeking new division of roles between planning and situated actions. As architectural components are refined and deployed, personalization and user modeling will increasingly become an important research area. Technologies must be developed that (1) permit support communities to easily configure mobile systems to suit the unique 'universe of one' abilities of each person and (2) allow systems to

Fig 4 A group of stakeholders exploring an urban design problem with the *Envisionment and Discovery Collaboratory*.

intelligently 'adapt' to each person's abilities and learning styles through use.

**Going large: Envisionment and Discovery Collaboratory**

Large interactive surfaces provide affordances that conventional desktop computer systems cannot support. The *EDC* (Arias *et al*. 2001) integrates an interactive table and a large vertical display in order to support collaborative design and learning. We can create unique collaborative learning environments using the *EDC* alone and in combination with personal mobile devices.

The *EDC* supports face-to-face collaboration in complex collaborative design activities, such as urban planning, emergency management and design of learning environments. Figure 4 shows a group of stakeholders exploring an urban design problem using the *EDC*. Face-to-face collaboration, grounded by large, computationally enhanced physical boards and design objects, is critical in building a shared understanding and facilitating social debate and discussion among stakeholders with different backgrounds. Manipulations of physical objects of the *EDC* are sensed wirelessly by the board and fed to an underlying computational model; therefore, the *EDC* is able to provide dynamic feedback and relevant background information to stakeholders, extend passive technologies for face-to-face collaboration, and open fundamental new research challenges and opportunities.

The architecture of the *EDC* supports *reflection-in-action* (Schön 1983) with the following components:

- The *action space* supports collaboration around the table through a physical and computational model appropriate for the particular application domain.
- The *reflection space* supports the capture, creation, presentation and modification of hypermedia information and provides a portal to a dynamic, user-extensible, emergent Web-based information environment.
- Knowledge-based mechanisms, such as *computational critics*, contextualize information by finding information in the reflection space that is relevant to a specific event or situation occurring in the action space.

In addition to supporting face-to-face collaboration, the *EDC* is a rich environment for studying *distances* in collaborative design and learning (Fischer 2005):

- *Spatial distance* is supported in the *EDC*. Because reflection spaces are accessible via the Web, questionnaires, discussions and background information can be accessed and contributed from anywhere.
- *Temporal distance* plays an important role in the *EDC* because design problems take place over periods of weeks and months, requiring that design rationale be captured in the reflection space to preserve the decision-making processes of others, and remind stakeholders of decisions they have made in the past.
- *Conceptual distance* is explored with a focus on communities of interest (which brings different communities of practice together) in which the individuals do not share a common work practice, but rather come together for the purpose of solving a particular problem.

Unique opportunities exist at the intersection of 'going large' and 'going small'. *Caretta* (Sugimoto *et al*. 2004) is an extension of the *EDC* that integrates individual and social design activities (Fischer *et al*. 2005) by using wireless and mobile devices to bridge personal and collaborative work within and across different interaction spaces in face-to-face settings. Caretta provides users with personal spaces for individual reflections (based on PDAs), a shared space for group discussions (based on boards similar to the *EDC*), and intuitive transition methods between these spaces. Caretta users can discuss and negotiate with each other in the shared space by manipulating physical objects, each of which is enhanced by a radio frequency tag for rapid object recognition. An augmented reality technology for overlaying virtual graphics onto the shared space through a liquid crystal display projector creates an immersive collaborative environment that enhances interactions and mutual awareness among users.

The mobility and the affordance provided by the *EDC* and Caretta support participants to create shared understanding and learn collaboratively through social interactions. It is important to discover which social situations are more conducive to the creation of this shared understanding. For example, important aspects to study include determining the utility of a trained facilitator, the efficacy of participant facilitators, and the effect that such interventions would have on 'putting the owners in charge'. By analysing how the *EDC* is utilized during design activities, we will assess the social and technical dimensions of how shared understanding can be created.

### Going everywhere: *QueryLens*

A third research project explores a distributed intelligence environment for information access and contribution by embedding Radio Frequency IDentification (RFID) transponders (Want *et al*. 1999) into everyday objects thereby creating the infrastructure that allows people to engage in informed participation. The 'Going Everywhere' approach is different from 'Going Small', in which learners primarily interact with a small personal device such as a wireless PDA. In 'Going Everywhere', computation is distributed in the physical environment. People can, for instance, engage in peer-to-peer or other forms of learning through the interactions with multiple, computationally enhanced physical objects.

In our everyday life, it is a common practice to attach notes written on a piece of paper (e.g. Post-It® Notes) to a physical object. Such physically contextualized information artifacts have been used as a personal memory aid or a means to share information with others. Taking a close look at this existing practice, we implemented a mobile information-sharing environment called *QueryLens* (Konomi 2002) that accumulates queries, connects them to a relevant physical object, allows learners to share and modify them, and uses them to capture answers. It uses an off-the-shelf PDA device with a hardware extension that provides the capability to read and write data from/to RFID transponders.

*QueryLens* extends 'digital sticky notes' to function in dynamic and social environments, where learners can participate in the process of designing and extending the information space and engage in peer-to-peer learning. For example, *QueryLens* can integrate learning in a music lover's weekly shopping experiences. As she browses around a music store, she uses *QueryLens* to scan a CD's RFID tag and access the artist's biography, discography, comments and latest news, professional reviews, consumer opinions, similar/related CDs, etc. She can also obtain specific information based on her unique interests and situations. 'Why is the man on the jacket cover asleep?' 'Which one of this artist's CDs should I buy for my sister?' When she cannot identify and articulate her information needs about the CD, she can use *QueryLens* to learn what others wanted to know about it. If her information needs cannot be fulfilled by searching existing databases, they can be fulfilled by contributions from various people including the store's staff, in-store and remote knowledgeable fans and the artist. Of course, she can also contribute information if she has certain impetus to do so.

Each PDA device manages private and shared information spaces using a mobile database management system that periodically synchronizes the local data space with the global data space on a server. Unlike conventional mobile information-sharing environments, *QueryLens* is based on a socio-technical approach to empower learners by facilitating them to engage in informed participation rather than forcing them to be the consumers of existing information environments. Embodying this approach is the architecture illustrated in Fig 5, which facilitates learners to articulate and share information needs *in context* using the query server so as to incrementally accumulate the 'right' information in the 'right' physical objects. RFID-chipped smart physical objects are used for facilitating communication and end-user contribution as well as automatic indexing and delivery of information. Ogata and Yano (2004a) proposed a similar distributed intelligence environment that uses everyday objects in order to support learning.

*QueryLens* was used in a small scale at a university festival in Japan, where citizens visited a number of

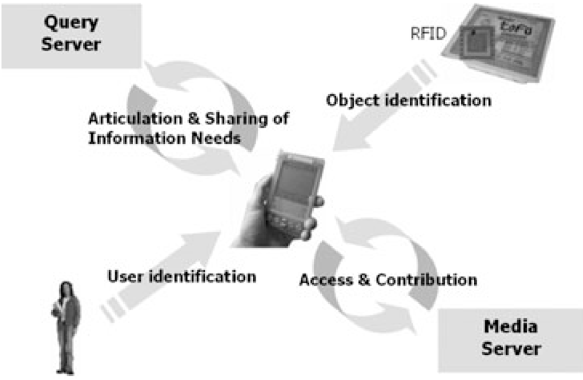


Fig 5 An information sharing architecture that supports informed participation.

small interactive events, exhibitions and food tents. People were encouraged to exchange queries and answers about exhibitions and other events using their mobile phones. This preliminary use experiment suggested the possibility of context awareness in overcoming the information overload problem. However, we also faced challenges of system deployment as well as socio-technical issues in motivating users to contribute.

Other research in the $L^3D$ centre uses computationally enhanced physical objects as construction kit elements that support learning activities of children. *QuiltSnaps* (Buechley *et al*. 2005) is a fabric-based construction kit consisting of a set of computationally enhanced quilting pieces. *SmartTiles* (Elumeze & Eisenberg 2005) are small lightweight, independently programmable tile objects that can be combined to cover various sorts of planer surfaces; each touch-sensitive tile contains its own computer and Light Emitting Diode (LED), and communicates with neighbouring tiles to enact cellular-automaton programs.

## Reflections on opportunities and pitfalls

Our experiences with the three application systems have shown that wireless and mobile technologies can create exciting opportunities for learning by supporting intelligence augmentation, social creativity, informed participation and support of unique needs of users in achieving their tasks and engaging in personally meaningful activities. Wireless and mobile technologies, however, are not without potential pitfalls, including getting trapped in gift-wrapping and techno-determinism, a limited understanding of the roles of tools in distributed intelligence, the destruction of place, violations of privacy and a limited understanding of the innovation potential.

### From gift-wrapping and techno-determinism to co-evolution

To exploit the full potential of wireless and mobile technologies in education, we need to transcend *gift-wrapping* (Fischer 1998) approaches and *techno-determinism*. There is nothing wrong with *gift-wrapping*, but it is limited in scope and innovation. For example, teachers can 'webify' a course by making teaching materials available on the Web rather than distributing them as paper copies. Simple push-button devices such as *clickers* (Dubson 2003) can be used to precisely measure responses to a teacher's question rather than manually counting the raised hands of many students. These technologies may change the economics of teaching and learning; however, they contribute little to introducing fundamentally different approaches to learning (Fischer 1998).

### Roles of tools

Distributed intelligence creates a framework to emphasize and promote *tools for living* versus *tools for learning* in education. Understanding the implications of this distinction is a critical problem for educational decisions. There are numerous activities that people cannot do without tools. In these cases, there is no choice but to rely on *tools for living*. Wireless and mobile technologies have the important potential to make tools available at all times and all places, thereby making the *tools-for-living* perspective more viable for numerous applications (Oppermann 2005). A lack of focus on *tools for learning* can lead to deskilling and learned helplessness because people becoming over-dependent on their tools. Our experiences with the *Mobility-for-All* project suggest the importance of understanding this distinction for individual users based on their unique capabilities.

### Always on

Wireless and mobile technologies are making it possible to access digital information resources, use online services, and communicate with remote people anywhere at any time, creating a distributed intelligence environment across the boundaries of place and time. Breaking the conventional boundaries introduces the pitfalls of *destroying the notion of place and the time for reflection.* Considering this issue, the *EDC* is designed to support the notion of a place in face-to-face collaboration settings (Olson & Olson 2001).

**Capturing context**

Determining the context for an individual located somewhere in the world (or a group distributed all over the world) is a substantially more difficult problem than for people gathered in an office or a classroom. Building truly context-aware learning environments (Lonsdale *et al*. 2003; Ogata & Yano 2004a, b) presents a greater challenge than using data transmitted by wireless and mobile computing devices (such as GPS, RFID and other sensors); it requires shared understanding between humans and their computational environments (Dey *et al*. 2001).

In design, a large fraction of context-relevant information cannot be inferred from the environment because the context resides outside the environment, is unarticulated, or exists only in the head of a designer; however, without access to the stakeholders' intentions, a system is unable to detect that problems exist. If a system provides mechanisms to articulate intentions explicitly, using, for example, a specification component (Nakakoji 1993), and designers are willing to do so, the additional context can be used to identify the breakdown situation and provide designers with opportunities for reflection and learning. This also has certain implications for the design of mobile information sharing environments. The *QueryLens* system captures users' context automatically as well as manually by using a mechanism for motivating and facilitating user input.

**Privacy**

It is necessary to understand users and their tasks in order to provide 'the "right" information, at the "right" time, in the "right" place, in the "right" way, to the "right" person' in a distributed intelligence environment (Konomi 2004). Decontextualized information delivery such as Microsoft WORD's 'Tip of the Day' could be avoided if the system understands users' preferences and their current tasks. However, the desire to know more about users and tasks may interfere with users' privacy needs.

Privacy is an essential factor in intellectual processes and learning in a distributed intelligence environment: 'at the intellectual level, individuals need to process the information that is constantly bombarding them, information that cannot be processed while they are still "on the go" ' (Westin 1967).

**Innovation**

How innovative are our ideas about the use of wireless and mobile technologies in education? Our innovations should not be restricted to new technologies, but they should support the co-evolution of social practices, new media and new learning organizations (Brown 2003; Roschelle 2003). It is not technology *per se* that matters, but *technology-in-use.* To deeply understand the real impact of wireless and mobile technologies on education, we need to shift the discourse from a concern about who has access to new information technologies to who can use them in interesting ways for personally meaningful tasks (Barron 2004).

## Conclusion

The last decade has seen far-reaching changes in living, learning, working and collaboration, fundamentally influenced by information and communication technologies, specifically the World Wide Web. Projecting 10 years into the future (Roschelle *et al*. 2005), we may ask what the impact of wireless and mobile technologies will be. We should take up the challenge that the future is not 'out there' to be discovered (like Columbus discovered America), but has to be invented and designed, and as wireless and mobile technologies become widely available, the WMTE community should be a major force in this challenge – not only to promote the technologies, but to make major contributions to fundamentally rethinking, reinventing and redesigning the future of education.

## Acknowledgements

The authors thank the members of the Center for LifeLong Learning and Design ($L^3D$) who have contributed to the conceptual frameworks and socio-technical environments described in this paper. Special thanks to Jim

Sullivan, Stefan Carmien and Andrew Gorman for the development of the *Mobility-for-All* system and to Hal Eden and Ernesto Arias for the development of the *EDC*.

This paper is based on a keynote presentation by G. Fischer in November 2005 at the Third IEEE International Workshop on Wireless and Mobile Technologies in Education, IEEE Computer Society, Tokushima, Japan and a short paper documenting this presentation (Fischer & Konomi 2005). The authors thank the conference organizers for the opportunity to present their work to the conference participants.

The research was sponsored by: (1) a grant from the Coleman Institute, Boulder, CO; (2) the National Science Foundation, Grant IIS 0456053 'SGER: Designing and developing mobile computing infrastructures and architectures to support people with cognitive disabilities and caregivers in authentic everyday tasks'; and (3) SRA Key Technology Laboratory, Inc., Tokyo, Japan.

## References

Arias E.G., Eden H., Fischer G., Gorman A. & Scharff E. (2001) Transcending the individual human mind – creating shared understanding through collaborative design. In *Human–Computer Interaction in the New Millennium* (ed. J. M. Carroll), pp. 347–372. ACM Press, New York, NY.

Barron B. (2004) Learning ecologies for technological fluency: gender and experience differences. *Journal of Educational Computing Research* **31**, 1–36.

Brown J.S. (2003) Foreword. In *Open Innovation* (ed. H. Chesbrough), pp. ix–xii. Harvard Business School Press, Boston, MA.

Brown J.S. & Duguid P. (2000) *The Social Life of Information*. Harvard Business School Press, Boston, MA.

Brown J.S., Collins A. & Duguid P. (1989) Situated cognition and the culture of learning. *Educational Researcher* **18**, 32–42.

Bruner J. (1996) *The Culture of Education*. Harvard University Press, Cambridge, MA.

Buechley L., Elumeze N., Dodson C. & Eisenberg M. (2005) QuiltSnaps: a fabric based computational construction kit. In *Proceedings of the Third IEEE International Workshop on Wireless and Mobile Technologies in Education (Tokushima, Japan)*, pp. 219–221. IEEE Computer Society, Los Alamitos, CA.

Buxton W. (2002) Less is more (more or less): uncommon sense and the design of computers. In *The Invisible Future – the Seamless Integration of Technology in Everyday Life* (ed. P. J. Denning), pp. 145–179. McGraw-Hill, New York, NY.

Carmien S. (2006) *Socio-technical environments supporting distributed cognition for persons with cognitive disabilities*. Unpublished PhD Dissertation. University of Colorado at Boulder, Boulder, CO. [WWW document.] URL http://l3d.cs.colorado.edu/~carmien/dissertation_sm.pdf (last accessed 22 March 2007).

Carmien S. & Fischer G. (2005) Tools for living and tools for learning. In *Proceedings of the HCI International Conference (HCII) (Las Vegas, July 2005)* [CD-ROM]. Lawrence Erlbaum, Mahwah, NJ.

Carmien S., Dawe M., Fischer G., Gorman A., Kintsch A. & Sullivan J.F. (2005) Socio-technical environments supporting people with cognitive disabilities using public transportation. *Transactions on Human–Computer Interaction (TOCHI)* **12**, 233–262.

Dey A.K., Abowd G.D. & Salber D. (2001) A conceptual framework and a toolkit for supporting the rapid prototyping of context-aware applications. *Human–Computer Interaction* **16**, 97–166.

Donald M.W. (2004) Is a picture really worth a 1,000 words? Review essay of *Computers, Visualization and History: How New Technology Will Transform Our Understanding of the Past (by David S. Staley). History and Theory: Studies in the Philosophy of History* **43**, 379–385.

Dubson M. (2003) *'Clickers': Electronic Audience Feedback in the Classroom*. [WWW document.] URL http://www.colorado.edu/physics/EducationIssues/HITT/HITTDescription.html (last accessed 5 October 2006).

Elumeze N. & Eisenberg M. (2005) SmartTiles: mobility and wireless programmability in children's construction and craft. In *Proceedings of the Third IEEE International Workshop on Wireless and Mobile Technologies in Education (Tokushima, Japan)*, pp. 230–237. IEEE Computer Society, Los Alamitos, CA.

Fischer G. (1998) Making learning a part of life-beyond the 'gift-wrapping' approach of technology. In *Lifelong Learning and its Impact on Social and Regional Development* (eds P. Alheit & E. Kammler), pp. 435–462. Donat Verlag, Bremen. [WWW document.] URL http://l3d.cs.colorado.edu/~gerhard/papers/giftwrapping-98.pdf (last accessed 22 March 2007).

Fischer G. (2001) User modeling in human–computer interaction. *User Modeling and User–Adapted Interaction (UMUAI)* **11**, 65–86.

Fischer G. (2005) Distances and diversity: sources for social creativity. In *Proceedings of Creativity and Cognition) (London, April 2005)*, pp. 128–136. ACM Press, New York, NY.

Fischer G. (2006) Distributed intelligence: extending the power of the unaided, individual human mind. In

*Proceedings of Advanced Visual Interfaces (AVI) Conference (Venice, May 23–26, 2006)*, pp. 7–14. ACM Press, New York, NY.

Fischer G. & Konomi S. (2005) Innovative media in support of distributed intelligence and lifelong learning. In *Proceedings of the Third IEEE International Workshop on Wireless and Mobile Technologies in Education (Tokushima, Japan)*, pp. 3–10. IEEE Computer Society, Los Alamitos, CA.

Fischer G. & Nakakoji K. (1992) Beyond the macho approach of artificial intelligence: empower human designers – do not replace them. *Knowledge-Based Systems (Special Issue on AI in Design)* **5**, 15–30.

Fischer G. & Sugimoto M. (2006) Supporting self-directed learners and learning communities with sociotechnical environments. *International Journal of Research and Practice in Technology Enhanced Learning (RPTEL)* **1**, 31–64.

Fischer G., Arias E., Carmien S., Eden H., Gorman A., Konomi S. & Sullivan J.F. (2004) *Supporting Collaboration and Distributed Cognition in Context-Aware Pervasive Computing Environments*. Paper presented at the 2004 Meeting of the Human Computer Interaction Consortium 'Computing Off The Desktop'. [WWW document.] URL http://l3d.cs.colorado.edu/~gerhard/papers/hcic2004.pdf (last accessed 22 March 2007).

Fischer G., Giaccardi E., Eden H., Sugimoto M. & Ye Y. (2005) Beyond binary choices: integrating individual social creativity. *International Journal of Human–Computer Studies (IJHCS) (Special Issue on Computer Support for Creativity)* **63**, 482–512.

Gardner H. (1991) *The Unschooled Mind*. Basic Books, New York, NY.

Hollan J., Hutchins E. & Kirsch D. (2001) Distributed cognition: toward a new foundation for human–computer interaction research. In *Human–Computer Interaction in the New Millennium* (ed. J. M. Carroll), pp. 75–94. ACM Press, New York, NY.

Horvitz E., Jacobs A. & Hovel D. (1999) Attention-sensitive alerting. In *Proceedings of the Conference on Uncertainty and Artificial Intelligence (UAI '99) (Stockholm, Sweden)*, pp. 305–313. Morgan Kaufmann, San Francisco, CA.

Konomi S. (2002) QueryLens: beyond ID-based information access. In *Proceedings of the Fourth International Conference on Ubiquitous Computing (UBICOMP 2002)*, pp. 210–218. Springer, Berlin.

Konomi S. (2004) Personal privacy assistants for RFID users. In *Proceedings of the International Workshop Series on RFID 'Information Sharing and Privacy' (Tokyo, November 2004)*. [WWW document.] URL http://www.slrc.kyushu-u.ac.jp/rfid-workshop/ (last accessed 22 March 2007).

L$^3$D (2005) *Center for LifeLong Learning and Design, University of Colorado, Boulder*. [WWW document.] URL http://l3d.cs.colorado.edu/ (last accessed 5 October 2006).

Lonsdale P., Baber C., Sharples M. & Arvanitis T. (2003) A context awareness architecture for facilitating mobile learning. In *Proceedings of MLEARN 2003: Learning with Mobile Devices.* pp. 79–85. Learning and Skills Development Agency, London.

Mumford E. (1987) Sociotechnical systems design: evolving theory and practice. In *Computers and Democracy: A Scandinavian Challenge* (eds G. Bjerknes, P. Ehn & M. Kyng), pp. 59–76. Avebury, Aldershot, UK.

Nakakoji K. (1993) *Increasing shared understanding of a design task between designers and design environments: the role of a specification component*. Unpublished PhD Dissertation. University of Colorado at Boulder, Boulder, CO.

Norman D.A. (1993) *Things That Make Us Smart*. Addison-Wesley, Reading, MA.

Ogata H. & Yano Y. (2004a) Context-aware support for computer supported ubiquitous learning. In *Proceedings of the Second IEEE International Workshop on Wireless and Mobile Technologies in Education*, pp. 27–34. IEEE Computer Society, Los Alamitos, CA.

Ogata H. & Yano Y. (2004b) Knowledge awareness map for computer-supported ubiquitous language-learning. In *Proceedings of the Second IEEE International Workshop on Wireless and Mobile Technologies in Education*, pp. 19–26. IEEE Computer Society, Los Alamitos, CA.

Okada M., Yamada A., Tarumi H., Yoshida M. & Moriya K. (2003) DigitalEE II: RV-augmented interface design for networked collaborative environmental learning. In *Proceedings of the International Conference on Computer Support for Collaborative Learning (CSCL2003)* (eds B. Wasson, S. Ludvigsen & U. Hoppe), pp. 265–274. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Olson G.M. & Olson J.S. (2001) Distance matters. In *Human–Computer Interaction in the New Millennium* (ed. J. M. Carroll), pp. 397–417. ACM Press, New York, NY.

Ong W.J. (1982) *Orality and Literacy*. Routledge, London.

Oppermann R. (2005) Situated learning in the work process. In *Proceedings of the HCI International Conference (HCII) (Las Vegas, July 2005)* [CD-ROM]. Lawrence Erlbaum, Mahwah, NJ.

Pea R.D. (1993) Practices of distributed intelligence and designs for education. In *Distributed Cognitions: Psychological and Educational Concicerations* (ed. G. Solomon), pp. 47–87. Cambridge University Press, Cambridge.

Pea R.D. (2004) The social and technological dimensions of scaffolding and related theoretical concepts for learning, education, and human activity. *Journal of the Learning Sciences* **13**, 423–451.

Roschelle J. (2003) Unlocking the learning value of wireless mobile devices. *Journal of Computer Assisted Learning* **19**, 260–272.

Roschelle J., Patton C., Chan T.W., Brecht J. & Bienkowski M. (2005) G1:1 scenarios: envisioning the context for WMTE in 2015. *Proceedings of the Third IEEE International Workshop on Wireless and Mobile Technologies in Education (Tokushima, Japan)*, pp. 112–119. IEEE Computer Society, Los Alamitos, CA.

Sackmann S., Strüker J. & Accorsi R. (2006) Personalization in privacy-aware, highly dynamic systems. *Communication of the ACM* **49**, 32–38.

Salomon G. (1993) *Distributed Cognitions: Psychological and Educational Considerations*. Cambridge University Press, Cambridge.

Schön D.A. (1983) *The Reflective Practitioner: How Professionals Think in Action*. Basic Books, New York, NY.

Sharples M. (2000) The design of personal mobile technologies for lifelong learning. *Computers and Education* **34**, 177–193.

Simon H.A. (1996) *The Sciences of the Artificial*. The MIT Press, Cambridge, MA.

Streitz N.A., Röcker C., Prante T., vanAlphen D., Stenzel R. & Magerkurth C. (2005) Designing smart artifacts for smart environments. *IEEE Computer* **38**, 41–49.

Suchman L.A. (1987) *Plans and Situated Actions*. Cambridge University Press, Cambridge.

Sugimoto M., Hosoi K. & Hashizume H. (2004) Caretta: a system for supporting face-to-face collaboration by integrating personal and shared spaces. In *Proceedings of ACM Conference on Human Factors in Computing Systems (CHI2004) (Vienna, Austria)*, pp. 41–48. ACM Press, New York, NY.

Sullivan J. & Fischer G. (2003) Mobile architectures and prototypes to assist persons with cognitive disabilities using public transportation. In *Proceedings of the 26th International Conference on Technology and Rehabilitation (Atlanta, GA)* (published on a CD). RESNA Press, Arlington, VA.

Terveen L.G. (1995) An overview of human–computer collaboration. *Knowledge-Based Systems (Special Issue on Human–Computer Collaboration)* **8**, 67–81.

Want R., Fishkin K.P., Gujar A. & Harrison B.L. (1999) Bridging physical and virtual worlds with electronic tags. In *Proceedings of the ACM Conference on Human Factors in Computing Systems (CHI′99)*, pp. 370–377. ACM Press, New York, NY.

Weiser M. (1991) The computer for the 21st century. *Scientific American* **265**, 66–75.

Westin A.F. (1967) *Privacy and Freedom*. Atheneum, New York, NY.