British Journal of Educational Technology (2009)
doi:10.1111/j.1467-8535.2008.00912.x

Leveraging mobile technology for sustainable seamless learning: a research agenda

Chee-Kit Looi, Peter Seow, BaoHui Zhang, Hyo-Jeong So, Wenli Chen and Lung-Hsiang Wong

Chee-Kit Looi is Head of the Learning Sciences Lab of the National Institute of Education (LSL, NIE), Nanyang Technological University (NTU). He has over two decades of experience with educational technology research in research institutes and universities. He is an editorial member of the International Journal on AI & Education *and the* International Journal on CSCL. *Peter Seow is a senior software engineer with the LSL, NIE. He has over 10 years of industrial experience in leading projects, consulting and systems development. Zhang BaoHui is an assistant professor in the Learning Sciences and Technologies Academic Group (LSTAG) and LSL, NIE, Nanyang Technological University (NTU). His current research foci are designing and assessing interactive environments when using computer-based modelling or mobile technologies for inquiry-based science learning. So Hyo-Jeong is an assistant professor in the LSTAG and LSL, NIE, NTU. Her research focuses on designing interactive online learning environments, and students' scientific knowledge building through collaborative inquiry. Wenli Chen is an assistant professor in the LSTAG and LSL, NIE, NTU. Her research interests and expertise are computer-mediated communication, virtual learning environment, mobile learning and community of learners. Lung-Hsiang Wong is an assistant professor in the LSTAG and LSL, NIE, NTU. His research interests are information and communication technology-enhanced Chinese language learning, teachers' professional development, agent technology for learning and mobile learning. Address for correspondence: LSL, NIE, NTU, 1 Nanyang Walk Singapore 637616. Email: cheekit.looi@nie.edu.sg*

Abstract

Over the next 10 years, we anticipate that personal, portable, wirelessly networked technologies will become ubiquitous in the lives of learners—indeed, in many countries, this is already a reality. We see that ready-to-hand access creates the potential for a new phase in the evolution of technology-enhanced learning, characterised by 'seamless learning spaces' and marked by continuity of the learning experience across different scenarios or contexts, and emerging from the availability of one device or more per student. The challenge is to enable learners to learn whenever they are curious and seamlessly switch between different contexts, such as between formal and informal contexts and between individual and social learning, and by extending the social spaces in which learners interact with each other. In this paper, we review the potential of mobile learning research for designing seamless learning environments that can bridge both formal and informal learning, present a research agenda and discuss important methodological issues that concern research into formal and informal learning.

Introduction

Our students live in a digital world, and the use of technologies such as instant messaging, video sharing, photo sharing, social network tools, podcasting and blogging are integrated into their lifestyles. Cellphones are used not only for making calls, but also for taking pictures and uploading them to shared spaces, creating mobile blogs or accessing the web on the move. The use of these technologies facilitates communication, collaboration, sharing and learning in informal settings with their peers, friends and family unbounded by time and location. Students spend more time in such 'informal' settings than in 'formal' settings in the school. One of the fundamental challenges for the 21st century learners is not only what they learn, but also how and when they learn. We want to understand more deeply about how learners learn informally, and use that understanding to inform formal and informal learning practices.

Personal, portable, wirelessly networked technologies will become ubiquitous in the lives of learners. With quick and ready access to these technologies, we enter into a new phase in the evolution of technology-enhanced learning (TEL), characterised by 'seamless learning spaces' and marked by continuity of the learning experience across different scenarios or contexts, and emerging from the availability of one device or more per student ('one-to-one') (Chan *et al*, 2006). These developments, supported by theories of social learning, situated learning and knowledge building, will influence the nature, the process and the outcomes of learning. One-to-one TEL will push the frontier of technology use in formal and informal learning. The ingenious, emergent or pervasive uses of one-to-one devices in some usage contexts may be close to the tipping point in terms of effecting fundamental shifts in the ways students learn inside and outside schools.

Previous mobile learning research, however, has typically focused on either formal or informal settings and failed to examine the integrated and synergetic effects of linking these two contexts or environments of learning (Beale, 2006; Sharples, 2006). Given the increasingly pervasive and ubiquitous nature of mobile technology, it has now arrived at a point where it is becoming more affordable to students to possess and use these tools in both formal and informal settings. However, a large research gap exists, and that is to bridge the two settings in order to construct a seamless learning environment and conduct longitudinal studies to explore the affordances of such learning environments in promoting 21st century knowledge, skills and positive attitudes towards learning.

In this paper, we propose perspectives and approaches to address this research gap. We do this by building on some research work on mobile learning we have conducted in schools in Singapore, by highlighting a seamless learning framework and by discussing important research methodological issues.

One-to-one TEL

One-to-one TEL has the potential to 'cross the chasm' (Moore, 1991) from early adopters conducting isolated design studies to adoption-based research and widespread implementation, with the help of research and evaluation that gives attention to the digital divide and other potentially negative consequences of pervasive computing (Chan *et al*, 2006).

The portability and versatility of mobile devices has significant potential in promoting a pedagogical shift from didactic teacher-centred to participatory student-centred learning. In this type of learning culture, teachers act as a facilitator and learning partner rather than a sole expert of knowledge. Previous research on learning with mobile technology has clearly shown that the mobility and connectivity of technological tools enable students to become an active participant, not a passive receiver in learning activities. For instance, instead of sitting in front of a desktop computer and watching a video simulation, students with mobile devices can go out to the field, directly and physically explore our world, and share their experiences with others (Colella, 2000; Roschelle, 2003; Squire & Klopfer, 2007). While it is not to say that abstract knowledge and media-replicated experiences are not desirable in learning processes, one of the critical problems in traditional schooling practices is the excessive amount of decontextualised information, indirect and abstract knowledge, and second-hand experiences confined in classroom contexts (Barab, 2002).

Another significance of learning mediated by mobile technology is to challenge the traditional dichotomous distinction between formal learning and informal learning by creating seamlessly connected learning experiences. While research on cognition and learning during the past decades has emphasised the importance of linking learning in the classroom and learning in the field, the dominant characteristic of school learning is still a strong focus on individual cognition, pure mental activity without tool use and overly context-general learning (Brown, Collins & Duguid, 1989; Resnick, 1987). Moreover, there has been a tension between formal learning, which is based on fixed curricula enacted in classroom environments, and informal learning where learners are participating in intentional or unintentional experiences outside school settings. We believe that the two forms of learning should not be seen as dichotomous and conflicting situations (Barron, 2006; Sharples, 2006). Instead, by utilising affordances of mobile technology, we can bridge the gap between formal and informal learning, and encourage students to learn in naturalistic settings for developing context-specific competences.

Seamless learning environment bridges private and public learning spaces where learning happens as both individual and collective efforts and across different contexts (such as in-school versus after-school, formal versus informal). 'We spend a lot of time trying to change people. The thing to do is to change the environment and people will change themselves' (Watson, 2006, p. 24). When thinking about K-12 learning scenarios, people often revert to a mental image of the classroom with all seats facing the teacher. The presumption is that learning happens at fixed times and fixed places. However, with the diffusion of technology, the notions of place, time and space for learning have changed. The learning space is no longer defined by the 'class' but by 'learning' unconstrained by scheduled class hours or specific locations. With the mobile technologies at hand, students can learn seamlessly—both in classroom and out of classroom, both in school time and after school time. While learning can be facilitated or scaffolded by teachers or peers, at other times it could be student-initiated, impromptu and emergent.

In the next section, we discuss two previous mobile learning projects we have conducted: (a) Project 3Rs (reduce, reuse and recycle), and (b) inquiry-based learning with mobile devices.

Mobile devices to mediate experiential learning

In August 2006, we designed and implemented an activity to learn the 3Rs using mobile and online technologies in six primary schools in Singapore with the collaboration of Singapore Temasek Polytechnic and the National Environment Agency in designing an activity to learn the 3Rs using mobile and online technologies (Chen, Tan, Looi, Zhang & Seow, 2008; Seow, Zhang, Chen, Looi & Tan, in press). The mobile devices used were HP RX3715 Pocket PCs (Hewlett-Packard Company, Palo Alto, CA, USA) incorporated with functionalities such as a digital camera, wireless capability, Internet browser and text input function. The pedagogical approach is a challenge-experiential approach, which is based on 'experiential learning' where learning occurs through the process of experience, and knowledge is created 'through a transformation of experience' (Kolb, 1984). Based on the pedagogical model, software applications were designed by researchers to lead the students to carry out their learning tasks in the challenge-experiential cycle (Figure 1).

Figure 1: The challenge-experiential model

- **Challenge:** Teacher presents 3Rs issues and the challenge to the students with the environmental problem of having too much garbage. By filling in the KWL (what I Know, what I Want to know, what I Learned) charts, students are asked to record some of their prior knowledge through questions such as what their predictions are or what they expect to see.
- **Experience:** Students are involved in activities that they intend to learn from. In a supermarket, they study different sizes and materials for food packaging and take photos of them, observe and record how many plastic bags are dispensed at the checkout counter, interview customers about their attitudes and practices of 3Rs, and upload the data collected wirelessly to an online forum.
- **Reflecting:** During the field activity in the supermarket, students reflect on their experiences by using Pocket PCs. Back in class, students reflect on and share their experiences in an online portal. This helps the students develop their logical reasoning, verbalise their thoughts and share their experience with others.
- **Planning:** Students create plans to promote 3Rs ideas at home and their communities.
- **Applying:** Students are asked how they would apply at home and in school what they have learned about 3Rs.

The 3Rs software is designed to provide affordances for enhancing thinking skills through instant feedback, organising and capturing thinking processes, providing visual representations and modelling problem-solving approaches to scaffold the student's problem-solving skills. Each Pocket PC has a database to store data collected by the students, including the pictures taken on the reusable items in the supermarket. The software generates an HTML file of the students' experiences, reflections and plans, which is then uploaded over a wireless network. The results of the learning activity were encouraging as students had significant learning gains in the understanding of the 3Rs and increased confidence in the use of mobile devices (Chen *et al*, 2008).

An ongoing extension project to the 3Rs project focuses on designing and implementing a seamless learning environment for inquiry-based science learning among primary school students. Our goal is to allow students to link their field experiences to concepts they learn in classroom and build their understanding through collaborative inquiry with peers. The new application addresses two shortcomings in Project 3Rs. First, the mobile learning activity should be sustainable and scalable for the school to use throughout the year and across different levels. Second, teachers have a role to play in designing the learning activity and integrating it into their class curriculum. Mobile learning and online forum, therefore, would facilitate the learning processes both in and out of classrooms.

Towards addressing these shortcomings, we created an application by which teachers can create, share and modify inquiry-based lessons for the seamless learning shown in Figure 2. Our purpose was to create templates on mobile devices and web portals for teachers to easily create a variety of inquiry-based learning projects in the school. They can be shared and reused. The inquiry learning path on the application is shown in

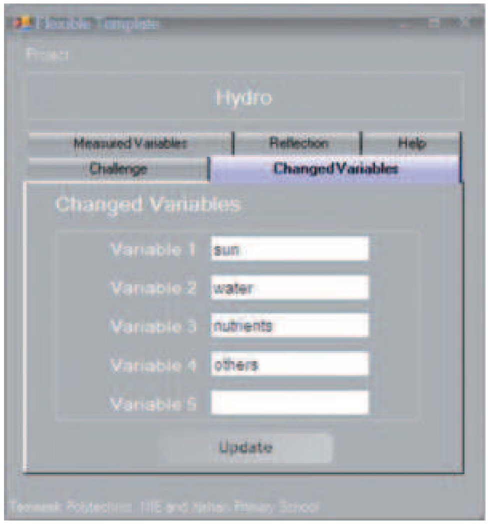

Figure 2: Desktop application for teachers to create, share and modify inquiry-based lessons

Figure 3. Students will follow the inquiry path in the following sequence: challenge, plan, experience, conclusion and reflection. The mobile software supports building primary school students' science processing skills by guiding them to plan an experiment, observe, collect data, infer from data, draw conclusions and reflect during their inquiry. Students can upload their data over to an online class portal where they view the data collected by other students, raise questions for discussion and modify their own conclusions based on their own data and that of their classmates. The online portal provides a platform where students can move from the individual space on the mobile devices to the public space to facilitate collaboration and sharing.

A seamless learning framework

Our initial two projects on mobile learning suggest that a suitable lens for interpreting seamless learning activities is the distributed cognition theory proposed by Hollan, Hutchins and Kirsch (2001). The authors just mentioned proposed three principles in which cognitive processes occur: they are distributed across the members of the social group; they are distributed over time; and the operation of a cognitive system involves coordination between internal and external (material or environmental) structure. Applying these principles to seamless learning, learning takes place through individual learning in private learning spaces, collaborative learning in public learning spaces, and cognitive artefacts created across time and physical or virtual spaces mediated by technology within a context. There will be occasions where learners are engaged in self-learning or discovery, and at other times they will interact with others, such as their peers, teachers or experts. In these learning spaces, learners may create digital artefacts with mobile devices which they share, modify, build upon existing artefacts, and inte-

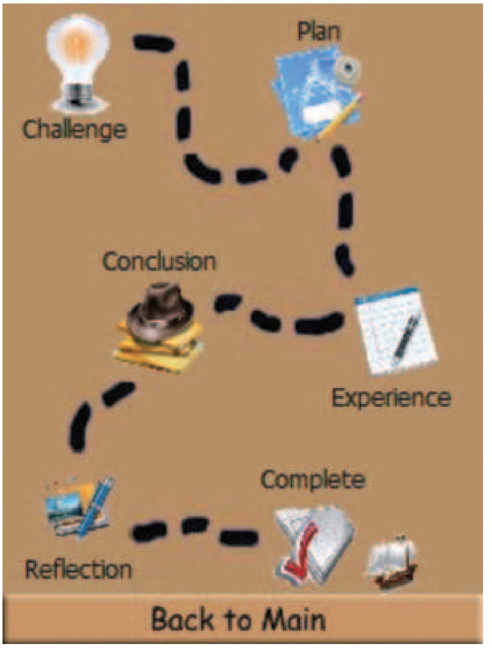

Figure 3: A structure inquiry path on the mobile software

grate them together that may result in building new knowledge. Artefacts facilitate knowledge construction and social discourse, and mediate interaction among a community of learners (Stahl, 2000).

Through these activities, different cognitive learning processes take place individually, in the group and through operating on artefacts mediated by technology. The physical space or virtual space in which the learners are engaged in can be very conducive for learning (Milrad, Hoppe, Gottdenker & Jansen, 2004). Similarly, time can play an important role in shaping and evolving inquiry (Latour, 1987) in a seamless learning environment. Over time, when learners operate on artefacts, collaborate with peers, teachers and experts or conduct discovery, they acquire and build knowledge (Hewitt & Scardamalia, 1998). Figure 4 depicts our notion of this seamless learning framework we have described (Seow, Zhang, So, Looi & Chen, 2008).

Methodological issues for seamless learning research

Design experiment is used to design and implement our seamless learning research. The choice of design experiment is ideal as this method stresses upon systemic thinking on the interdependence of design elements, and the importance of examining emerging issues through progressive refining processes (Collins, Joseph & Bielaczyc, 2004). More important, in order to design sustainable 21st century learning environments, as

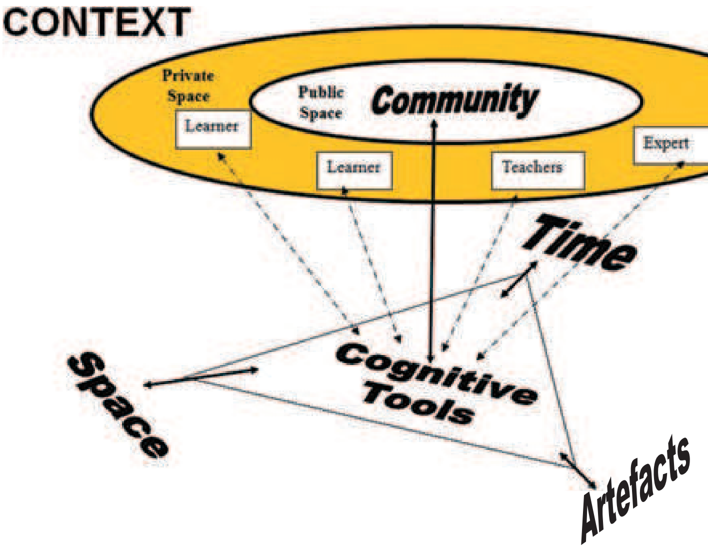

Figure 4: Seamless learning framework

researchers, we need to make a commitment to conduct sustained research (Nardi, 2001), and this necessitates theoretical and methodological lenses congruent with the goals of this research.

An important consideration in seamless learning research with mobile devices is understanding the enactment of learning activities that unfold in various situations. Previous research that examined the use of mobile devices in informal settings has shown both promises and challenges (eg, Chen & Kinshuk, 2005; Sharples, 2006; Squire & Kloper, 2007). Mobile technologies with portability, connectivity and versatility enable learning to be ubiquitous in and out of classrooms, provide potential opportunities for collaborative learning, and enrich learning experiences with the support of technologies. For instance, Price and Rogers (2004) suggest that mobile devices can be used to help students explore digitally augmented physical environments where contextually relevant information and resources are provided. In such digitally enhanced settings, students using mobile devices can explore, capture and manipulate both physical and virtual (or digital) objects for active understanding. From design and research perspectives, however, mobile learning in informal settings is challenging because students are 'on the move' across different modes of space (both physical and virtual) and time. Thus, an ethnographic approach (Anderson-Levitt, 2006) can be integrated into design research for observing how students are engaged in informal and formal learning settings in their interaction with their handheld devices, peers, teachers and other people in their learning community (eg, Barron, 2006; Squire & Klopfer, 2007).

Studies that focus on examining short-lived learning experiences, such as user satisfaction surveys and strict comparisons of test measures, fail to provide comprehensive perspectives on learners' meaningful experiences across settings over time. Indeed, mobile learning researchers face methodological challenges in terms of the scales of space and time (Lemke, 2000): how to record learning across different physical spaces and different technological media, and how to examine learning in the longer timescale including informal learning outside school contexts. However, because of the novelty of the proposed study, there is no 'off-the-shelf' methodology for us to adopt. As Alan Schoenfeld (2006) has stated, 'It was not until heavier-than-air mechanical flight became a reality that a theory of aeronautics could get off the ground' (p. 193). For data collection, the learning trajectory of students using mobile technologies for learning across subjects and over time needs to be recorded. Possible data sources include, but are not limited to, observations, field notes, audio and video recordings, interviews, student artefacts, self-documentation by participants, and log files on computers. There are also methodological issues involved in observations such as distorted behaviours and artificial tasks (Gardner, 2000) and also ethics and privacy issues for observing students outside school settings (Hsi *et al*, 2006). Researchers should aim to minimise potential problems by employing unobtrusive methods such as log files, which provide an authentic, time-efficient means of recording student learning behaviours (Buckley, Gobert & Horwitz, 2006). Log files can capture a range of data that reflect student practices, activities, contexts, situations and events (Cole, 1995). In situ sampling of the students' daily experiences with mobile devices can be captured using the experience sampling method (Csikszentmihalyi & Larson, 1987). This method may provide us with a better understanding and natural assessment of how students are engaged in informal learning every day with mobile devices as they are using it. For instance, MyExperience (Froehlich, Chen, Consolvo, Harrison & Landay, 2007) is a recent data collection tool for in situ research that combines experience sampling, context logging and application usage logging.

In sum, by employing ethnographic methods, in situ self-report procedures, constant comparisons and sustained observations, as well as analysing quantifiable measures, we can critically examine how learners use mobile technology across subject areas and how different user experiences and motivation levels affect learning over time.

Technical issues for seamless learning research

Besides methodological challenges, there are important considerations for technical and the related pedagogical dimensions of seamless mobile learning.

The choice of mobile device for school use is a function of many considerations: the learning activities it will support, the cost, the connectivity (data, phone, broadband, etc), the subscription plan, the range of available software, the weight and robustness of the device, and functionalities such as a built-in camera or Global Positioning System. The affordance of a mobile device determines the type of learning activities that can be designed. For example, students can use the built-in camera on a mobile device to collect visual artefacts during inquiry. These artefacts can be shared with others by uploading them onto a common shared space over the wireless mobile network while the students are on the move. The affordances might result in student learning, such as tagging, explaining and creating argumentation. Researchers must consider the necessity of certain affordances or features in a device in the research. For example, in deciding a mobile device for Primary 2 or 3 students, we have to consider whether an external keypad or inbuilt QWERTY keyboard on the device is necessary for students to be able to type substantial amounts of text, or a lower-cost device that relies on a digital keypad or handwriting options might suffice. Most of the affordances come at an additional cost. Schools and researchers must delicately balance the trade-offs between phone affordances to support learning activities and cost, which may impact scaling up for schoolwide deployment. Table 1 shows the different affordances in choosing a mobile device for research in school.

The choice should also consider the longer-term life span of the device. With the rapid obsolescence of personal digital assistants and cellphone models, a challenge for researchers is investing in research using that device for, eg, 2 years, but the device becomes no longer in vogue or popular use after the period of research. For software applications, we could focus on the platforms such as Windows Mobile Pocket PCs, Windows Mobile Phones or Ultra Mobile PCs, which run on a variety of devices rather than on a single platform device.

In a seamless learning environment, another consideration of the technology selection is that the devices should allow software to be compatible when accessing common spaces. There will be a basic set of educational software tools underlying these different types of devices.

While the advances of mobile devices are changing rapidly, important commonalities remain the same: portability, mobility and versatility. These functions make learning ubiquitous in and out of classrooms, provide potential opportunities for collaborative learning, and enrich the learning experiences with the support of technologies (So & Kim, 2008).

Assessment issues for seamless learning research

Important assessment issues loom in the space of seamless learning. With students' use of devices for informal learning, what are the indicators of learning? Or what accounts for learning in the first place. One well-cited definition of learning is 'changing through experience … acquiring relatively permanent change in understanding, attitude, knowledge, information, ability and skill through experience' (Wittrock, 1977). To us, the more important change might be in student value and character change, which can gauge students as lifelong learners and persons-to-be. Therefore, challenges exist in assessing the skills, knowledge, identity, values and epistemology (Shaffer, 2007) as students become adept in using the mobile device as routine practices in the classroom and out of the classroom.

One approach for assessment in seamless learning environment is to adopt a preparation for future learning (PFL) framework (Bransford & Schwartz, 1999) to emphasise assessment for learning. The purpose of PFL is to promote deep understanding and

Table 1: *Different affordances in choosing a mobile device for school-based research*

Affordances	*Factors*	*Decision considerations*
Platform	Platform operating system	The device is running on a platform that also runs on different devices by other manufacturers A community of developers and software companies creates applications on the platform
Form Factor	Weight	The device must be light enough for a primary pupil to carry to school along with some books
	Size	The device must be small enough to be carried in a bag or easily carried by hand by primary school children
	Screen resolution	The device must have a good screen resolution and provide acceptable viewing experience outdoors
Mobility	'Paperback book' mobility	The device offers users the mobility to use them in school, out-school and at home. It is unlikely that students will carry them around pervasively because of the size and weight, despite their mobility
	'Pocket size' mobility	Users are likely to carry these small mobile devices with them pervasively because of their pocket size. These devices can be used in in-school, out-school, home and informal activities
Connectivity	WiFi	The device can connect to the Internet or to a local network through WiFi
	Bluetooth	The device can connect wirelessly to other devices with Bluetooth feature and even the Internet
	3G high-speed mobile broadband technology—eg, EDGE, HSPDA	The device can connect to the Internet through 3G or 3.5G directly The device has a USB port to use a modem for mobile broadband access if it does not have direct 3 or 3.5 G capability
	2G-based technology eg, GPRS	The device can connect to the Internet using GPRS
Applications	Web-based applications	Pupils can access web-based applications from the device
	Ready Learning and Mobile Learning applications	There are available mobile learning applications on the market for the device platform
	Software development kit (SDK) to create mobile learning applications	The device platform or manufacturer releases SDK for the development of applications on the device. Some points regarding the SDK: • How mature is the SDK in the market? • How open is the SDK? Is it proprietary or open source? • How widely used is the SDK by developers? • What are the tools to build the applications with the SDK and the availability of those tools?
	Integration to servers	Applications allow the device to upload or download information from or to a server
	Applications can operate off-line or online	Applications on the device can operate off-line. With connection to the Internet, the applications can upload or download information from the server

Table 1: Continued

Affordances	*Factors*	*Decision considerations*
Voice	Telephony support	The device can be used as a telephony device through cellular networks, eg, GSM The device can be used as a telephony device using voice-over-IP technology, eg, SKYPE
Battery	Battery	The device should be easily charged and have a long battery life for fieldwork
Durability	Robust	The device should not be too fragile for handling by primary school children
Cost	Cost is affordable for adoption by schools and parents	The device should be reasonably priced to be bought by school or parents of the students
Support	Available maintenance and support for school by the supplier	Good support and maintenance is available for the device by the manufacturer or distributor. The device should be replaceable, or an equivalent replacement should be available if it is under repair or lost
Features	Camera	The device has a camera for students to capture still shots or record video
	Pen-based input	The device has a touch-sensitive screen to allow direct pen input
	Keyboard	The device has a QWERTY keyboard for input
	Ease of use on the interface	The device interface is simple and intuitive to use
	Voice or Audio	There is audio input on the device to record voice or sound The device can play back audio in MP3 or WAV format
Memory storage	On-board	There is a large on-board memory to install and run applications on the device
	Expandable	The device has expansion slots for additional memory, eg, SD card
	Backup	Information on the device can be backed up easily on another computer or storage: • Cable connection to another computer • USB port for thumb or portable drives • Slot for mini-SD, micro-SD or SD card

EDGE, Enhanced Data rates for Global Evolution; HSPDA, High-Speed Downlink Packet Access; GPRS, General Packet Radio Service; GSM, Global System for Mobile Communication; IP, Internet Protocol; MP3, MPEG Audio Layer 3; WAV, Windows Wave Audio Format; USB, Universal Serial Bus; SD, Secure Digital.

knowledge transfer in multiple contexts, and mobile devices can act as a mediating tool enabling such learning transfer. Traditional approaches of assessment focus on measuring student abilities to directly apply their previous knowledge to new problems without help or resources. This type of direct application, however, fails to measure the zone of proximal development (Vygotsky, 1978), ie, students' potential abilities to learn in knowledge- and resource-rich environments. In seamless learning research, researchers can explore difference sequencing of learning conditions such as (a) formal versus informal learning, (b) intentional versus unintentional learning, and (c) abstract context-general versus concrete context-specific settings in order to identify enabling conditions that better prepare students for future learning.

The motivation for promoting informal learning probably first started from training workplace skills because it involves obvious costs (Malcolm, Hodkinson & Colley, 2003). Another term we have not mentioned is 'non-formal' learning, which refers to learning that happens in formal learning settings but is not tested or assessed in traditional ways. So formal, informal and non-formal learning are all learning. As we have argued, learning can happen in any situation and context. However, how to capture learning that is not planned, not fixed and probably without validated instruments to measure, and usually individualised, poses great challenges to learning-science researchers. Our proposal is to use behavioural or performance indicators that can be captured by techniques such as what we have described in the methodological issue section. We need also to collect multiple data sets over time for triangulation purposes. When considering the linkage between formal and informal learning, we might be able to infer the effectiveness of informal learning through assessing the conceptual equivalents specified in formal curricula. On the other hand, performances in informal settings can be a result of formal learning in terms of preparing the students for future learning.

Studying school-based learning and following through with after-school learning will enable the exploration of a theory of mobile learning for seamless learning tied strongly to empirical evidence. For instance, the PFL perspective can be adopted to frame the use of mobile devices in informal settings as enabling students to familiarise themselves with a problem and its context before in-school learning of formal concepts. Our findings will be used for further understanding of the application of the PFL framework as well as providing evidence of the efficacy of different sequencing of formal and informal learning activities.

Discussion and conclusion

Research into seamless learning needs a strong focus on pedagogy, professional development of teachers, co-design of lessons with teachers, a design research perspective and affordable mobile learning devices. International collaboration and innovation can contribute towards the broader research agenda. By organising and sharing information across design experiments in diverse settings, a collaboration of researchers can more rapidly and systematically explore the design space (Hawkins, 1997). For instance, the same-grade classrooms across different countries can implement mobile learning devices for all subject areas, allowing a broad examination of solutions and challenges. By collaborating across the globe, researchers could take advantage of different student device preferences, exchange curriculum ideas, understand cultural differences and better address issues of scale.

Our research agenda can help us further examine our understanding of how students engage in inquiry-based learning, experiential learning and knowledge building in mobile learning environments. By collecting multiple sources of data, we seek to understand students' learning process at both the level of the individual learner and the level of group of learners through the theories of distributed cognition and collaborative learning both within and outside classroom contexts. We hope this paper will stimulate further discussions on how to design and study seamless learning environments that can foster 21st century knowledge and skills among the young generation of learners.

Acknowledgements

We wish to thank Elliot Soloway, Cathy Norris, other members of our mobile learning research team and the anonymous *BJET* reviewers for their comments on earlier drafts of this paper.

References

Anderson-Levitt, K. M. (2006). Ethnography. In P. B. Elmore, G. Camilli & J. Green (Eds), *Handbook of complementary methods in education research* (pp. 279–298). Washington, DC and Mahwah, NJ: AERA & Lawrence Erlbaum Associates.

Barab, S. (2002). Human-field interaction as mediated by mobile computers. In T. Koschmann, R. Hall & N. Miyake (Eds), *CSCL 2: carrying forward the conversation* (pp. 533–537). Mahwah, NJ: Lawrence Ealbaum.

Barron, B. (2006). Interest and self-sustained learning as catalysts of development: a learning ecologies perspective. *Human Development*, *49*, 4, 193–224.

Beale, R. (2006). How to enhance the experience without interfering with it. In M. Sharples (Ed.), *Big issues in mobile learning* (pp. 10–14). LSRI, University of Nottingham.

Bransford, J. D. & Schwartz, D. L. (1999). Rethinking transfer: a simple proposal with multiple implications. *Review of Research in Education*, *24*, 61–100.

Brown, J. S., Collins, A. & Duguid, S. (1989). Situated cognition and the culture of learning. *Educational Researcher*, *18*, 1, 32–42.

Buckley, B. C., Gobert, J. D. & Horwitz, P. (2006). *Using log files to track students' model-based inquiry*. Paper presented at the International Conference of the Learning Sciences, Bloomington, IN.

Chan, T.-W., Roschelle, J., Hsi, S., Kinshuk, Sharples M., *et al* (2006). One-to-one technology-enhanced learning: an opportunity for global research collaboration. *Research and Practice of Technology Enhanced Learning*, *1*, 1, 3–29.

Chen, J., Kinshuk (2005). Mobile technology in educational services. *Journal of Educational Multimedia and Hypermedia*, *14*, 1, 91–109.

Chen, W., Tan, N., Looi, C.-K., Zhang, B. H. & Seow, P. (2008). Handheld computers as cognitive tools: technology-enhanced environmental learning. *Research and Practice in Technology-Enabled Learning, World Scientific*, 231–252.

Cole, M. (1995). The supra-individual envelope of development: activity and practice, situation and context. In J. Goodnow, P. Miller & F. Kessel (Eds), *Cultural practices as contexts for development*. San Francisco: Jossey-Bass.

Colella, V. (2000). Participatory simulations: building collaborative understanding through immersive dynamic modeling. *Journal of the Learning Sciences*, *9*, 4, 471–500.
Collins, A., Joseph, D. & Bielaczyc, K. (2004). Design research: theoretical and methodological issues. *Journal of the Learning Sciences*, *13*, 1, 15–42.
Csikszentmihalyi, M. & Larson, R. (1987). Validity and reliability of the experience sampling method. *Journal of Nervous and Mental Disease*, *175*, 9, 526–536.
Froehlich, J., Chen, M., Consolvo, S., Harrison, B. & Landay, J. (2007) MyExperience: a system for in situ tracing and capturing of user feedback on mobile phones. In Proceedings of MobiSys 2007, San Juan, Puerto Rico, pp. 57–70.
Gardner, F. (2000). Methodological issues in the direct observation of parent–child interaction: do observational findings reflect the natural behavior of participants? *Journal of Clinical Child and Family Psychology Review*, *3*, 3, 185–198.
Hawkins, J. (1997). *The national design experiments consortium: final report*. New York: Center for Children and Technology, Educational Development Center.
Hewitt, J. & Scardamalia, M. (1998). Design principles for the support of distributed processes. *Educational Psychology Review*, *10*, 1, 75–96.
Hollan, J., Hutchins, E. & Kirsch, D. (2001). Distributed cognition: toward a new foundation for human-computer interaction research. In J. M. Carroll (Ed.), *Human computer interaction in the new millennium* (pp. 75–94). New York: ACM Press.
Hsi, S., Sabelli, N., Krajcik, J., Tinker, R. & Ellenbogen, K. (2006). Learning at the nanoscale: research questions that the rapidly evolving interdisciplinarity of science poses for the learning sciences. *Proceedings of the 7th international conference on Learning sciences*, Bloomington, Indiana, 1066–1072.
Kolb, D. (1984). *Experiential learning*. Englewood Cliffs, NJ: Prentice Hall, Inc.
Latour, B. (1987). *Science in action: how to follow scientists and engineers in society*. Cambridge, MA: Harvard University Press.
Lemke, J. L. (2000). Across the scales of time: artifacts, activities, and meanings in ecosocial systems. *Mind, Culture, and Activity*, *7*, 4, 273–290.
Malcolm, J., Hodkinson, P. & Colley, H. (2003). The interrelationships between informal and formal learning. *Journal of Workplace Learning*, *15*, 7/8, 313–318.
Milrad, M., Hoppe, U., Gottdenker, J. & Jansen, M. (2004). Exploring the use of mobile devices to facilitate educational interoperability around digitally enhanced experiments. In J. Roschelle, C. Kinshuk & S. J. H. Yang (Eds), *Proceedings of the 2nd IEEE International Workshop on Wireless and Mobile Technologies in Education (WMTE 2004)* (pp. 182–186). Taoyuan, Taiwan: Mobile Support for Learning Communities.
Moore, G. A. (1991). *Crossing the chasm: marketing and selling high-tech products to mainstream customers*. New York: HarperCollins Publishers.
Nardi, B. A. (2001). Activity theory and design. In R. H. T. Koschmann & N. Miyake (Eds), *CSCL 2: carrying forward the conversation* (pp. 229–232). Mahwah, NJ: Erlbaum.
Price, S. & Rogers, Y. (2004). Let's get physical: the learning benefits of interacting in digitally augmented physical spaces. *Computers & Education*, *43*, 137–151.
Resnick, L. (1987). Learning in school and out. *Educational Researcher*, *16*, 9, 13–20.
Roschelle, J. (2003). Keynote paper: unlocking the learning value of wireless mobile devices. *Journal of Computer Assisted Learning*, *19*, 3, 260–272.
Schoenfeld, A. H. (2006). Design experiments. In P. B. Elmore, G. Camilli & J. Green (Eds), *Handbook of complementary methods in education research* (pp. 193–206). Mahwah, NJ: Lawrence Erlbaum Associates.
Seow, P., Zhang, B. H., Chen, W., Looi, C. K. & Tan, N. (in press). Designing a seamless learning environment to learn 3Rs (reduce, reuse and recycle) in environmental education. *Journal of Mobile Learning and Organisation*.
Seow, P., Zhang, B. H., So, H.-J., Looi, C.-K. & Chen, W.-L. (2008). *Towards a framework for seamless learning environments*. Paper presented at ICLS, Utrecht, The Netherlands.
Shaffer, D. W. (2007). *How computer games help children learn*. New York: Palgrave.

Sharples, M. (2006). How can we address the conflicts between personal informal learning and traditional classroom education. In M. Sharples (Ed.), *Big issues in mobile learning* (pp. 21–24). LSRI, University of Nottingham.

So, H. J. & Kim, B. (2008). Teaching and learning with mobile technologies: educational applications. In M. Pagani (Ed.), *The encyclopedia of multimedia technology and networking*. Hershey, PA: Information Science Reference, 1366–1372.

Squire, K. & Klopfer, E. (2007). Augmented reality simulations on handheld computers. *Journal of the Learning Sciences*, *16*, 3, 371–413.

Stahl, G. (2000). Collaborative information environments to support knowledge construction by communities. *AI Society*, *14*, 71–97.

Vygotsky, L. S. (1978). *Mind in society: the development of higher psychological processes*. Cambridge, MA: Harvard University Press.

Watson, L. (2006). *Designing space for effective learning: A guide to 21st century learning space design*. Bristol, UK: Higher Education Funding Council for England. Retrieved May 5, 2008, from http://www.jisc.ac.uk/uploaded_documents/JISClearningspaces.pdf.

Wittrock, M., ed. (1977). *Learning and instruction*. Berkeley, CA: McCutchan.