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Mobile technology, learning, and achievement: Advances in understanding and measuring the role of mobile technology in education

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ABSTRACT

Studying *mobile learning* – the use of personal electronic devices to engage in learning across multiple contexts via connections to media, educators, peers, experts, and the larger world – is a relatively new academic enterprise. In this special issue, we interrogated the promise and unexamined expectations of mobile learning, the theories and ideas developing around it, and the devices that afford it. The articles introduce mobile and wearable technologies as key components of empirical research and demonstrate ways that learning conducted with such devices (1) affects the process and products of learning via interactions with other psychological constructs; (2) affords new opportunities to directly influence learning process or outcomes; and (3) provides opportunities to collect previously unobtainable data that improve understanding and modeling of the learning process. In this introduction, we overview the emergence of mobile learning theory and its contemporary conceptualization. Then we highlight ways that mobile technologies can be used to enhance learning processes and an understanding of them. All special issue contributors conceptualize and align their work with both psychological theories of learning and instruction as well as emerging theories of mobile learning. The commentary authors appraise mobile learning research critically and analytically, and recommend ways mobile learning theory might build upon research methodology and knowledge grounded empirically in psychological and sociocultural theories of learning. Overall, we believe this special issue achieved our goal to produce a balanced consideration that highlights the advancements in learning and learning theory mobile devices might afford, and to temper any premature enthusiasm about these potential benefits.

Mobile devices – including phones and tablets – are the most prevalent digital technology on earth; 96 percent of United States adults own cellphones, 81 percent own a smartphone, and 52 percent own a tablet computer, with each ownership category rising over the last five years (Pew Research Center, 2019). This rapid proliferation of mobile technology is striking compared to declining trends in desktop and laptop computer ownership, which was down to 73 percent in the latest Pew Research Center survey (Anderson, 2015). Children eight years old and younger spend, on average, 2.3 h a day using digital technologies and the percentage of that time on mobile devices has tripled since 2011, from 15 to 48 min a day. Wearables such as smart watches and fitness trackers are also increasing in prominence and are notable for their ability to monitor their owners' activities during every waking hour, and even as they sleep (Lutze & Waldhör, 2015). Given the rapid rise and scope of mobile technologies, one growing area of scholarly interest is mobile learning, which involves "learning across multiple contexts, through social and content interactions, using personal electronic devices" (Crompton, 2013, p. 4).

Paralleling the increase in the prevalence of mobile devices, scholars have produced sufficient research, almost exclusively published in technology-specific venues, to warrant systematic reviews of mobile learning practices and their conceptual foundations, such as configurative reviews (e.g., Crompton, Burke, Gregory, & Grabe, 2016) and meta-analyses of mobile technology effects on learning (e.g., Wu et al., 2012). Theoretical frameworks specific to mobile learning or "m-learning" (e.g., Sharples, Taylor, & Vavoula, 2016) and mobile learning specific pedagogical or instructional design (e.g., Laurillard, 2007) have also emerged, and they are both exciting and problematic. The potential learning opportunities theorists describe suggest mobile learning may confer ample benefit to learners (e.g., "seamless learning" across formal and informal settings may promote people's ability to transfer), but conceptualizations of the way mobile learning spans these environments and involves multiple users interacting in multiple ways across multiple physical environments are as of yet more conceptual than operationalized, making systematic, empirical study of theoretical assumptions a challenging endeavor.

For all of the contributions of the m-learning scholarship, there has been a lack of integration of these frameworks with broader theories of learning and instruction, and likewise a growing need to introduce and integrate mobile technology affordances into the scholarship on learning. Much can be learned from the host of studies involving m-learning technologies, processes, and outcomes. However, without the integration and synthesis of m-learning and broader learning literatures, and reconciliation of their underlying theoretical

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conceptualizations, educational technologists and educational psychologists will struggle to develop truly comprehensive models of the affordances and constraints of mobile learning technologies and their relationships with cognitive, metacognitive, motivational and affective processes.

For example, on the one hand, researchers have demonstrated many ways mobile technology devices have been used to enhance learning. Students use their mobile devices as platforms to enact learning strategies (Jeng, Wu, Huang, Tan, & Yang, 2010), seek help (Reeves & Sperling, 2015), and engage in computer supported collaborative learning (Hsu & Ching, 2013; Lai & Wu, 2006). Positive effects on learning have been identified in literacy (Kim, Katz, Lambert, & Brown, 2014; Wong, Hsu, Sun, & Boticki, 2013) science (Crompton, Burke, Gregory, & Gräbe, 2016; Kantar & Dogan, 2015), mathematics (Song & Kim, 2015), history (King, Gardner-McCune, Vargas, & Jimenez, 2014; Nakasugi & Yamauchi, 2002), and art (Katz-Buonincontro & Foster, 2013). Recently, researchers have shown wearable technologies can be used to prompt productive behaviors that increase student engagement during learning (Chen et al., 2017). On the other hand, mobile technologies have been associated with self-regulatory challenges in classrooms (Ravizza, Uitvlugt, & Fenn, 2017), poorer recall and performance than traditional methods of note-taking (Mueller & Oppenheimer, 2014), and negative effects not only on those who use these mobile technologies, but also those around them (Ragan, Jennings, Massey, & Doolittle, 2014). Clearly, more research is needed regarding how mobile technologies interact with other constructs (e.g., motivation, self-regulation, literacy) and various contexts (e.g., formal and informal) to both foster and hinder learning, so that researchers can create comprehensive models of these phenomena. Then, such models could allow educators to create technology-infused environments that capitalize upon the affordances, and minimize the challenges, of these increasingly omnipresent mobile devices. Such models could also point toward ways of helping people more effectively use mobile devices for learning.

Mobile devices also hold great promise as a means of collecting trace data (i.e., digital records that students produce when they make use of the features provided by a learning technology; Bernacki, 2018) on both the processes and products of students' learning. This relatively new and exciting methodology affords the opportunity to unobtrusively capture learning processes, offering a unique window into learning compared to self-report and other participant-driven data collection methods. Traces from mobile devices can provide a unique, real-time data source for modeling learning processes (Sha, Looi, Chen, & Zhang, 2012), and even provide ongoing formative assessment data to teachers, who can adjust their instruction accordingly within and across lessons and class periods (Holstein, McLaren, & Aleven, 2017; Reeves, Gunter, & Lacey, 2017). Likewise, mobile devices can capture data wherever learning occurs, in both public and private domains, inside and outside of formal educational environments. Nonetheless, again, the great potential of these devices must be married with classic and contemporary research on measurement of learning and associated phenomena (e.g., Greene, Deekens, Copeland, & Yu, 2018), to guide the use of these tools. Similar to any source of data, information from mobile learning devices must be properly collected, understood, analyzed, and theorized for valid inferences and implications to result.

We developed this special issue to interrogate the great promise and unexamined expectations of mobile learning, the theories and ideas developing around it, and the devices that afford it. The articles in this special issue introduce mobile and wearable technologies as key components of empirical research conducted across learning contexts, and demonstrate the ways that learning conducted with such devices (1) affects the process and products of learning via interactions with other psychological constructs; (2) affords new opportunities to directly influence learning process or outcomes; and (3) provides opportunities to collect previously unobtainable data that improve understanding and modeling of the learning process. In addition to providing an exposition of the ways mobile technologies can be used to enhance learning processes as well as an understanding of them, we asked authors to conceptualize and align their work in light of both psychological theories of learning and instruction as well as emerging theories of mobile learning. We also asked authors to reconcile their findings against each guiding theory and make attempts to integrate across these previously disconnected theoretical traditions. Finally, we pressed authors to interrogate their results with a critical-analytical perspective (Alexander, 2014). Adopting this perspective promotes a balanced consideration to highlight the advancements in learning and learning theory mobile devices might afford, but also to temper the potentially premature enthusiasm that often accompanies the emergence of new technologies that have yet to be scrutinized as to their actual potential to improve learning.

In the remainder of the introduction, we provide a brief summary of contemporary mobile learning theory, an overview of the history that produced it, and an examination of cognate theories within the educational and psychological study of learning. Having abstracted and aligned the key features of these theories, we consider the special issue articles as exemplars for the convergence of mobile and psychological theories of learning in a commentary (Bernacki, Crompton, & Greene, 2019). We highlight the opportunities mobile devices provide for conceptualizing, studying, and supporting learning, and ourselves take a critical-analytical position to propose a principled research agenda and methodological approach that will be necessary to substantiate the value of mobile devices as a platform for learning and the observation of it.

1. Mobile learning theory

1.1. Definition

Mobile learning is "learning across multiple contexts, through social and content interactions, using personal electronic devices" (Crompton, 2013, p. 4). This multifaceted definition highlights the move away from traditional pedagogies (i.e., sedentary teacher-focused, single context learning Merchant, 2012) and tethered technologies (i.e., corded technologies, such as desktop computers) to provide new affordances for learning including seamless engagement across environments. Connectivity is a primary purpose of a mobile device, and affords learners the ability to communicate with peers, educators, experts, and the world, as well as interact with content (i.e., consuming, editing, and producing) devoid of spatial and temporal constrictions. The final part of the definition describes the technology as a "personal electronic device" to avoid use of a specific technology, or terms that can quickly become dated (Crompton, 2013).

1.2. Historical context

Early in the digital epoch, Kay (Kay & Goldberg, 1977/2001) conceptualized a device the size of a notebook with a similar capacity and functionality of today's mobile devices. Such devices became more commonplace on the market in the 1990s, with tools such as the Palm Pilot that had a calculator, calendar, contacts, memos, photos, and a notepad. Mobile devices have evolved and include tablets that have achieved sufficient market penetration to warrant educators' increased attention in the past decade. Mobile device evolution and a concomitant progression towards learner-centered education with such a device developed into the field of mobile learning (Laoris & Eteokleous, 2005). The early 21st century mobile learning paradigm of anytime, anywhere learning (Attewell, & Savill-Smith, 2005) has been extended to just-in-time learning (i.e. learning presented at a time when the learner is needing that information) and just-for-me learning (i.e. learning that fits the style, time, location of the learner) (Shih, 2007), shifting from the learner-centered (i.e., chosen by the educator to fit the needs of the learner) to a learner-driven (i.e., chosen by the student to fit his/her learning goals with guidance from the educator) paradigm.

During this time, scholars in countries such as Europe and Asia worked on extending theories of mobile learning. In Europe, the MOBILearn initiative from 2002 to 2005 involved 24 partners from universities and industry to develop the first personalized and context-aware platform for mobile learning. The work of MOBILearn led to a shift in focus from the mobile device to the mobility of the learner (Kukulska-Hulme, Sharples, & Milrad, 2009). In Asia, theory development focused on seamless learning (i.e., continuous learning as people move across contexts; Wong & Looi, 2011), one-to-one learning (i.e., where each student has access to a device; Chan et al., 2006), and context-aware ubiquitous learning (i.e., where digital technology is a ubiquitous part of learning while the learner also interacts with the larger geographical context this can also include location services; Hwang, Tsai, & Yang, 2008). The functionality and portability of mobile devices has opened opportunities for expanding learning pedagogies to account for students' movement beyond spatial and temporal confines. Additional avenues of inquiry have been directed towards how teachers can effectively integrate these new approaches to learning with mobile technologies into their practice.

1.3. Mobile devices and instructional practice

As scholars have called for educators to consider how technology is integrated into the curriculum (e.g., Heflin, Shewmaker, Nguyen, 2017; Kukulska-Hulme et al., 2009), frameworks have emerged to support this task. The technological, pedagogical, and content knowledge (TPACK) framework (Mishra & Koehler, 2006) was developed to highlight the necessity that educators have knowledge and skills that span these distinct TPACK areas. Mishra and Koehler postulated that all of these varieties of knowledge and instructional skills should be integrated when using technology in teaching, and that teachers should consider how to adjust TPACK-informed instruction to student factors, such as age, preferences, and culture.

Trends toward such integration are evident in the changing standards for technology use. Early standards focused on the importance of teaching basic computer use and software skills. Standards from the 1990s focused on teachers' skills, such as preparing teachers to know how to use software such as Microsoft's Excel and Power Point (e.g., ISTE, 1997). As technology became increasingly common in schools, technology integration foci shifted from teacher technology skills to preparing educators to incorporate technology into the curriculum and pedagogical practice (e.g. ISTE, 2008). Enthusiasm for the affordances of technology and its growing prominence in work and life led to calls to incorporate it into formal education, alas with insufficient concern for what technology could add to the learning context; rather educators focused on what it could replace (e.g., printed worksheets became digital worksheets). Indeed, educators often used mobile devices to conduct activities that did not benefit from the unique affordances of mobile devices, effectively using 21st century technologies for 20th century teaching (Crompton, 2017b). This failure to recognize the transformative nature of technology highlighted the need to develop pedagogical frameworks that truly leverage the unique affordances of mobile technology to advance the science and practice of learning.

The substitution, augmentation, modification, redefinition (SAMR; Puentedura, 2009) framework helped educators look through a different lens to understand the benefits of mobile technology in relation to non-technologies. The SAMR framework is a continuum with substitution at the bottom, describing when technology is being used for a task that could be accomplished without technology. At the other end of the continuum, redefinition is when technology is used to create new opportunities that were previously inconceivable without technology. To provide an example, consider the use of Google Docs on a mobile device. At the substitution level, the student would type into Google Docs, print the document, and hand it to the teacher; there is little difference from paper and pencil. At the augmentation level, the text-to-speech feature may be used to automatically place text into the document or multiple students may collaborate on the same document synchronously. At the modification level, multimedia features, such as video, audio, or links, could be added to the document to reconceptualize how the information is conveyed. For redefinition, add-in features, such as SAS Writing Reviser, can be used in the Google Doc. This uses artificial intelligence to provide specific feedback in a fraction of a second on the student's own writing in relation to writing principles, from misplaced modifiers to run-on sentences. SAS Writing Reviser can highlight the student text and explain through text boxes what the student needs to revise. The joint speed and accuracy of the feedback would be impossible for humans to replicate.

Recent technology integration standards (e.g. ISTE, 2017) reflect this move to transformative learning practices that allow new realizations of mobile learning theory and design (e.g., dynamic, real-time feedback and scaffolding). The cutting edge of m-learning theory privileges the unique affordances of technology to redefine and reshape learning theory and practices themselves, such as by leveraging the affordances of augmented reality to explore the potential of multimedia learning (Mayer, 2014). Other frameworks have gone beyond the overarching technology integration focus of TPACK and SAMR to acknowledge the many systems involved in m-learning. The social ecological mobile learning integration framework (Crompton, 2017a) includes how individuals interact with technology as well as environmental factors affecting mobile learning, such as the technological resources available in different physical environments (e.g., wireless networks, sensors and detectors). This framework is based on Bronfenbrenner's (1979) ecological framework for human development, with the educator placed in the center of five overlapping circles. In the center circle, the educator brings numerous relevant beliefs on the role of the teacher, socio-cultural influences, self-efficacy, and past experiences, each of which can affect how mobile technology is implemented in the learning context. The microsystem is the next circle out, representing the school and includes access to digital tools, teacher training, technology support, and whether the students are face-to-face or online. Next is the mesosystem, which shows the interconnections between microsystems. The exosystem is the school district and highlights policies, funding for technology support and technologies, and textbook as well as course adoption. The final circle is the macrosystem, which is the national educational system and includes standards, internet connectivity, and social and cultural technology norms.

The social ecological mobile learning integration framework (Crompton, 2017a) highlights the many systems and axiomatic practices involved in technology integration. The interconnected network of these components is illustrated via the mesosystem. For example, teachers' beliefs are influenced by the training they have on how to integrate the device into the curriculum as well as the interactions of policy, cultural norms and other factors. As another example, tensions can develop between a teachers' advocacy for student agency, control, choice and access to knowledge via mobile technology versus the educational system's tendency towards control, achieved through policies aimed at standardization within finite resources and infrastructure (Traxler, 2010).

Much of mobile learning theory has been generated by teacher educators, who have focused on the key features that define mobile learning as a learner-driven experience that affords opportunities to engage with rich digital media, peers, and instructors. To this point, these theories of mobile learning have yet to be appraised for their intersection with the many theories of learning developed and interrogated by scholars in educational psychology and the learning sciences. In addition to effort focused on integrating mobile devices into instructional contexts, we consider further how psychological theories of learning might be integrated to improve mobile learning theory, as well as the quality of the experience of those who learn with these devices.

Table 1
Connections between mobile learning and psychological learning theories.

Aspect of mobile learning	Psychological learning theories
Learning across multiple contexts	Transfer; situated learning; informal learning
Connections with peers, educators, experts, the world	Socially shared regulation of learning; collaborative learning; scaffolding; help-seeking; feedback; design-based research
mLearning integration social ecological framework	Sociocultural learning theory
Heutagogy of lifelong learning	Self-determination; self-regulated learning; emotions; constructivism

2. Connections between mobile and psychological learning theories

When intentionally designed, mobile devices and device applications are intended to afford the opportunity to learn seamlessly across formal and informal learning environments as well as enable learners to engage with rich digital resources, other learners, and their instructors. For those who study educational processes and draw on theories of cognition, motivation, and contextual factors in education, many features described in theories of mobile learning are discussed and investigated in their field as well, but perhaps by different names. When mobile and psychological learning theories are integrated, they afford numerous innovative and promising directions for research. We point out conceptual overlaps across these mobile and psychological learning theories in Table 1, and provide several exemplars of how such connections can benefit research and practice on both psychological and mobile learning. In the following sections, we elaborate by focusing on transfer, socially shared regulation of learning, scaffolding, and informal learning. By making these connections explicit, we hope to identify current coherences between these theories as well as ways in which the theories complement and expand one another.

2.1. Transfer and mobile learning

The cross-contextual nature of mobile learning, inherent in its definition, calls into question how to conceptualize both a classical as well as a situated view of learning with mobile devices. Researchers studying classical cognitive theories of transfer have focused upon how people construct abstract symbolic representations from previously known representations and effectively utilize them when confronted with new, structurally similar cases (Day & Goldstone, 2012). Barnett and Ceci (2002) created a taxonomy to delineate the kinds and degrees of transfer. What counts as transfer can vary across researchers, including what knowledge can and should be transferred (e.g., procedural knowledge vs. conceptual knowledge), what the criteria are for successful performance (e.g., increasing speed or accuracy), and whether changes in conditional knowledge are sufficient or if the inclination to notice opportunities for transfer matters as well. Likewise, the degree of transfer can vary from near to far. The transfer context can differ from the original context in terms of the knowledge domain, physical context (i.e., formal vs. informal environments), temporal context (e.g., same day vs. weeks later), functional context (i.e., formal vs. informal environments), social contexts (i.e., individual vs. collective), and modality (e.g., analog vs. technology context or tools).

Intuitions about transfer and its necessity in life have proven difficult to empirically substantiate in a convincing manner, with this challenge increasing from near to far transfer (Barnett & Ceci, 2002). Indeed, it is difficult to find compelling evidence of far transfer or interventions that successfully promote it (Melby- Lervåg, Redick, & Hulme, 2016). Such difficulties have led some researchers to advocate abandoning the idea of transfer as a solely cognitive activity, instead arguing for a situated view where the idea cannot be understood except in the dynamic interaction of person and context (Lave, 1988). Contexts, the people in them, as well as the practices and norms those people establish in those contexts all interact to influence what successful learning and achievement are, and how individuals are and are not enculturated to participate in such practices to learn and achieve. Situated views of learning do not so much argue against classical cognitive views of transfer as they render them narrow and somewhat moot, moving the focus of analysis toward understanding what aspects of context make successful performance more or less likely (e.g., similarities in physical or functional contexts, Barnett & Ceci, 2002). Some researchers have argued for less situated, but broader conceptualizations of successful transfer than classical ones, including the idea that prior knowledge can shape how people understand and conceptualize future learning challenges (i.e., preparation for future learning; Belenky & Nokes-Malach, 2012; Bransford & Schwartz, 1999), as well as arguments that any effects of prior knowledge on activity in a new context should be considered examples of transfer (i.e., actor-oriented transfer; Lobato, 2012). Mobile technology provides a useful context within which to investigate what transfers and how across contexts, which can thus inform a synthesis of mobile learning and transfer theories.

For example, mobile technologies allow language learners to bring affordances and tools out of formal educational contexts and into the world (Kukulska-Hulme, Lee, & Norris, 2017). To what degree and in what ways do learners access and successfully transfer the affordances of these tools from instructional to real-life situations? Do similarities in Barnett and Ceci's (2002) functional context (e.g., using the same mobile application) increase the likelihood of transfer across physical contexts that would be considered far transfer (e.g., from school to the outside world)? Does the incorporation of similar social contexts via mobile technology help to increase the likelihood of far transfer across knowledge domains (e.g., using the same expert help-seeking application in both science and history learning)? Finally, from the mobile learning perspective, to what degree and in what ways do learners transfer what they learn via mobile technology to contexts in which that technology is not available or relevant (e.g., across temporal and functional contexts, also called seamless learning; Wong & Looi, 2011)? Integrating mobile learning theory into transfer research can reveal ways to enhance educators' ability to leverage mobile technology for learning across ecological systems, as well as provide a malleable context for understanding the scope and variance in learning for transfer.

2.2. Socially shared regulation of learning and mobile technology

Mobile technology, by its nature, affords unique opportunities to explore and afford collaboration, and the psychological processes that result (Crompton, 2017a). The growing emphasis on collaborative learning in modern educational reform (Miyake & Kirschner, 2014) has brought with it the recognition that working with others is not innate or easy, and therefore people must be taught how to recognize and manage the many cognitive, emotional, and motivational challenges that can emerge (Järvenoja, Volet, & Järvelä, 2013; Näykki, Isohätälä, Järvelä, Pöysä-Tarhonen, & Häkkinen, 2017; Lobczowski, in press). Psychologists have studied how groups of people work together to actively and thoughtfully manage tasks and their own interactions, as well as how they struggle to do so, via theories of socially shared regulation of learning (SSRL; Hadwin, Järvelä, & Miller, 2018). Such research has shown that collaboration and effective regulation can diversify and improve learning and achievement (Miyake & Kirschner, 2014) as well as help learners develop the knowledge and skills to succeed in the modern workplace (Cohen & Lotan, 2014). Much of this work has been conducted with technology via studies of computer-supported collaborative learning (CSCL; Järvelä & Hadwin, 2013; Kreijns, Kirschner, & Vermeulen, 2013), involving both synchronous and asynchronous interactions mediated by technology (e.g., chat rooms, shared documents, group-based learning tasks).

Mobile technology is increasingly being used to achieve social, interactive, and collaborative educational goals, with subsequent effects upon how people collaborate and the quality of their work (Orben, Dienlin, & Przybylski, 2019). As but one example, mobile task management and communication applications allow users to asynchronously contribute to group projects whenever and wherever they are notified of others' work (e.g., Tuhkala & Kärkkäinen, 2018). Such affordances bring with them empirical questions. For example, in what ways is learning afforded by spaced, real-time engagement in group tasks, and what are the emotional and motivational effects of such tasks bleeding into informal and non-academic parts of a user's day? Clearly, CSCL researchers must incorporate mobile learning theory to better understand the technology modern learners use to collaborate as well as how that collaboration can be afforded and complicated by that technology. Likewise, investigations of the social aspects of mobile learning must take into account the cognitive, emotional, and motivational challenges users face, and how they do and do not successfully regulate them on their own and in interaction with others (Järvelä & Hadwin, 2013).

2.3. Scaffolding and mobile technology

Learners use mobile technology to collaborate on projects, but they also use it to seek help on their own work (Crompton & Burke, 2018). Mobile messaging applications, or communication features within mobile applications, allow learners the ability to reach out for support in a just-in-time manner. The literature on technology-based support for learning is well-established (e.g., Aleven, McLaughlin, Glenn, & Koedinger, 2016), with an important distinction between providing help and scaffolding (Wood, Bruner, & Ross, 1976). In some cases, learners simply need a brief provision of help or assistance to move past a misunderstanding or challenge (Aleven, Stahl, Schworm, Fischer, & Wallace, 2003). On the other hand, sometimes learners need more extensive support to internalize understanding and skills. In such cases, it is not sufficient to simply provide an answer or hint. van de Pol et al. (2010) outlined how scaffolding differs from the provision of help by being contingent upon and responsive to a learner's current understanding, with gradual fading of that support as the learner gains facility with the knowledge or skill. Such scaffolding results in a transfer of responsibility and the ability to complete the task moving from the teacher to the learner. Often, learners will not be able to internalize help in ways that allow them to use it autonomously; fading and transfer of responsibility via scaffolding are required. Theories of mobile learning would be enriched by accounting for this distinction when assessing the efficacy of such technology for learning (e.g., Zydney & Warner, 2016). Likewise, psychological research on scaffolding has shown that its success depends upon the quality of teacher fading (van de Pol, Mercer, & Volman, 2019), therefore there is much to be learned about how fading can be enacted via learners' use of mobile technology outside of formal learning environments, including how scaffolding and fading can differ from the classroom to the outside world.

2.4. Informal learning and mobile technology

Mobile learning theory blurs the traditional continuum spanning "formal" learning environments (e.g., classrooms, libraries) and "informal" learning environments. Indeed, most of people's learning activity occurs outside of formal environments and often in implicit or tacit ways (Alexander, Schallert, & Reynolds, 2009), but mobile learning theory demonstrates that a change in context does not necessarily mean that learners cannot access more formal or traditional means of instruction and support. Indeed, one of the key affordances of mobile technology, as outlined in mobile learning theory, is the ability to extend the advantages of formal learning beyond those environments. The extensive amount of research into formal pedagogies (e.g., what works, for whom, under what conditions, and why; Darling-Hammond et al., 2019) can and should be applied to pedagogies beyond formal contexts via mobile technology and learning theory (i.e., extending learning across multiple contexts; Crompton, 2013).

In order to integrate mobile learning theory with theories of both formal and informal learning, informal learning theory must be expanded to account for both formal and informal pedagogy and learning that can occur across formal or informal contexts. This will require a considerable amount of research into the learning processes that occur in informal settings, and mobile devices may afford instruments to undertake this effort (e.g. Lee, Fischback, & Cain, 2019; Xie, Heddy, & Vongkulluksn, 2019). Setting aside formal learning in formal contexts (e.g., lectures in a classroom), mobile learning theory provides a frame through which to imagine formal learning in informal contexts (e.g., watching a video lecture on a bus), informal learning in informal contexts (e.g., learning norms about social interaction via communal gaming), and informal learning in formal contexts (e.g., CSCL in the classroom). Typically, research informed by psychological theories of informal learning have not taken into account these variations, largely focusing on autonomous, self-directed, or self-regulated learning (e.g., Zimmerman, 2013), or sociocultural or situated views of apprenticeship and legitimate peripheral participation (Lave & Wenger, 1991). Certainly, those ways of thinking about learning are relevant to studies of mobile learning, and in particular how to help learners use mobile technology more intentionally and effectively. Nonetheless, the integration of mobile learning theory into psychological theories of learning would also expand the idea of informal learning beyond its definition in opposition to formal contexts, and toward a broader conceptualization of the affordances and constraints of formal and informal pedagogy and environments in interaction with one another (Khaddage, Müller, & Flintoff, 2016). Likewise, the engagement often assumed in studies and theories of informal learning has numerous aspects (i.e., cognitive, behavioral, motivational, emotional or affective; Azevedo, 2015) that could and should be measured and understood to best leverage the affordances of informal environmental for mobile learning.

2.5. Overview of articles in the special issue

Five articles compose the empirical entries in this special issue, and each represents a way of integrating mobile and psychological theories of learning. The authors examined the experiences of middle school, high school, and undergraduate learners who engage with mobile platforms, across a broad range of academic domains. Xie et al. (2019) leveraged mobile devices and experience sampling methods (ESM) by developing a mobile app that produces data that can refine theory on engagement. The author team developed ESM-Mobile and loaded it onto mobile devices used by pre-service teachers to manage their study in undergraduate courses. These students periodically used the mobile app to engage in planning of study sessions and when they elected to follow these study plans, they reported on their motives for doing so, as well as the location of the session and ways they chose to engage with their study material. These data are novel in that they capture studying behaviors in vivo via an application that is instrumented to prompt self-reports on cognitive processes and details about the context in which they occur. These developments are an instrumental step in investigating the person-in-context conceptualization of engagement (Sinatra, Heddy, & Lombardi, 2015) and further extend research on cognitive and behavioral forms of engagement in learning. The authors' findings confirm that contextual factors moderate the way students engage in studying, and their initial documentation of contextual features foreshadows how additional instrumentation that can represent features of a learning context, through GPS tracking and other forms of metadata, can refine conceptualizations of engagement as it occurs along the continuum of formal to informal learning environments.

Epp and Phirangee (2019) extend the issue's focus on cognitive learning processes by investigating the potential for mobile devices to promote *microlearning*: the recapture of small periods of time available for learning that fall outside of or between scheduled educational activities (Edge, Searle, Chiu, Zhao, & Landay, 2011). The minutes spent before, between, or after scheduled learning activities provide brief, episodic opportunities to engage in learning, so long as learning goals are precise and can be accommodated by learning strategies that can be initiated quickly, endure for only brief periods (i.e., seconds to minutes), and that are known to have an impact on key learning outcomes such as performance or retention. Epp and Phirangee identified that language learning is an appropriate subject for microlearning and argued that vocabulary acquisition benefits from rehearsal. Drawing upon psychological theories of learning related to retrieval, they hypothesized that microlearning sessions are akin to retrieval practice (Roediger & Karpicke, 2006) and should confer benefits to students who conduct them. Further, they proposed optimal spacing of such practice can improve retention (i.e., the spacing effect, Karpicke & Roediger, 2007). Thus, microlearning can address a key language learning challenge: how English language learners can find time and means of acquiring vocabulary outside of formal instruction and contexts. This is difficult for these learners because their informal environments seldom provide natural opportunities to engage in rehearsal of English; few of the people whom they encounter choose to speak English in home or public settings. Because students carry their mobile devices and can initiate a microlearning session in seconds, the devices afford opportunities to practice in brief periods during (and out of) school that are not focused on other learning activities. In addition to functionality that supports rehearsal, the app provides learners with the opportunity to engage with digital media, share content with peers, and make requests to experts for assistance and additional resources. Each of these features align to dimensions of mobile learning theory, and data on use of these functions can help clarify the extent to which learners make use of and benefit from such digital engagement when it is available to them.

Complementing this focus on cognitive dimensions of engagement, Harley and colleagues (Harley et al., 2019) explored the affective dimension of engagement when learning with mobile devices. The authors introduced a mobile learning application designed to allow learners to explore an immense informal learning environment (i.e., the City of Edmonton) and engage with rich digital media that are bound to geographic locations and provide information related to queer history across the city. The authors adopted control-value theory (Pekrun & Perry, 2014) to probe students' affective experiences while learning with the app. They also embraced a mobile learning theory (Sharples, Arnedillo-Sánchez, Milrad, & Vavoula, 2009) to examine how a learner (i.e., the subject) engages with digital objects (i.e., mediating artifacts) that are virtually place-bound based on geographic anchors to promote virtual, physical engagement with the informal learning space, with the goal of revising and gaining new knowledge about the topic. Their results confirm that students found the learning experience to be positively, affectively engaging (i.e., high enjoyment, low boredom), and that this positive affective experience was promoted by the learner-driven nature of the design. This feature of the app is an essential element of the design of mobile learning environments. Relations to learning are tacit but begin a line of inquiry into the ways students engage in mobile learning of history, how affective and behavioral engagement influence the learning experience, and how features of the mobile application can promote more positive engagement that is theorized to improve learning and performance.

Fabian and Topping (2019) extended research into the affective experience of students who learn with mobile devices by investigating middle school students' geometry learning in a randomized control study. Students who were randomly assigned to learn with a mobile platform made use of camera and annotation functions in order to allow them to identify objects and consider their angles, perimeter, and symmetry to other objects in the environment. Compared to students assigned to engage in paper-based activities that required them to draw and label figures and assignments requiring work with manipulatives, the mobile conditions produced similar effects on geometry learning. However, qualitative results revealed that the design of the application showed potential to leverage germane cognitive load to provide a productive learning experience, so long as researchers can find ways to mitigate the extraneous load induced by students having to learn a new platform. These findings contribute to an emerging theme in the special issue: that mobile developers would benefit from partnership with educational psychologists and learning scientists, who ensure that multimedia design choices within mobile apps are informed by the body of research on cognitive and motivational factors that influence learning processes and outcomes (c.f., Kirschner, 2002; Mayer, 2017).

The final empirical contribution to the special issue by Lee et al. (2019) extended the consideration of mobile devices in education by demonstrating how wearable technologies can produce data on informal learning. When learners wore wristbands that measured electrodermal activity during learning activities hosted in a makerspace, these mobile devices provided a measure of cognitive engagement that could be aligned with video data from chest mounted cameras. Video data captured students' interactions with physical materials for making, peers engaged in parallel and sometimes collaborative making activities, as well as periods of direct instruction provided by teachers. When interpreted by researchers, the data that were unobtrusively collected during making could be used to investigate periods of high cognitive engagement during student-driven, informal learning. Inferences drawn from the alignment of these channels of multimodal data can extend study of cognitive and behavioral engagement in learning tasks, as well as provide opportunities to investigate the emergent theory on making activities (Bevan, 2017).

In addition to the empirical contributions to the special issue, we invited commentaries from prominent scholars in the study of learning with technology, and offer our own critical analytical appraisal. Danish and Hmelo-Silver (2019) propose a taxonomy by which mobile learning theorists and researchers might consider the many components of mobile learning platforms and environments, and the ways they interact. Mayer's (2019) commentary concisely summarizes the contributions made by the empirical articles and underscores the importance of a systematic, experimental approach to obtain evidence that can test and refine assumptions of mobile learning theories. We build on Mayer's recommendation that mobile learning research may benefit from the scholarly tradition of more established fields. In our commentary, (Bernacki et al., 2019) we acknowledge that mobile learning theory has only recently coalesced to include an emergent set of features, and that researchers presently focus on learning processes – such as affective and cognitive engagement – that are antecedent to the learning and performance outcomes that confirm the value of an educational technology. We thus propose a convergence where mobile learning theorists leverage insights derived from extant psychological theories of learning, whereas those who study these theories (e.g., engagement, control value theory) might improve their research by leveraging mobile devices to collect timely data across the physical environments where students choose to learn, and by considering how these contextualized events involving connection to media, peers, experts, and instructors can refine theoretical assumptions. This kind of convergence can enable mobile learning theory to mature rapidly, and to integrate into broader theoretical conceptualization about learning.

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