Review of Augmented Paper Systems in Education: An Orchestration Perspective

Luis P. Prieto¹, Yun Wen¹, Daniela Caballero² and Pierre Dillenbourg¹
¹CHILI Lab, École Polytechnique Fédérale de Lausanne, Switzerland // ²Pontificia Universidad Católica de Chile, Santiago, Chile // luis.prieto@epfl.ch // yun.wen@epfl.ch // dccaball@uc.cl // pierre.dillenbourg@epfl.ch
*Corresponding author

ABSTRACT
Augmented paper has been proposed as a way to integrate more easily ICTs in settings like formal education, where paper has a strong presence. However, despite the multiplicity of educational applications using paper-based computing, their deployment in authentic settings is still marginal. To better understand this gap between research proposals and everyday classroom application, we surveyed the field of augmented paper systems applied to education, using the notion of “classroom orchestration” as a conceptual tool to understand its potential for integration in everyday educational practice. Our review organizes and classifies the affordances of these systems, and reveals that comparatively few studies provide evidence about the learning effects of system usage, or perform evaluations in authentic setting conditions. The analysis of those proposals that have performed authentic evaluations reveals how paper based-systems can accommodate a variety of contextual constraints and pedagogical approaches, but also highlights the need for further longitudinal, in-the-wild studies, and the existence of design tensions that make the conception, implementation and appropriation of this kind of systems still challenging.

Keywords
Paper computing, Augmented paper, Classroom, Orchestration, Review

Introduction
In spite of the high investments made, information and communication technologies (ICTs) are still not fully integrated in the everyday practice of our classrooms (Cuban, 2001), which are still dominated by other legacy tools like pen and paper. Human-computer interaction (HCI) researchers have long proposed to exploit this ubiquity of paper in our everyday life to better integrate computing into it (Wellner, 1993), through paper-based computing technologies, also termed “augmented paper” (Mackay & Fayard, 1999). This broad notion includes not only the use of augmented reality (AR) along with paper objects, but also any technology that uses paper artifacts (e.g., documents) as interfaces to the digital world (Kaplan & Jermann, 2010).

Researchers have proposed to apply these technologies to education, under the rationale that paper, so deeply ingrained in educational practices, would provide seamless interaction with digital educational artifacts (e.g., augmented educational books, digital pen note-taking systems). Over the years, advances in computing power, computer vision and other related technologies have made this kind of systems increasingly affordable, to the point that we can see such products for mass market consumption (such as Sony’s Wonderbook™, http://www.sony.com/pottermore/gh/book-of-spells). However, even though such systems are now affordable for schools, their deployment in authentic educational settings is virtually non-existent. We cannot help but wonder about the reasons for this gap between research proposals and classroom implementation.

This paper attempts to answer that question by performing a systematic review (Kitchenham & Charters, 2007) of the research proposals that apply paper-based computing systems to education, trying to organize and classify their advantages and constraints. In a second stage of analysis, we identify those proposals that have been evaluated in authentic formal educational contexts, and try to understand what might be the missing link between the variety of research proposals and the lack of actual deployment. To aid us, we use the notion of “classroom orchestration” (Dillenbourg, Järveli, & Fischer, 2009), which is related to the application of novel technologies in the complex multi-constrained setting of an authentic classroom (as opposed to research done in a lab or other controlled settings) (Roschelle, Dimitriadi, & Hoppe, 2013). This paper thus concentrates on the available evidence beyond single-user usability analyses (as suggested by previous reviews of the field, Cheng & Tsai, 2013), to the wider circle of how these (paper-based) technological innovations fit in the socio-technical system of a classroom (Dillenbourg et al., 2011).
Paper-based computing

As noted by Sellen and Harper (2002), paper is still around in many of our everyday activities and settings, despite the undeniable advantages of digital media. Our schools and university classrooms are one of the clearest examples of this resilience of paper: it is very difficult to find one where books, notebooks and other paper elements are not used profusely.

Researchers have argued that this resilience is connected to the way paper has been entangled with our practices over centuries (Johnson, Jellinek, Klotz, Rao, & Card, 1993), due to paper’s unique affordances: we find it easier to read compared to a screen, it is easy to annotate and organize, cheap, can be drawn on, and it is portable (Sellen & Harper, 2002; Kaplan & Jermann, 2010; Steimle, 2012). The idea of exploiting the affordances of paper in connection with the digital world can be traced back to HCI research in the nineties: Wellner (1993) proposed a hybrid digital/paper desktop environment to leverage the advantages of both digital and physical documents. Around the same time, Johnson et al., (1993) proposed to use our familiarity to handle paper as a way to control computers more easily (using classic paper forms and optical character recognition to control computer tasks, thus effectively creating a “paper user interface”).

To “augment” paper, several kinds of technologies are often combined. Input devices include cameras, barcode readers, RFID readers, scanners are used to identify and locate the paper artifacts (e.g., in conjunction with visual markers like barcodes), as well as digital pens (e.g., the Anoto™ technology) that allow the capturing of freeform writing, automatically converting it to a digital equivalent. These systems use the typical range of output devices (screens, projections, sounds and, of course, paper itself through printers). These technologies can be combined in many different ways to implement concrete augmented paper applications, which roughly fit into five basic interface form factors (Steimle, 2012):

- **Augmented Cards and Post-Its**: the paper artifact is treated as a physical token that allows accessing and managing digital resources, which are represented by the (paper) physical objects (e.g., Miura, Sugihara & Kunifuji, 2009).

- **Augmented Books**: the book itself has value independently from the digital resources, although usually includes printed markers to link its contents to additional/complementary media (e.g., Chen & Chao, 2008).

- **Augmented Notebooks**: the notebook, initially empty, synchronizes a paper-based and a digital version of the same resource/contents, allowing free handwriting and sketching (e.g., Lee, Maldonado, & Kim, 2007).

- **Augmented Printed Documents**: often work with a pre-printed document, where users can fill in forms, make annotations or mark parts of the document. These actions are then is translated to a digital counterpart (e.g., Kimbell et al., 2005).

- **Augmented Tables, Flipcharts and Whiteboards**: combine paper-based media with interactive tabletop and/or wall displays, allowing a close integration of paper and digital media (e.g., Do-Lenh, 2012).

These paper-based systems have been applied to a wide variety of fields: augmented cartography in tourism, worksheets in museums, desktop office work, workplace meeting applications, collaborative sketching and prototyping, air traffic control, or entertainment and “edutainment” (Choi, 2009; Huang, Hui, Peylo, & Chatzopoulos, 2013; Shaer & Hornecker, 2010; Steimle, 2012). However, in this paper we are especially interested in the application of these systems to education, given that paper is ubiquitous in our schools already. Aside from the fact that paper artifacts are cheap to produce, several authors have noted the intrinsic qualities of paper for educational settings: paper interfaces can be used to integrate computing in schools more seamlessly than mouse, keyboards and screens (Malmborg, Peterson, & Pettersson, 2007); its tangibility and flexibility allow paper to be easily manipulated, carried around, or passed from one student to another (Horn, AlSulaiman, & Koh, 2013; Luff et al., 2007); as a tangible element, paper can help learning spatial skills (Cheng & Tsai, 2013; O’Malley & Fraser, 2004; Schneider, Jermann, Zufferey, & Dillenbourg, 2011), and it can make the activity workflow visible (Dillenbourg et al., 2011). But, before we analyze educational applications of augmented paper, let us look into the notion of “classroom orchestration” and how it can help us understand the educational use and deployment of these technologies in authentic settings.
Classroom orchestration in educational technology research

We are trying to understand why paper computing solutions have not been widely deployed yet in everyday classroom practice. This gap between the variety and number of research proposals and their implementation in everyday classroom practice is actually a common problem highlighted in educational technology research (e.g., Chan, 2011). Under the label “orchestrating learning,” it has been noted as one of the grand challenges of technology-enhanced learning research (Sutherland & Joubert, 2009).

Dillenbourg et al. (2009) define orchestration as “the process of productively coordinating supportive interventions across multiple learning activities occurring at multiple social levels.” Roschelle et al. (2013) note that orchestration aims at “more meaningful research by acknowledging the complexity and variability of classrooms and the mediating role of the teacher.” Dillenbourg et al.’s (2011) explains orchestration as a change in the focus of attention in the design and study of educational technologies, from individual usability or the study of small-group work, to a wider focus on the usability of educational technologies at a classroom level, including the multiple constraints (time, curriculum, etc.) present in real classrooms. A more complete discussion of the multiple dimensions of this notion can be found elsewhere (Prieto, Holenko-Dlab, Abdulwahed, Gutiérrez, & Balid, 2011; Roschelle et al., 2013; Fischer et al., 2013).

Authors highlight a variety of aspects on what orchestration is and how it should be addressed, with a large amount of overlapping with each other, but also containing marked differences (due to the different research perspectives and educational contexts their authors address). In order to help us analyze existing paper computing systems to explore their orchestration potential, we have tried to find which of these elements are key in defining orchestration, by compiling the most-often appearing elements from previous literature on orchestration. We found eight such elements, some of them marking general agreement among orchestraation-related authors, others marking disagreements or tensions that can be resolved in different ways (as noted by Roschelle et al., 2013). The agreements are mostly about:

- **Pragmatism/Constraints.** Complying with the specific contextual constraints of the (authentic) educational setting is of the utmost importance: lesson time limitations, classroom space constraints, assessment requirements, teacher energy levels, curriculum relevance, discipline constraints, etc. (e.g., Dillenbourg, 2013; Nussbaum & Díaz, 2013; Roschelle et al., 2013). Regardless of the potential of an innovation in the lab, it will never be adopted if it does not comply with these constraints.

- **Empowerment/Control/Management.** Orchestration is largely about the logistics of managing the different learning activities taking place in the classroom at different social levels, using different tools (Prieto et al., 2011; Dillenbourg, 2013). Classroom technologies should empower teachers (and students) in this management, e.g., by making it more efficient (automations), or by letting users control them easily (Cuendet, Bonnard, Do-Lenh, & Dillenbourg., 2013).

- **Visibility/Awareness/Monitoring.** The perceptual processes taking place during enactment are crucial, to know what is happening and how student learning progresses (Dillenbourg, 2013; Looi & Song, 2013; Balaam, 2013). Technological systems for the classroom should facilitate such perceptual processes, e.g., by supporting visibility of the learning activities, or their assessment.

- **Flexibility/Adaptation.** Learning situations in authentic settings often require making run-time changes to the original plan of the learning experience (e.g., Cuendet et al., 2013; Looi & Song, 2013; Tchounikine, 2013), to address unexpected events (latecomers, interruptions, etc.), and take advantage of emergent learning opportunities and students’ input (e.g., for debriefing activities). Classroom systems should be flexible enough to accommodate such changes and opportunities.

- **Minimalism.** Given this multiplicity of tasks and processes going on in the classroom, technologies should be simple, providing the most-often-needed functionalities (Balaam, 2013; Dillenbourg, 2013; Looi & Song, 2013).

Authors also point out other elements as being very important for orchestration, even if they do not always agree on how to address them, or how to resolve the tensions they represent:
• **Teacher-centrism and sharing the load.** Most authors acknowledge the crucial role that teachers play in the technology-enhanced classroom (Roschelle et al., 2013). However, different educational contexts and different moments call for different “balances of power” between teachers, students and technology. The central role of the teacher in the classroom can lead to an excessive management burden, calling for systems that allow sharing the orchestration load (e.g., with students, see Sharples, 2013).

• **Designing for preparation, appropriation and enactment.** Certain authors focus orchestration more on the run-time management of the learning situation (Dillenbourg, 2013), while others highlight the activities that happen prior to the classroom enactment itself, including the de-contextualized pedagogical and technological design (scripting), the customization of those designs for a concrete learning setting, as well as other preparation work regarding the appropriation of those elements by teachers and students (Hämäläinen & Vähäsantanen, 2011; Kollar & Fischer, 2013). Technological systems should make this preparation and appropriation easy.

• **Multi-level integration and synergy.** Orchestration is said to be about aligning or combining the multiple elements in the classroom to achieve a more effective learning experience, e.g., by combining different technologies, by combining individual, group and class activities to enhance the learning about a subject, or even by combining different learning and pedagogical theories in a sort of “theoretical ecumenism” (Dillenbourg, 2013; Kollar & Fischer, 2013; Looi & Song, 2013). This aspect also includes how the system integrates with existing classroom practices, workflows and contents, and with other technologies being used in the classroom (Cuendet et al., 2013).

From these aspects we can gather an operational definition of “technology for orchestration,” as a technology that is usable and effective within the pragmatic constraints of authentic educational settings, by supporting the perception and management of the learning activities (individual, in groups or at classroom level), and/or being flexible enough to be easily integrated in such management. To better understand the applicability of paper-computing proposals to authentic educational settings, we propose to look at existing paper-based computing systems through these eight orchestration aspects.

**Review methodology**

We performed a systematic literature review following the guidelines by Kitchenham and Charters (2007). The concrete goals of this review were: (a) to identify and organize paper-based computing systems applied to education (to acknowledge their advantages and disadvantages); and (b) to further analyze those efforts that performed evaluations in authentic formal education settings from an orchestration perspective (to assess their potential and the outstanding challenges of their use in authentic practice).

Regarding the need for such a review, several authors have performed reviews in related fields such as AR (Grasset, Dunser, & Billinghurst, 2008; Choi, 2009; Billinghurst & Duenser, 2012; Cheng & Tsai, 2013; Huang et al, 2013; Santos et al., 2014) or tangible interfaces (O’Malley & Fraser, 2004; Shaer & Hornecker, 2010). There also exist reviews on paper-based systems in general (Steimle, 2012). However, there exists no review systematically focusing on the educational uses of paper-based computing systems (Lim and Park, 2011, focus only on the augmented book form factor). Especially, there is no review that looks into the ecological perspective of whether these systems “work” in the context of authentic classrooms.

To find relevant literature sources, we used seven well-known online research databases related to education and technology (IEEExplore, Science Direct, Sciverse Scopus, ISI Web of Science, ACM Digital Library, Springerlink and ERIC). Furthermore, we also queried Google Scholar to ensure the inclusion of “grey literature” (Kitchenham & Charters, 2007). Using the query string: (“paper computing” OR “augmented paper”) AND (education) AND (classroom OR school OR university), we obtained 209 references from the databases, and 634 from Google Scholar. We screened these sources for relevance to paper-based computing and education, eliminating studies that did not involve a concrete system/intervention (e.g., literature reviews). After eliminating duplicates (e.g., sources with similar authors describing the same system in similar settings), and adding expert and reviewer recommendations as well as more recent work by authors and research groups detected as relevant, a total of 40 references were left. These are analyzed in the “Review results” section.
To address the two goals of the review, our analysis followed two stages. First, we synthesized the 40 educational augmented paper systems, clustering their purported advantages and affordances for educational settings. In the second stage, we analyzed the 15 references that included system implementation and evaluation in authentic formal education settings (or that tried to emulate such settings explicitly), using the eight orchestration themes presented in the previous section.

**Review results**

**Stage 1: General overview of paper-based systems in education**

Among the 40 analyzed proposals (see Table 1) we can find examples of every kind of form factor (see “Paper-based computing” section above). For instance, Bayon, Wilson, Stanton, & Boltman (2003) propose KidPad, an environment for primary school students to create and retell stories, using augmented cards with barcodes as placeholders for drawings, audio and other media. Shih, Wang, Chang, Kao, & Hamilton (2007) propose augmented books featuring barcodes which, along with PDAs, facilitate access to additional contents (including also tools for teachers to customize such content, see Figure 1). A form of augmented notebook to support creation/sharing of sketches is proposed by Lee et al. (2007). Hitz and Plattner (2004) propose a generic architecture to augment printed documents to enable students to access additional contents using mobile devices (Figure 2). Finally, Cuendet (2013) proposes Tinkerlamp, an augmented table that uses paper elements to control different simulations in logistics vocational education (see Figure 3).

<table>
<thead>
<tr>
<th>Form factor</th>
<th>Proposal evaluation stage</th>
<th>Total #</th>
</tr>
</thead>
<tbody>
<tr>
<td>Augmented cards/Post-Its</td>
<td>Liarokapis &amp; Anderson, 2010; Montemayor, 2003</td>
<td>Bayon et al., 2003; Kerawalla, Luckin, Seljeflot, &amp; Woolard, 2006; Miura et al., 2009</td>
</tr>
<tr>
<td>Augmented books</td>
<td>Grasset et al., 2008; Horn et al., 2013; Wang &amp; Chang, 2007</td>
<td>Chen &amp; Chao, 2008; Martín-Gutiérrez et al., 2010; Shih et al., 2007</td>
</tr>
<tr>
<td>Augmented printed documents</td>
<td>Fraser et al., 2003; Luff, Pitsch, Heath, &amp; Wood, 2010</td>
<td>Alessandrini, Cappelletti, &amp; Zancanar, 2014; Chen &amp; Tsai, 2013; Lu, 2008; Teng, Chen, &amp; Lee, 2011</td>
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</tbody>
</table>
Paper-based systems have been proposed for almost every educational level: from preschool and elementary school storytelling environments (e.g., Bayon et al., 2003), to secondary education books (e.g., Wang & Chang, 2007), vocational training tabletop systems (e.g., Do-Lenh, 2012) and university-level lecturing support systems (e.g., Mitsuhara et al., 2010). Similarly, augmented paper systems have been proposed to aid in a wide variety of subject
matters, including math (e.g., Sharma et al., 2013), science (Kerawalla et al., 2006), history (e.g., Fraser et al., 2003), etc. Other efforts focus on specific skills rather than subject content: storytelling (Bayon et al., 2003), spatial skills (e.g., Martin-Gutierrez et al., 2010) or even guitar playing (Liarokapis & Anderson, 2010). Yet others are aimed at supporting activities more peripheral to learning, such as note-taking (e.g., Pietrzak et al., 2010), and thus could be applied to learning multiple kinds of content/skills. The proposed systems cover learning activities throughout the whole spectrum of social planes: from individual activities (e.g., Chen & Chao, 2008) to small group activities (e.g., Hook et al., 2013) or even whole-class collaborative learning activities (e.g., Alvarez et al., 2013).

Table 2. Synthesis of augmented paper advantages for education, including examples

<table>
<thead>
<tr>
<th>Role of paper</th>
<th>Paper documents contain hyperlinks (e.g., visual markers)</th>
<th>Contents of paper are synchronized with digital resources</th>
<th>Paper as a tangible token to access/control digital content</th>
<th>Hybrid of augmented document and tangible controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advantages</td>
<td>Paper documents</td>
<td>Contents of paper</td>
<td>Paper as a tangible token to access/control digital content</td>
<td>Hybrid of augmented document and tangible controller</td>
</tr>
<tr>
<td>Flexibility</td>
<td>Augmented books [Ha et al., 2011; Zhao et al., 2014]</td>
<td>Augmented paper notebooks [Hong &amp; Jung, 2005]</td>
<td>Augmented paper cards with digital pens [Miura et al., 2009]</td>
<td></td>
</tr>
<tr>
<td>Learning process and outcomes become more explicit and accessible</td>
<td>Augmented books [Shih et al., 2007]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Enables complex interaction preventing cognitive/visual overload</td>
<td></td>
<td>Augmented paper notebooks [Pietrzak et al., 2012]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bridges the gap between physical and virtual to enhance visual/spatial ability</td>
<td></td>
<td>Augmented paper cards with digital pens [Ferdinand et al., 2005; Kerawalla et al., 2006]</td>
<td>Augmented tabletop [Bonnard, 2012; Cuendet, 2013; Do-Lenh, 2012; Grammenos et al., 2011]</td>
<td></td>
</tr>
<tr>
<td>Management of documents in an effective way</td>
<td>Augmented books [Zhao et al., 2014]</td>
<td>Augmented paper notebooks [Lai et al., 2007; Lee et al., 2007; Mitsuhara et al., 2010; Steimle et al., 2009]</td>
<td>Augmented printed documents [ Lu, 2008]</td>
<td></td>
</tr>
</tbody>
</table>
If we look at the system rationales and advantages portrayed by their authors, we can synthesize several augmented paper affordances for education (see Table 2 for more details and example references). Some of these advantages directly stem from paper’s intrinsic properties. Paper can be easily and intuitively used, and thus can provide a means for interaction with less perceived effort, e.g., the ease of navigating through content by flipping pages on an augmented book (tangibility or manoeuvrability). Paper can also support a range of activities (e.g., passing it around to others, or moving it in the area of a desk), thus making it simple to configure digital systems by moving paper around (flexibility).

Other systems leverage digital resources’ intrinsic advantages. Since digital resources can be linked or animated at a distance, and they can be easily searched, shared, duplicated or archived, these systems can enable an immersive experience including visual, audio and other media (e.g., enhancement of a paper map with multimedia content). They also can make the learning process and outcomes more explicit and accessible, through recording and tracking interactions with the systems (e.g., recording the sequence of logistic simulation parameters tried out by a group of students).

Authors also mention other advantages of these systems, which relate to the benefits of combining paper and digital media. The expansion of the interaction space resulting from linking paper documents and digital resources enables complex interaction without excessive cognitive overload. These systems also bridge the gap between physical and virtual objects, which may assist in enhancing students’ visual and spatial abilities (e.g., projecting abstract notions like angle measures over a paper polygon). Also, the seamless transition between paper and digital documents enables effective information searching, quick navigation, or convenient conversion, storage and retrieval.

However, what kind of evidence do we have of all these advantages? Many of the analyzed proposals (47.5%, see Table 1) only provided a first prototypes of the system, or preliminary pilots or user studies (and thus there is little evidence of their affordances in actual educational use). Other studies perform controlled experimental designs, often in a lab setting (15%), and thus their ecological validity in an authentic, non-controlled setting is limited.

In fact, only 15 of the selected studies (37.5%) depict the usage of the system in an authentic setting, or try to mimic real classroom constraints (in terms of space, time, curriculum, etc.). We could ask ourselves to which extent those affordances are useful for teachers and students within the multiple constraints of actual classrooms.

Stage 2: Orchestration analysis of paper-based classroom interventions

From the 15 studies that had been evaluated in authentic or authentic-like settings (see Table 3), we can also extract several features. Most of them are relatively recent, maybe indicating that only lately the involved technologies have been reliable and affordable enough to be studied out of a controlled lab setting. The studies use a variety of research designs and methodologies, from quasi-experimental designs with a control group to design-based research and participatory longitudinal studies. Although the studies report a wide range of findings, there is a notable lack of studies actually studying learning effects of using the technology, with many of them rather focusing on other constructs like usability (Bayon et al., 2003) or student engagement (Alvarez et al., 2013; Miura et al., 2009). From those studies that try to measure learning effects, many do not find statistically significant results when compared with learning the same material using other methods (e.g., Cuendet, 2013).

Among these 15 systems there are also representatives of all five interface form factors. The proposals provide different levels of learning activity support: some focus especially on the provision of subject matter content (e.g., the 3D models in Martín-Gutiérrez’s augmented book, 2010), others on the content-independent support of a specific task (e.g., Bayon et al.’s environment for storytelling in which teacher and students create freely the contents to be added, 2003), and yet others focus on supporting a learning activity as a whole (e.g., Cuendet’s tabletop system provides both contents and task support to enhance carpenters’ spatial skills, 2013). Looking at these 15 studies from the point of view of the eight key orchestration elements (see the “Classroom orchestration” section above), we notice the following:
Pragmatism/constraints

The analyzed efforts comply with many of the constraints of the real classrooms they were designed for. Most of the studies used curriculum-relevant contents and activities, often co-designed with teachers (e.g., Bonnard’s geometry activities based on the Swiss primary school curriculum, 2012). They also considered classroom space constraints (e.g., using webcams and displays already existing in the classroom, in Kerawalla et al., 2006) and time constraints (e.g., lesson length of a typical lecture in Miura et al., 2009). The impact of the system/intervention into teachers’ energy levels is less clearly addressed in general: while some studies appear to have no impact on teacher effort (e.g., Lee et al.’s student note-taking system, 2007), or even appear to require less effort than the traditional enactment alternative (e.g., Alvarez et al.’s automation of the data flow between digital pens and shared display, 2013), several others mention a certain teacher effort involved in the preparation of materials (Mitsuhara et al., 2010), or the improvisation of debriefing activities (Chen & Chao, 2008). Interestingly, several studies mentioned how the limited range of applicability of the system (e.g., the fact that their usage covers only a small part of the curriculum) may affect adversely system adoption (Bonnard, 2012; Kerawalla et al., 2006).

Table 3. Summary of the augmented paper systems used in authentic settings

<table>
<thead>
<tr>
<th>Form factor</th>
<th>Study</th>
<th>Aim</th>
<th>Subject</th>
<th>Main findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Augmented paper cards with digital pens</td>
<td>Bayon et al., 2003</td>
<td>Enhance children’s creativity and collaboration</td>
<td>Storytelling</td>
<td>* It was easier to draw with pen/paper, rather than with the mouse</td>
</tr>
<tr>
<td>Kerawalla et al., 2006</td>
<td>Incorporate AR content into UK primary school lessons</td>
<td>Earth sciences</td>
<td>* Child participation and engagement lower in AR role-plays</td>
<td></td>
</tr>
<tr>
<td>Miura et al., 2009</td>
<td>Facilitation of collaborative and interactive learning in regular lectures</td>
<td>(Generic)</td>
<td>* Improved student motivation/enjoyment (enjoyable competition)</td>
<td></td>
</tr>
<tr>
<td>Augmented books</td>
<td>Shih et al., 2007</td>
<td>Compare ubiquitous, multimodal e-Learning with alternatives</td>
<td>(Generic)</td>
<td>* Increased information overload when using augmented books</td>
</tr>
<tr>
<td>Chen &amp; Chao, 2008</td>
<td>Explore context-aware learning support to assist in paper textbook comprehension</td>
<td>Programming</td>
<td>* Recommended annotations may assist in knowledge construction</td>
<td></td>
</tr>
<tr>
<td>Martín-Gutiérrez et al., 2010</td>
<td>To investigate the use of AR for improving spatial abilities of engineering students.</td>
<td>Engineering</td>
<td>* AR application was helpful for improving student spatial abilities</td>
<td></td>
</tr>
<tr>
<td>Augmented paper notebooks</td>
<td>Alvarez et al., 2013</td>
<td>Support New Media Literacies teaching and curriculum in classroom</td>
<td>Math</td>
<td>* The system can be well integrated in classroom teaching</td>
</tr>
<tr>
<td>Lee et al., 2007</td>
<td>Ecologically valid paper-based system and effects on design culture</td>
<td>Design education</td>
<td>* Longitudinal impact of augmented paper interactions on design practice</td>
<td></td>
</tr>
<tr>
<td>Liao et al., 2007</td>
<td>Combine physical artifacts (paper) with communication and archival infrastructure</td>
<td>Engineering</td>
<td>* Feasibility of paper interface to support student-instructor communication in active learning.</td>
<td></td>
</tr>
<tr>
<td>Mitsuhara et al., 2010</td>
<td>Compare learning effects and note-taking behavior of augmented paper</td>
<td>(Generic)</td>
<td>* Changes in note-taking behavior: less changes in gaze direction, less time spent writing</td>
<td></td>
</tr>
</tbody>
</table>

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Several issues come to our attention when we analyze the management of classroom activities using paper-based systems. In many of the analyzed systems the teacher is the central “manager” of the flow of the class. However, only a few of the systems provided teacher-specific user interfaces with special capabilities (e.g., Do-Lenh, 2012; Steimle et al., 2009). Certain proposals are specifically designed to facilitate the management of emergent activities like debriefing (Kimbell et al., 2005). Regarding the mode of activity management (socially vs. technology-mediated), very often the proposed systems are managed flexibly in a social manner, without intervention from the system (e.g., Alvarez et al.’s social regulation of the use of the digital pens by students when needed, 2013). Several systems were conceived for easy/flexible navigation, without a specific activity flow (e.g., Lee et al., 2007), although an order is sometimes suggested by the paper binding of a book (as in Martin-Gutierrez et al., 2010). In fact, certain systems did use the paper elements to embody the class workflow (e.g., in Bonnard’s sheets printed with the activity description - see Figure 4), which can even be taken out of the classroom to interact with external actors (Do-Lenh, 2012).

**Empowerment/control/management**

![Figure 4. Bonnard’s (2012) printed sheets including activity description](image.png)
Visibility/awareness/monitoring

Several levels of awareness are possible in the classroom, related to the social plane at which the learning activities happen (individual, small-group or classroom-wide). Digital pen systems often provide very limited visibility beyond the individual; tabletop systems such as Bonnard (2012) normally have good individual or small-group visibility, but not so good classroom awareness from a distance. Thus, there are systems that complement the paper-based system with a shared display in the front of the classroom, as a collective memory and to help teachers be aware of student actions (e.g., Alvarez et al., 2013; Miura et al., 2009). Some authors note that the physical layout of the system elements (e.g., the paper pieces) in the class may help signal aspects of classroom workflow (e.g., Cuendet, 2013). Aside from shared displays, a few systems include specific tools for teacher awareness (e.g., to follow the navigation patterns and learning outcomes of possibly distant students, in Shih et al., 2007). Several systems also provide automated feedback about the learning task to students/teachers (e.g., Chen & Chao, 2008; Cuendet, 2013).

Flexibility/adaptation

A paper-based system can be flexible and adaptable in many different ways. Many of the portrayed systems are flexible to navigate, thanks to paper’s handling ease (e.g., using barcodes on paper cards to freely navigate between a story’s events, in Bayon et al., 2003). However, the fact that some systems provide multimedia learning content poses a limitation to this flexibility, as the lesson cannot step out of the previously prepared contents (as in Mitsuhara et al., 2010). Conversely, systems that are content-independent (e.g., Alvarez et al., 2013; Steimle et al., 2009) may have a larger range of applicability. Other systems use paper elements like cards to flexibly adjust system features and the difficulty of learning tasks (Cuendet, 2013), and the automatic recording of student information and learning outcomes can be used for spontaneous debriefing activities (e.g., Miura et al., 2009).

Minimalism

The reviewed systems comply with this guideline to different degrees. To obtain a simple activity flow, certain systems propose simple, modular activities without many inter-dependencies among them (e.g., Bonnard, 2012). Several systems try to minimize their feature set by doing away with the notion of login/identification, which often are not essential for learning itself (e.g., Do-Lenh 2012; Kerawalla et al., 2006). Strategies to minimize orchestration load include the automation of the workflow (e.g., transparent/automatic sharing of student outcomes in Lee et al., 2007). Yet, we also find systems breaking this simplicity principle, either increasing user perception of cognitive load (e.g., Shih et al., 2007), veering towards clutter due to the multiple tangible interface elements (noted by Cuendet, 2013) and shared student artifacts (Liao et al., 2007). Certain works also mention teachers’ rejection of complex technology setups (e.g., upon Cuendet’s suggestion of using multiple augmented tabletops in a classroom).

Teacher-centrism and sharing the load

Paper-based systems can support very varied role distributions among actors, depending on the classroom dynamic to be supported. In a teacher-centric situation, several systems support “traditional” roles such as teachers lecturing with students as passive receivers (as in Mitsuhara et al., 2010), although more often teacher is seen as a facilitator (especially in creative activities, like storytelling in Bayon et al., 2003). On the other end, certain systems are designed to work independently of the presence of a teacher, for student individual study or problem resolution (e.g., Martín-Gutiérrez et al., 2010; Shih et al., 2007). Some of the systems actually provide more flexible orchestration roles, enabling teachers to share with students a part of the orchestration “power,” for example in the form of cards enabling certain features (e.g., Bonnard, 2012; Cuendet, 2013). We observe also a great variety of balances between teachers and researchers, especially regarding who (if anyone) has to handle the preparation of the learning activity and its materials (see also the following aspect).
Designing for preparation, appropriation and enactment

Although the design and implementation of all the proposed systems was done by researchers/specialists, the customization and preparation of the learning activities for the concrete classroom took different forms (although it is often insufficiently described). Certain systems require very little physical preparation, especially those that rely more on student input like note-taking (Alvarez et al., 2013; Steimle et al., 2009) than in the provision of multimedia content or feedback. Other systems, however, require a researcher or specialist to intervene during preparation (e.g., of augmented slides before the lectures in Liao et al., 2007). How this preparation is performed varies greatly, and normally no authoring tool is provided (with the exception of the one depicted in Shih et al., 2007). Only a few systems allow for the rapid and flexible preparation of activities just before the lesson (as in Bonnard’s symmetry exercises, 2012), which can lead to easier appropriation of the system by teachers.

Multi-level integration and synergy

Generally, the proposed systems are well integrated with existing classroom workflows, practices and tools (especially paper-based ones, but not only): using paper as a free drawing tool (e.g., Lee et al., 2007), or as a permanent memory (e.g., use of activity sheets, Do-Lenh, 2012). Other systems infiltrate the use of existing elements like rulers and other drawing tools (Bonnard, 2012, Cuendet, 2013 – see Figure 5). Another common tool synergy involves paper-based elements (for more natural individual/group work) and a shared display (for classroom awareness), as in Do-Lenh (2012) or Alvarez et al. (2013). Other systems try to integrate ubiquitously with existing student practices (such as mobile device-based support for individual study, Chen & Chao, 2008). Many of the proposed systems support some kind of transition between the individual, group and classroom social planes (e.g., in Alvarez et al., 2013, the activity flow includes collaborative problem solving at all three levels). However, the interoperability of augmented paper data and activities with other technological tools and systems (e.g., online LMSs) is much less discussed, aside from the physical persistence of paper artifacts themselves.

![Figure 5. Variety of tools used in Cuendet’s (2013) system](image)

Discussion: Challenges and future research for augmented paper systems in the classroom

As we have seen, researchers have proposed augmented paper (in its many forms) as more subtle way to enhance the classroom with digital media. From the first stage of our systematic review, we elicited several potential affordances of this kind of systems, like tangibility or manoeuvrability, the ability to manage documents in an effective way, or to bridge the gap between physical and virtual worlds. We also saw how paper-based computing applications for education is still a field in flux, exploring creatively divergent lines of research and system form factors, but with little continuity beyond preliminary usability/engagement studies with a few subjects. Strangely enough, the actual affordances for learning itself often are not thoroughly investigated, and comparatively few studies address teachers’ perceptions and system compliance with real classroom constraints. As noted by Cheng and Tsai (2012) and Santos et al. (2014), despite initial evidence of benefits for learning of spatial skills or science conceptual understanding, the number of studies is still small, especially for longer, in-the-wild measurements of learning (an issue also highlighted in Lee et al., 2007; Shaer & Hornecker, 2010).
In this paper we have focused specifically on this dimension of usage and adoption in authentic educational settings, through the analytical lens of classroom orchestration. Our orchestration-based analysis of the systems evaluated in authentic settings was limited by the lack of descriptions or explicit consideration of certain orchestration aspects. In latest works, however, classroom usage and the learning value of the technology have begun to be taken into consideration (e.g., Alvarez et al., 2013, Do-Lenh, 2012, and others). Nevertheless, the available studies confirm paper’s protean qualities for classroom use, accommodating a variety of classroom dynamics and multi-level activity integration. However, as noted before, the learning effects of the proposed systems often have not been thoroughly studied yet, with clear benefits present only in certain tasks with an important spatial component.

As technology designers, we could take an alternative approach and focus on the orchestration advantages of paper-based systems at the classroom level, rather than on the individual learning effects (although, of course, studies should ensure that learning is not hampered by using the system in a classroom). In this sense, paper-based systems have also shown to be able to accommodate a variety of pragmatic classroom context constraints. The technology design of the augmented paper systems leveraged different paper-based affordances and advantages: intuitive interaction, accommodating emergent debriefings and flexible navigation sequence, as well as the awareness properties of the different system elements at group and classroom social levels (e.g., paper elements as visible workflow, often in synergy with a shared display for further classroom awareness).

From an educational technology designer perspective, we should note that this compliance with the classroom constraints was the consequence of long and careful co-design processes. Paper-based technologies are still difficult to design and prototype, and it is even more difficult to design systems that let end-users (e.g. teachers, students) appropriate them. As Santos et al. (2014) mention, some systems are starting to provide this kind of end-user support. We foresee that the advances in web technologies and mobile devices can make this kind of features possible, as already hinted by mobile AR browsers (see Muñoz-Cristóbal et al. for an example of a system that applies such technologies to let teachers and students shape their learning activities, 2013) and online paper/tangible solutions (e.g., Cuendet, 2013).

Our review also uncovered certain remaining challenges in this field, which represent interesting directions for future research in this area: a) the design space defined by augmented paper advantages and system form factors (see Table 2) is still sparsely populated, indicating potential paths for the design of novel systems of this kind; b) teachers’ understandable resistance to more complex technical setups, the increased length of the co-design processes in order to address these real classroom constraints, and the limited range of applicability of many of the resulting systems point towards the need of specific design guidelines and processes for the conceptualization and implementation of this kind of systems; c) addressing the design, preparation and customization of the learning activities before enactment itself is also unresolved, as it often requires quite specialized technical knowledge and careful interaction design – augmented paper toolkits and user-created paper UIs are another promising avenue of future work.

Finally, the analyzed systems also illustrate certain design tensions (Tatar, 2007) in applying paper-based systems to the classroom: a) flexible, easy to use paper UIs can quickly become scattered (with interface clutter breaking the minimalism principle); b) designing the system as a scarce, unique resource in the classroom, versus having one-to-one setups, in which increased access to technology has to be balanced with minimalism and teachers’ natural fear of complex setups that can break down or become uncontrollable; c) paper’s natural affordance for flexibly navigating through content is counterbalanced by the need of such content to be prepared by teachers or specialized staff; d) the need to support awareness at different social levels, often using an ecology of different devices, again is in tension with the preference for a minimalist setup; e) computers’ ability to provide automated feedback is somewhat hampered if we make use of paper’s power as a flexible input source (due to the difficulty in converting freeform drawing to computer-interpretable form). These and other design tensions also mark pathways to be explored in future research work (e.g., through comparative studies in different classroom settings. Paper is making a comeback to the classroom, only it never really went away.

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References


