IllumiPaper: Illuminated Interactive Paper

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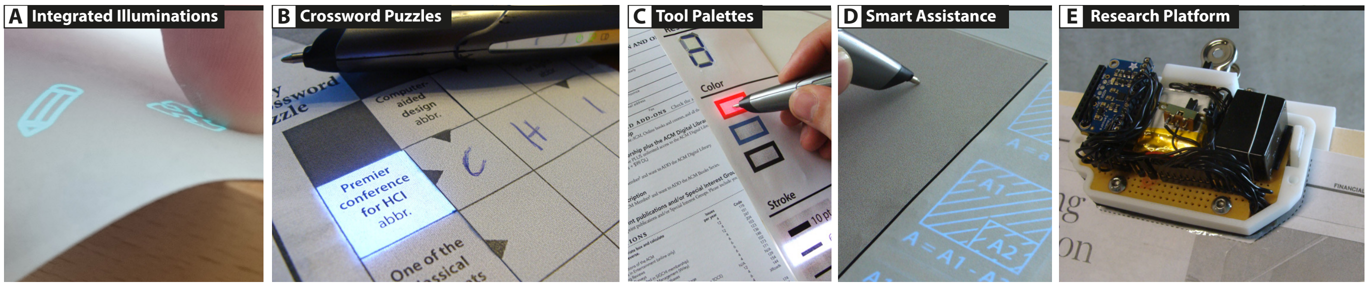

Figure 1. Our ILLUMIPAPER research platform (E) provides paper-integrated visual feedback without losing the sensory richness and flexibility of paper (A) and supports several applications including educational grid puzzles (B), interactive tool palettes (C) or even math exercise sheets (D).

ABSTRACT

Due to their simplicity and flexibility, digital pen-and-paper solutions have a promising potential to become a part of our daily work. Unfortunately, they lack dynamic visual feedback and thereby restrain advanced digital functionalities. In this paper, we investigate new forms of paper-integrated feedback, which build on emerging paper-based electronics and novel thin-film display technologies. Our approach focuses on illuminated elements, which are seamlessly integrated into standard paper. For that, we introduce an extended design space for paper-integrated illuminations. As a major contribution, we present a systematic feedback repertoire for real-world applications including feedback components for innovative paper interaction tasks in five categories. Furthermore, we contribute a fully-functional research platform including a paper-controller, digital pen and illuminated, digitally controlled papers that demonstrate the feasibility of our techniques. Finally, we report on six interviews, where experts rated our approach as intuitive and very usable for various applications, in particular educational ones.

Author Keywords

Digital pen and paper; electro-luminescence; pen interaction; visual feedback; Anoto; thin-film display; augmented paper.

ACM Classification Keywords

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INTRODUCTION

Over hundreds of years, the use of paper and writing has become a major cultural achievement and has maintained its importance until today's information age. The success of paper is based on its simplicity, sensory richness and versatility, which foster a widespread dissemination and ubiquitous availability. The affordances of paper for writing and sketching provide unique advantages over digital media [35, 34]. This becomes evident, for example, in active reading tasks when highlighting words, marking graphics or adding drawings. In addition, paper has been found to be the most direct, flexible and intuitive way to annotate documents [17]. Despite these advantages, the growing need of its digital integration into our daily life requires novel solutions. While maintaining the unique properties of paper, powerful software tools and computing functionality should be combined with real paper for added digital value.

The development of camera-based digital pens (e.g., with Anoto™ technology) or sensor-based versions laid the basis for recognizing and analyzing handwritten text on paper, but the provision of visual feedback, e.g., to communicate pen or system states, remains challenging. To address this problem, a wide range of modalities (cf. [55, 34, 59]), i.e., primarily visual feedback (e.g., [65]) as well as audio [44] and haptic [27, 28] or direct muscle feedback [33] have been investigated. However, until now visual feedback – while sometimes displayed on the pen or projected onto paper – is not *directly* integrated into the paper, which would allow providing feedback close to the ink and directly related to the content itself. This would eliminate the problem of visual inconsistencies between physically written content and digitally associated, but otherwise imperceptible information. Typical digital pen-and-paper applications which would benefit from this coexistence – besides many others – could be interactive educational exercise sheets, semantic layers in professional construction plans or simply adjustments of color, line thickness, etc. for writing or sketching in personal notepads.

Although ultra-thin high-resolution screens, such as flexible OLED or E-Ink displays, enable rich interactions [62] and will become available in the long term, we argue that these display types will perhaps always lack some of natural paper's properties (e.g., texture, tearing, folding) and might be too expensive and complex for replacing paper entirely.

In contrast, we see high potential in emerging printed electronics and displays technologies as an important enabling factor towards seamlessly integrated digital paper enhancements. Printed technologies provide ultra-thin, flexible and versatile input and output capabilities on standard paper, thereby preserve almost all unique paper properties and can even be produced in low-cost printing processes in large-scale [53, 60]. In our work, we aim to enable paper augmentation without additional projector setups or display devices, which often seem to be at odds with the flexibility and portability of paper and most of its natural advantages. Therefore, we focus on novel printed segment-based feedback technologies, which position themselves between simple feedback (e.g. LEDs) and next-generation displays (e.g. OLEDs, E-Ink) in their visual capabilities. Hence, our research questions are *where*, *how* and *when* paper-integrated, visual feedback can support user interactions in pen-and-paper user interfaces (PPUIs) and *which* interaction techniques and applications are suitable. Therefore, we examine these aspects in detail and contribute:

- **A systematic exploration** of combining digital pen-and-paper solutions with emerging, low-cost, paper-integrated thin display technologies to visually enhance common paper-related tasks along essential design dimensions.
- **A systematic feedback repertoire** for real-world applications including feedback components for paper widget controls, correctness checks, supporting layout and motion tasks as well as dynamic smart requests.
- **A fully-functional research platform** including a prototype that can be seamlessly clipped to digitally-enabled paper to get paper-based visual feedback in several different application scenarios. We introduce a set of interactive illuminated paper sheets, which demonstrate selected PPUI applications as representative examples.
- **A qualitative evaluation**, i.e., six semi-structured interviews in hands-on sessions with experts from the fields of psychology, education and HCI providing valuable insights.

The remainder of this paper is structured along these contributions: First, we sum up previous work to provide a systematic overview and position our own work. We then introduce our concept and contribute essential design dimensions for paper-integrated feedback along the axes position, type and time. Afterwards, we propose a systematic repertoire of generic feedback components. Subsequently, we describe the realization of our research platform and present a set of implemented applications that we evaluate in expert interviews. A discussion on challenges and future work will conclude our work. For illustrations, we use a color scheme that decodes visual feedback in **green** and user interactions in **blue**.

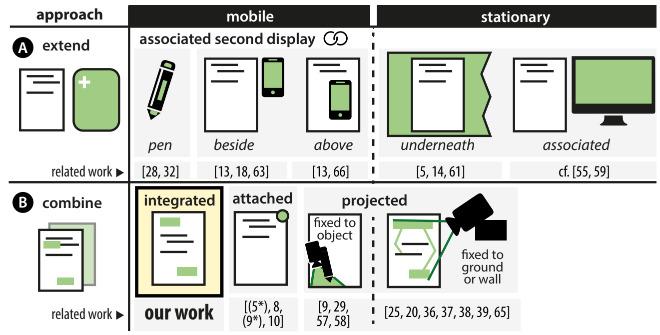

Figure 2. Visual feedback: Using additional screens (A); Combining a visual layer onto the paper itself (B). The overview considers only work that includes pen interaction, natural paper and active visual feedback.

BACKGROUND AND RELATED WORK

Since the objective of this paper is a synergistic approach that seamlessly bridges the gap between physical, handwritten content and virtual associated information, we focus on work that investigates visual augmentation approaches for pen-and-paper user interfaces as well as novel and promising paper-based technologies. Therefore, we group our related work section into visual feedback in PPUIs, paper-based electronics, and emerging thin-film display technologies that are suitable for a seamless paper integration.

Visual feedback in Pen-and-Paper User Interfaces (PPUIs)

The need for visual support in PPUIs has long been known and researchers introduced several approaches that are often based on new enabling technological developments, e.g., projectors, pico-projectors, tiny microcontrollers with LEDs, thin-film displays. Therefore, we classify visual feedback by the augmentation approach (see Figure 2, rows), which either *extends* the paper with dedicated displays (A) or *combines* a visual layer onto the paper itself (B). In addition, we consider the mobility of the approaches (see columns).

In order to visually *extend* a paper, additional screens have been used beside [14, 43], above [29] or underneath the paper. Personal mobile devices [13, 18, 66, 63] have been used to show additional information, and dedicated displays have been built into digital pens (e.g. small OLED screens [32], color-encoded LEDs [28, 32]), which provide simple feedback capabilities. This on-pen feedback is paper independent, enables the fast provision of generic information (e.g., scrolling text on an integrated OLED screen [32]), and uses electronics which are already integrated in digital pens. However, feedback is only provided on the pen and never directly on the paper, where it could be displayed position-dependently, e.g., for providing feedforward [64] and feedback information to the user at the right place. In contrast, stationary displays (e.g. monitors, tabletops [14, 61]) provide rich paper-associated feedback with a high information density, but lack a seamless integration and create a media break by physically separating input and output area.

Besides the extension of paper based on dedicated displays (A), a series of further augmentation approaches merge virtual information layers with physical paper directly (B). To *combine* paper with a visual augmentation layer, research has been primarily focused on *projection-based* approaches, which augment paper by wall-mounted [65, 37, 38, 36, 25, 39, 20], mouse-mounted [58], pen-mounted [57], mobile attachable [30] or even book-attached [9] projector and camera setups. The DIGITALDESK [65], VIDEO MOSAIC [37], ARIEL [38] and ENHANCEDDESK [25] are early examples of stationary projection-based workstations that consider the affordances of a real desktop and enable rich paper augmentation. Mackay et al. [36, 39] and Hurter et al. [20] also investigate the augmentation of flight strips for air traffic control. Song et al. [57, 58] examine spatially-aware mobile projection techniques and propose a design space including overlaid content layers, menus, 3D views and remote collaboration. While these approaches can provide dynamic and rich content overlays, they are limited in their seamless integration and miniaturization, since projectors basically require a minimal projection distance, cause image disorder by projected overlaps and mostly expect good lighting conditions.

Paper-Based Electronics

Since our work aims to integrate displays directly into the paper itself (see Figure 2, B), we use paper-based electronics as a basis to realize paper-integrated traces for illuminating elements and additional sensors by the application of conductive layers and tapes. Paper-based electronics utilize fabrication methods which include copper tapes [49], threads [8] and exposed [7] or vinyl cut [54] foils. Conductive microparticle pastes & pens [4, 12] enable circuit sketching, while nanoparticle inks [40, 42] can be printed instantly [24, 23]. To add functionality, capacitive and resistive sensing enables customizable [22], even cuttable [45], approaches for proximity, (multi-)touch and pressure recognition [16]. Utilizing the piezoelectric effect further provides pressure, temperature [51] and even deformation [52] detection. In addition, physical widgets have been integrated by crafting paper controls [48, 15] or attaching off-the-shelf components as soldered, clipped [47, 10, 21, 26, 22], adhesive [5, 19, 50] or magnetic [6, 11, 12] parts. As an alternative, thin-film technologies facilitate flexible components, that will be seamlessly integrated in the future. An emerging set of these components including soft batteries, paper speakers, membrane sensors, flexible controllers and thin-film displays are already available – the latter of particular importance for our work.

Thin-Film Display Technologies

In general, display technologies can be classified in pixel-addressable high-resolution displays (e.g. OLED, e-paper) and in segment displays, which highlight predefined shapes based on electrochromism (EC) [2], thermochromism (TE) [31] or electroluminescence (EL) [1, 46]. Although advanced display types, such as e-paper, have promising properties (e.g., preserving content without battery), we focus on lightweight, low-current-consuming, segment-based EL and EC displays, which are robust, inexpensive and easy to integrate with pen interaction. Previous work on EC displays investigated the manufacturing process [2], developed multi-layered color displays [41] and even demonstrated fast switching intervalls and high-contrast. Furthermore, flexible EL displays have been proposed by cutting segments from an EL film [1] or screen printing the substrate layers [46], which provides highly customizable printed displays. Olberding et al. [46] introduced a comprehensive design space of custom-printed EL displays and proposed application examples including interactive postcards, watchstraps and awareness plants. However, to the best of our knowledge, these display technologies have not been combined with digital pen interaction before.

CONCEPT: DESIGN OF VISUAL FEEDBACK

In this section, we first describe our *design goals*. Following this, we propose design dimensions for segment-based displays (being our technological basis), and identify *position*, *visual type* and *time* of feedback as important design criteria for the conception of paper-integrated feedback in PPUIs.

Design Goals

Our motivation drives us to develop a neat, robust and lightweight paper concept that builds on highly miniaturized, paper-thin emerging technologies to seamlessly integrate visual feedback in common natural paper sheets. To achieve this, we developed the following design goals:

(G1) **Utility:** The visual feedback should support users in their familiar work process and overcome inconsistencies between physically written and virtual content.

(G2) **Integration:** The advantages of normal paper (e.g. sensory properties) have to be preserved and the augmentation should be mobile, lightweight and subsidiary.

(G3) **Versatility:** A variety of applications should be supported by using specialized, domain-specific augmented papers or more generic papers addressing a wider range of tasks (e.g., paper buttons for annotations).

(G4) **Simplicity:** All augmentation techniques should be easy to use, not disturb established workflows and seamlessly work together in their application context.

Considering these design goals and currently available technologies, we decided to use segment-based, ultra-thin EL and EC displays, which basically consist of substrate layers that can be printed directly on standard paper and are able to illuminate (EL) or change color (EC) in predefined regions. Although segment-based displays are fixed in place and limited in their visual capabilities, we assume that their smart integration and use are a promising approach to support many simple paper tasks in a more ambient and casual style.

Where? – Feedback Position

Olberding et al. [46] introduce a five-dimensional design space for digital fabrication of printed displays concerning the fabrication process, shapes, substrates, input sensing and display primitives, thereby taking on a technical perspective. We extend the design space by the dimension of *feedback position*, which defines the spatial relation between user input and visual output respectively. We differentiate *in-place*, *close-by*, *page-related* and *book-related* feedback (see Figure 3), which we describe in the following.

In-place feedback (IP) provides an immediate visual response at the same physical position as its respective user input. This

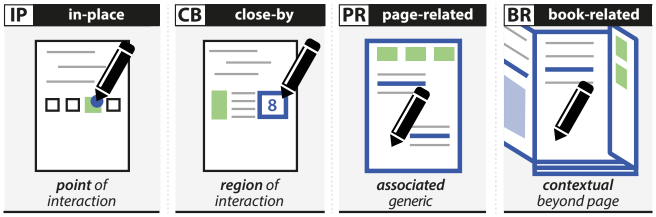

Figure 3. Visual Feedback Position: in-place (A), close-by (B), page- (C) and book-related (D). User feedback in green, interactions in blue.

feedback type requires predefined, visible interaction regions on the paper and is thereby suitable for applications with fixed placeholders (e.g., request forms, multiple choice tests) or paper control elements (e.g., buttons, sliders). The feedback can either support a state visualization (e.g., button on/off) or encode simple information (e.g., highlighting invalid fields). In-place visualizations afford a strong sense of system awareness for users, because input and output are linked directly.

Close-by feedback (CB) places illuminated elements in near proximity to task-related reference points, which are seamlessly linked to the semantic context (e.g., beside a task description). The loose coupling allows more flexible and greater interaction regions, which can be used for complex and area-based interactions. This could for example be an automatical correctness check of a calculation that displays the validity beside the task description after completion.

Page-related feedback (PR) elements are fixed in a well-arranged, clear layout position (e.g., page margins) and refer to dynamic interactions with the entire page. Thereby, they are typically not customized for a single task, but rather represent a visual encoding for more global information. Feedback can be of boolean type (e.g., content successfully saved), symbolic or numeric (e.g., average values or number of tasks solved on the page). Page-related feedback can be realized by means of reusable and flexible multi-segment displays.

Book-related feedback (BR) enables visual interaction capabilities beyond a single page and provides even more generic feedback. Therefore, the display must be visible for all pages. This may be done with foldable book flaps or flexible, attachable bookmarks, which provide additional augmented palettes, toolboxes or interactive color swatches. In addition, book-related feedback can also be integrated into a mobile clipboard, which let the display elements shine through paper. This could be especially beneficial for survey applications, which use a large amount of standardized form sheets.

Another important aspect is the side of the paper on which the display elements are printed. Illuminating elements, such as EL displays, can be printed either on the back (in a reverse substrate layer order) or directly on the front page. Back printed illuminations are invisible in a switched off state and shine through when they are turned on. Thereby, all overlaying paper regions can be printed and written on. Display elements that are printed on the front of a page are perceivable in any state, are non-writable and are thereby more present. Color-changing, non-illuminating elements, such as EC displays, must be printed at the front side – or at least the paper layer must be stenciled at this place (see Figure 1, C).

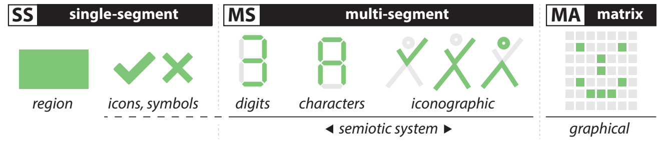

Figure 4. Visual Types: single-segment (SS), multi-segment (MU) and matrix (MA).

How? – Visual Types

In addition, the *visual type* of a segment display plays a central role in the design of integrated visual feedback since it specifies the visual capabilities in a decisive way. Basically, these displays can be classified along the axis of their addressable segments, spatial arrangements and overall page coverage (see Figure 4). Therefore, we group the displays into the categories of *single-segment* (SS), *multi-segment* (MS) as well as *matrix* (MA) arrangements (cf. [46]). Single-segment displays can illuminate a specific action item with an icon or highlight predefined regions, while multi-segment displays are capable of providing more complex semiotic information, including glyphs, digits or even custom sets of iconographic symbols for specific application tasks. Matrix arrangements are basically a minimalist form of pixel addressable displays and facilitate low-resolution graphical information.

Besides the visual appearance (e.g., brightness, color, contour) of a display, *temporal animation pattern* allow for a further design dimension. By turning the segments on and off, it is possible to direct the user's awareness or even decode more complex information based on a frequency modulated blink pattern (e.g., frequency visualizing a time countdown).

When? – Feedback Time

Depending on the current interaction tasks, the provision of visual feedback can be needed before, during or after a user interaction. Therefore, we identify the *feedback time* as an important dimension in the design of paper-integrated visual feedback and propose to differentiate into feedforward, continuous feedback and post-feedback (see Figure 5).

Feedforward (FF) is shown before an action is executed (cf. [64]). An example could be the highlighting of all mandatory fields of a form before the user begins to fill out the fields.

Continuous feedback (CF) is displayed during an action and becomes necessary whenever a user performs a prolonged, continuous action (e.g., follows a path), which requires immediate visual feedback (e.g., for a potential correction).

Post-feedback (PF) is provided after a user action and often visualizes an analyzed state (e.g., rating, validity) of the previous action subsequently. For text input, post-feedback is the only suitable feedback because the interpretation mostly makes sense if the input is already finished.

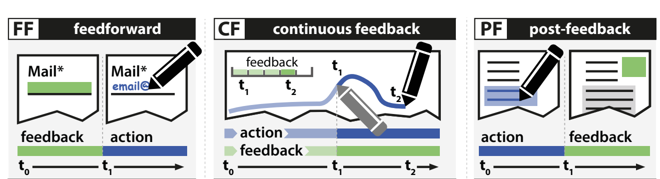

Figure 5. Visual feedback can be provided before (FF), during (CF) and after (PF) an interaction.

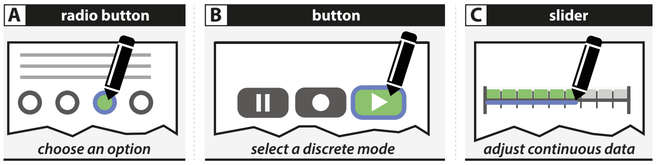

Figure 6. Controls and widget feedback: The active selection is highlighted exclusively (A). Each toggle button can indicate its state actively (B). Sliders provide a segment-based continuous feedback (C).

CONCEPT: FUNDAMENTAL FEEDBACK COMPONENTS

After we have discussed where, how and when feedback can be displayed directly on paper, in this section we describe, which typical interface tasks of PPUIs can benefit from dynamic feedback. We propose five fundamental visual feedback components using paper-integrated illuminations that can serve as basic building blocks for future ILLUMIPAPER applications. A wide range of generic interface components with dynamic feedback is introduced in the following, including paper widgets, validity control, smart requests, layout and motion sequence support.

1. Feedback for Controls and Widgets: Most currently available digitally-enabled notepads provide printed control elements at the header or footer to (de)activate specific functions such as capturing, tagging pages, sharing content or annotating slides [56]. A common problem of this interface design is the lack of clear system feedback that increases the risk of triggering incorrect actions (e.g., tap twice) since the user has no chance to recognize the state. To address this problem, we propose the use of immediate visual feedback for paper controls and widgets communicating the current state. Our visual feedback covers common control elements (see Figure 6) including radio buttons (A), functional buttons (B) and sliders (C). These and similar widgets can be easily used for graphical parameter control in existing digital pen notebook applications.

2. Validity Feedback: In many applications users might be interested in getting immediate (simple) validity feedback of their handwritten entries concerning a specific task (see Figure 7). This could for example be the proper completion of an application form (D) or the correct solution for a math calculation (E), multiple-choice question (F) or even a grid puzzle (see Figure 1, B and Figure 14, B2). Although these examples differ in their form and complexity, the underlying design principle remains the same: User's input in a predefined region is analyzed and compared to the correct answer, which might involve complex analysis algorithms. The result could be either visually decoded with a single segment display indicating (in)valid state or by using two separated or even a multi-segment display, which highlights both states actively. We assume that validity feedback works best when it is positioned in-place or close-by to the content and task at hand.

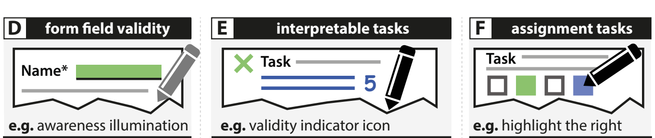

Figure 7. Validity feedback can be used to highlight invalid fields (D) and to visualize the correctness of different answer types (E, F).

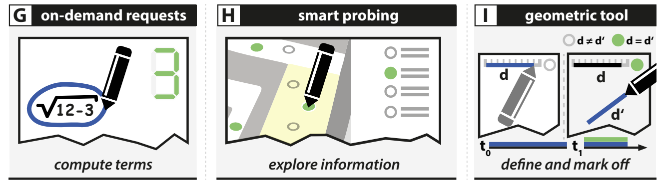

Figure 8. Smart requests comprise rich on-demand feedback (G), probing feedback (H) or even advanced visual tools (I).

3. Smart Request Feedback: To provide a paper tool repertoire including calculators, interactive graphics and rulers, we introduce the concept of smart requests (see Figure 8), which enables powerful paper-integrated analysis and visualization capabilities for a variety of tasks. We propose *on-demand requests* (G), *smart probing* (H) and a *geometric tool* (I) as promising interaction components taking advantage of our approach, creating added value (e.g., avoiding media breaks) and thereby simplifying common workflows.

On-demand requests (G) allow users to get seamlessly associated or even computed information by marking a written expression. For example, it is possible to compute complex, written mathematical terms directly on the paper by simply encircling a term. A paper- or notepad-integrated numeric display will show the results immediately (see also Figure 1, C, above the color widget). Thereby, the workflow will not be interrupted by switching to a calculator requiring to re-enter the whole term.

Smart probing (H) enables the fast perception of information associated with a point or region by using the pen as an exploration tool. For example, the smart probing can help to recognize tube or cable types in a construction drawing by simply moving the pen above. The paper legend key is linked to the associated section and illuminates immediately. Besides these predefined relationships, it is also possible to use the tool for dynamic probing. For example, a mathematical equation just written can be validated by touching the comparison operator with the pen.

Geometric tools (I) provide dynamic measurement capabilities. For example, if a user wants to draw a line with a specific length (e.g., 7 cm) with a digital pen, paper-integrated feedback can help to visualize the distance traveled. The current distance can either be visualized with multi-segment bars that show a linear progress of the achieved distance or with a single icon that uses a blink frequency to indicate the remaining distance. When the user reaches the desired distance, constantly illuminated feedback is provided until the user finishes the action. This feedback component allows to draw true to scale when a ruler is not available.

4. Layout Feedback: In addition to the previous feedback components, we introduce layout feedback (see Figure 9), which supports the user by providing on-demand *rulers* (J), different *grid systems* (K) or predefined design *templates* (L). All auxiliary layout illuminations can be enabled or disabled at any time, e.g., by tapping a paper button with the pen. Although these feedback components are simple and just provide visual guidance, we assume that they can enhance a variety of common tasks, such as writing properly, sketching perspectively, tracing templates or exercising geometry.

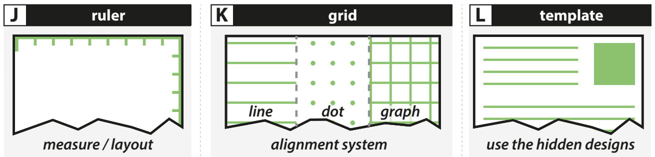

Figure 9. Layout feedback supports measurement & alignment (J), grid-based (K) and even template-based (L) layout tasks.

5. Feedback for Motion Sequences: PPUIs also provide further opportunities to analyze stylus motion patterns. The captured position data enables the comparison of spatial deviations to a given path or a predefined motion pattern concerning the accuracy, precision and speed. Exemplary application scenarios could include the training of handwriting (e.g., learning new characters and symbols) or the strengthening of physical capabilities with respect to dexterity (e.g., to combat a disease or a restricted range of motion). We propose the usage of multi-segment displays, which can visually encode more complex information caused by continuous values sampled during the motion. We devised the three motion feedback principles (see Figure 10) direct motion feedback (M), post motion feedback (N) and dynamic handling instructions (O).

Direct Motion Feedback (M) visually supports a user during her or his motion with regard to correctness. During a motion, we assume the user's awareness to be on the pen and the respective paper region. Multi-segment regions around the predefined path can be used, which illuminate when the user leaves the optimal path. In addition, we suggest to combine pen-integrated vibrotactile or even muscle feedback (cf. [33]) with visual feedback to address more sensory channels.

Post Motion Feedback (N) provides feedback after a motion sequence. Since motion sequences are basically not spatially bound, we propose the usage of page- or book-related semiotic displays, which provide some abstract feedback with regard to the success of the whole motion sequence.

Handling Instructions (O) provide visual feedforward information and can thereby support the user in sketching a path. Based on the current pen position and progress, future pen directions can be indicated. A multi-segment with eight radial navigation arrows can, e.g., display the next direction to take.

Extended Input: So far, we focused on single pen interaction to reduce complexity and gain a better understanding of the visual integration. However, it is possible to extended the input capabilities. In the following, we shortly discuss advanced input modalities that have the potential to work in concert with our introduced techniques.

Multiple pens allow collaborative interaction since most digital pens transmit unique identifiers. This enables user specific visual feedback, which can either support or even create novel applications. Depending on the usage context, for instance, different user roles (e.g., supervisor, student) can enable or limit interactions (e.g., result checking). Therefore, visual feedback can help visualizing this roles and respective interaction capabilities along a set of symbols or colors.

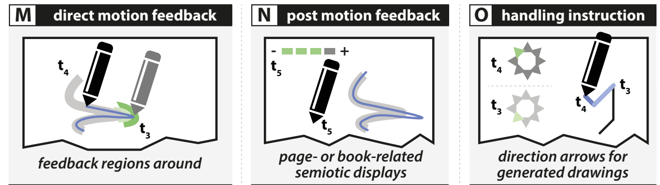

Figure 10. Direct feedback visualizes its validity in-place (M), while motion post-feedback displays the result after an interaction (N). In contrast, handling instructions (O) are used to indicate directions to take.

Another promising input modality is the *direct interaction with the paper itself*, enabled by smart paper-based electronics (cf. related work). As our techniques already require a conductive layer for the illuminating elements, we see a potential to extend the layer with *capacitive* and *resistive sensing* to further enrich the input side. Thus, one could bend a corner to bookmark a page or use touch input in combination with pen input, thereby supporting multimodal interaction.

ILLUMIPAPER PROTOTYPE

In order to apply and evaluate our previously introduced feedback components, we built a fully-functional research platform (see Figure 12, details 1-8). Technically, our setup consists of four components (see Figure 11 for details): A digital stylus (S), different augmented papers (P), a smart controller clip (C) and an Android device (D). We assume that the controller clip and Android application could become superfluous in the long term as a result of further miniaturization towards paper-thin microprocessors. In the following, we briefly describe each component in more detail, and refer for important design decisions to our design goals (G1-G4).

Digtal Stylus: We use an Anoto™-enabled Maxell DP-201 digital pen to stream its stroke and state data via Bluetooth to a server, which in turn forwards the data in the Open Sound Control (OSC) format via WiFi to our mobile device[1] (S►D).

Illuminated Paper: We build on standard paper (design goal G2) onto which we printed an Anoto™ Pattern to enable pen interaction. We also added a printed outline of the controller to indicate the smart clip position. Depending on the actual application (see below), graphical and textual content, e.g., multiple choice questions, are normally printed on top. In addition, we integrated all paper augmenting parts including EL segements (e.g., ✓, ✗), EC seven-segment displays, capacitive touch fields, a resistive paper identifier (Ω) and all necessary traces (≡) at the back. To investigate several designs, we used low-cost rapid prototyping methods (see Figure 13) instead of printing the necessary electronics directly on the paper. Therefore, we realized traces by sketching with a conductive pen [12]. All contacts (•) are strengthened with copper via an electrically conductive adhesive tape to prevent abrasion (Figure 13, C). The thin-film displays are created with off-the-shelf multi-contact EL foils, which we cut in suitable forms and covered each with a custom plotted stencil foil (Figure 13, A). This allows for fast, reliable and flexible design iterations (G3) with materials available to everyone. Already now, advanced fabrication methods (e.g.,

[1] Since Anoto™ introduced the commercial Android Live SDK, pens can be paired directly, which enable even faster mobile setups.

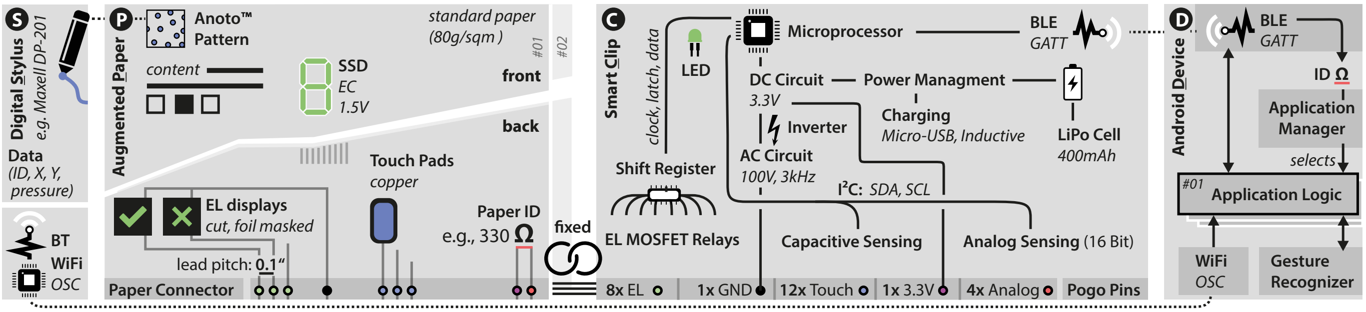

Figure 11. Technical schema: A digital stylus (S), different augmented paper sheets (P), a smart paper controller clip (C) and an Android device (D).

conductive inkjet printing [24] and EL screen-printing [46]) can be used to increase the degree of quality and integration. By completely printing our ILLUMIPAPERS with conductive tracks, illuminating substrates and inkjet content layers, scalability is facilitated and even potential mass-production can be achieved (cf. [53]).

Smart Clip: Our paper attachable controller basically consists of two electrical circuits. A low-voltage DC circuit powers the microprocessor including its associated logic parts, while a high-voltage frequency AC circuit is needed for the EL illumination. A battery provides electric power to both (see Figure 12, 2). The AC voltage is being generated by an inverter. We built in eight solid state relays, addressed by an 8-bit shift register, to switch the EL segments and handle the brief zero crossings (3). In addition, we used the I^2C bus to integrate twelve capacitive sensing channels for touch recognition as an additional modality and added four analog channels to identify paper sheets based on its unique resistance contact (cf. [39]) and to provide resistive sensing (G3). All signal traces are integrated inside a bulldog clip (1) that seamlessly establishes a physical connection (P≡≡C) to the conductive paper layer when it is closed (cf. [10, 21, 26, 22]) and is easy to use (G4). To avoid loose contacts caused by surface irregularities or lateral shifts, we propose the usage of 27 small spring-loaded pogo pins (7) and integrate a sideway limitation to ensure a safe contact and high robustness (G2). Further on, a built-in power management provides versatile charging capabilities (G4) via USB (1) or even with our integrated inductive wireless charging module (8). For data communication, we use the lightweight Generic Attribute Profile (GATT) over Bluetooth Low Energy (BLE). All components are built on breadboards, which are housed in a 3D printed case with a built-in clip mechanism (1, 7).

Android Device: Finally, we built an Android application, which receives digital pen data via OSC (S►D), handles the data for its application scenario and communicates respective state commands to the smart clip via BLE (C◄D). Therefore, we implemented the recognition of simple pen gestures (e.g., tap, hold), realized an intersection detection of predefined regions and integrated Vatavu et al.'s $P Point-Cloud Recognizer [3] to process character- and glyph-based input (G2). Based on a specified unique ohmic resistance (Ω) of each smart paper, our application selects the respective logical mapping for the encoded use case automatically (G3, G4).

Scalability: Our prototype demonstrates a variety of input and output capabilities using a exploratory configuration. However, we also pay attention to customization and scalability for further applications by using clock-driven components (e.g., shift register, I^2C parts) and tiny paper connectors. This allows us, for example, to control much more displays on a page by cascading additional shift registers. Furthermore, our augmented sheets can be taken to a next level by building an all-in-one production pipeline that prints the Anoto™ pattern, conductive and display layers at once.

Further details on the fabrication and additional technical resources are available on our research project website[2].

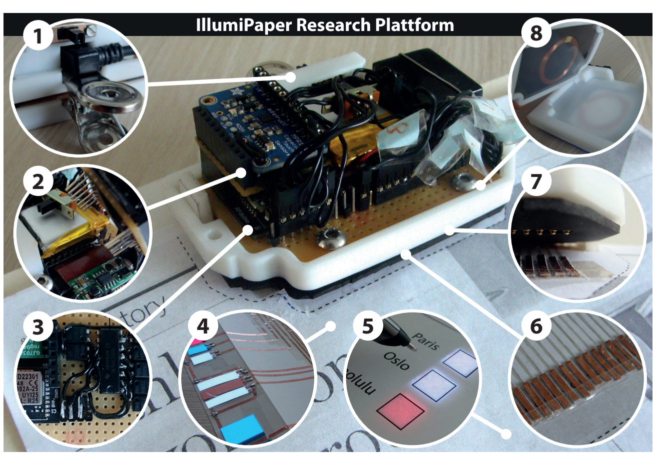

Figure 12. Our ILLUMIPAPER research platform and its components.

APPLICATIONS

In this section, we will illustrate how our ILLUMIPAPER concept and its prototypical realization can be practically applied to personal, educational and even professional daily-life activities. Out of the many possible applications, we describe five implemented real-world scenarios in more detail (see Figure 14, B), which fall into one of the three areas *multiple choice tests* (1), *grid puzzles* (2) and *mathematical applications* (3). These applications have also been used in our hands-on expert interviews. In addition, we provide an outlook to further application scenarios, which we have partly realized. All implemented applications make use of our previously introduced fundamental feedback components and use it in their specific application context.

[2]ILLUMIPAPER research website: https://imld.de/illumipaper/

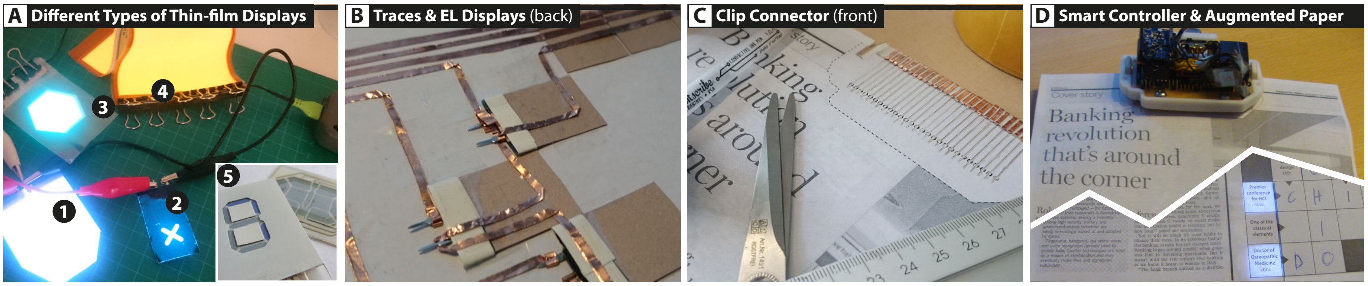

Figure 13. We considered several thin-film display technologies: cut (A1) & stenciled EL foils (A2), printed EL segments [46] (A3), elastomeric ELastoLite Panels® (A4) end printed EC SSDs [67] (A5). Finally, we used cut & stenciled EL foils in fast iterations. To realize paper traces we used combinations of copper (B) as well conductive tape with conductive ink (C). As a result, we came up with a 27 pin connector (C) for our smart clip (D).

Multiple Choice Tests: We implemented two multiple choice tests as a wide-spread method to examine knowledge (see Figure 14, B1). Our main idea was to improve current correction procedures (e.g., with solution templates) and to provide pupils or students with an interactive learning experience. We realized an application where the user can get the results of her answers immediately. For that, we extended traditional multiple choice tests by attaching EL foils at the back of each answer item (see also Figure 13, A1+B)[3]. We chose white colored regions to visualize correct and red ones to communicate incorrect or missing answer fields. The users can get the results either after finishing all questions or whenever a proof button is explicitly triggered. As examples, we chose a more generic geographic test including two questions with three possible answers each and an excerpt of an official driver's license test including two questions combining text and image. To discuss perception and interaction, we realized three variants. Our first variant highlights correct and incorrect fields, our second setting highlights only right answers and the last one illuminates wrong answers exclusively.

Interactive Grid Puzzles: As a second application, we realized a small picture and crossword puzzle with direct illuminated feedback (see Figure 1, B and Figure 14, B2). Such puzzles are not only entertaining, but help improving knowledge and even logical capabilities (e.g., sudoku). They are very popular in educational applications and among hobbyists. By touching the crossword with the digital pen, our ILLUMIPAPER controller is invoked. After a user has correctly solved a row or column, the respective question field illuminates immediately. As an alternative variant, we also implemented on-demand feedback. Thereby, feedback is only shown if the question field was explicitly triggered. For this application type, we see a high potential for classroom assessment techniques that are basically designed for self-study and -control.

Smart Mathematic Paper: In addition, we propose techniques to improve math exercises (see Figure 14, B3). Among them are *on-demand calculations*, *live result checking* and a set of *interactive exam tools* (e.g., time control, interim results, graphical hints, overall ratings) as important and recurring interaction tasks, which have the potential to take advantage of our visual feedback approach. Again, we aim to provide rich paper-integrated digital capabilities while preserving the unique paper properties. Workflows could be simplified, since additional calculators and corrections by supervisors or teachers might be superfluous.

On-demand calculations allow the user to compute complex written terms directly on the paper by simply encircling an expression. A paper- or notepad-integrated printed EC seven-segment displays will preview the results in real-time. Furthermore, it is often necessary to check single conversions in sequence to find a mistake. We propose *live result checking*, which provides instant visual feedback about the correctness of mathematical transformations and simplifications. Holding the pen on a comparison operator indicates its validity, which is visualized by a small green check mark or a red cross at the top of the page. Moreover, it is possible to utilize visual feedback for *interactive exam tools*, which include the visualization of the remaining time, the provision of interim results, the preview of graphical tips for a mathematical approach or an initial rating or grading tendency.

Further Applications: We briefly present two additional applications of interactive *paper forms* and *interactive tool palettes*, which are currently not completely implemented.

Standardized paper forms can be used for many applications, e.g., for medical records, industrial checklists or business purposes. They facilitate a fast and structured data collection and enable a simple as well as machine-friendly processing. Although automated checks can detect validity problems, it is often challenging for the user to fill out forms correctly without any assistance. This is due to the fact that users are unsure whether their input is valid, complete and interpreted correctly. We address this issues by proposing integrated visual feedback in forms and records applications. Based on our seamlessly integrated *validity feedback* components (see Figure 7) it becomes possible to highlight missing or invalid fields and visualize selection states. To highlight points of interest immediately and enable appropriate feedback, we decided to use region or symbolic illuminations, which can basically be positioned in or close-by the form field.

In addition, we propose *interactive tool palettes for educational scenarios* (see Figure 1, C). In this type of application supervisors and teachers comment or correct a text from a pupil or student using digital pen and paper. A foldable paper control column (cf. Figure 3, BR) can help them choosing the right graphical and didactical options. Colored and labeled check boxes or radio buttons can for example be used to define an annotation type (e.g., mistakes in red and comments in

[3] Please note that these tracks can be easily replaced by printed ones.

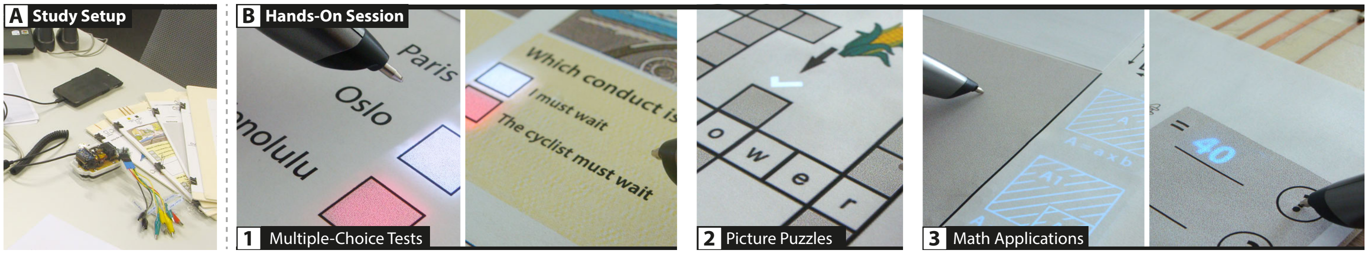

Figure 14. We conducted six expert interviews in our lab (study setup, A). Our hands-on session (B) consisted of five functional application scenarios, which are grouped into the three categories of *multiple choice tests* (1), *picture puzzles* (2) and *mathematical applications* (3).

green). The current selection is visualized with in-place EL feedback in the associated color for the teacher. Every annotation or correction is then stored with its type to be presented later on to the student using a computer system.

EXPERT INTERVIEWS

In order to evaluate our approach, we conducted a series of semi-structured expert interviews to gain a better understanding of how our paper-integrated feedback is assessed from *psychological*, *educational* and *HCI* perspectives.

Participants: We invited six interdisciplinary experts (3 female, 3 male) that split up into two masters in education (research associate + postdoctoral researcher with comprehensive teaching experiences), two psychologists (graduate assistant + postdoctoral researcher) and two HCI experts (research associates), which were recruited from our local university. Our participants are aged between 26 and 50 years (M = 32.83, SD = 8.79) and were unpaid.

Apparatus: To ensure a realistic evaluation in which participants can physically test multiple variants, we built a series of ILLUMIPAPER clipboards that can be used several times and require only the replacement of the paper layer itself. We integrated all display and trace layers into the clipboard and attached exchangeable paper sheets above. The clipboards are connected to our ILLUMIPAPER controller (see prototype section) via quickly exchangeable alligator clips and are controlled by our mobile application (see Figure 14, A).

Tasks & Procedure: Our participants were separately interviewed in a 60 minute hands-on session with five functional application scenarios, which cover a wide range of our proposed feedback components and are grouped into three categories (see Figure 14, B).

First, we demonstrated the digital pen system and introduced our experts to the topic. We pointed out possible inconsistencies between digital and physical properties. In addition, we presented ultra-thin display technologies to provide an overall understanding of our ILLUMIPAPER research platform.

In the main part of our evaluation, participants were asked to test our previously described applications (see Figure 14, B) and to comment on the usefulness, potential and also on possible problems of our paper-integrated feedback approach, including the applicability of features to their own everyday practices. Therefore, we first presented our generic multiple choice test with color-encoded in-place feedback and continued with a more specific application case of a driver's license test (1). Our second scenario was a picture puzzle (2) with symbolic close-by feedback and textual input. In the last category, we asked to solve two simple math applications (3), which support the user with numeric results on-demand or even provide graphical tips for the mathematical approach to solve a simple area calculation. Our experts received visual feedback as described in our feedback components and application sections. In addition, whenever appropriate, we discussed further ideas of our participants by using a contextual wizard-of-Oz simulation based on our mobile debug view that allowed us to switch on all illuminated elements manually.

Measures: To protocol our interview procedures and in-study observations, we made video recordings, kept the inscribed application papers, took notes during the interviews and used an additional secretary, who wrote a detailed record of the whole interview. All interviews were accompanied by questionnaires that include five-point scales (see Figure 15) and also a number of open questions to get qualitative feedback after each application category and at the end.

RESULTS & DISCUSSION

In the following, we provide insights into our promising findings (see Figure 15) and report on lessons we learned.

All experts were able to assess the validity of their multiple choice answers (see Figure 14, B1) with our proposed validity feedback. The experts in psychology felt that our in-place feedback techniques have clear advantages over traditional paper solution templates, which require in general a higher cognitive load to spatially associate and link items. In addition, one educational expert esteemed the capability of archiving interactive papers that could decrease the risk of lost knowledge (e.g., by an uninstalled e-learning application on a tablet) and is thereby beneficial for pupils, who want to look up already learned content. Moreover, we asked the experts to comment on our design. All participants agreed on our proposed solution that answers should be color-encoded (typically, green: correct answer; red: incorrect answer). They also should be displayed simultaneously to avoid any ambiguities, i.e., to highlight correct fields in green (or white) and at the same time wrong or inappropriate fields in red.

The provision of validity feedback for logical grid puzzles (see Figure 14, B2) became the subject of a controversial debate. Some HCI and psychology experts liked the idea to solve the puzzle without any assistance and argue that the design of a grid puzzle is already a suitable feedback mechanism. However, all experts did comment that they advocate the use of this application for educational purposes to support, for instance, children in preschool (see Figure 15, Q3).

In addition, one expert also suggested the illumination of single cells to support the exploration of spelling mistakes.

Our math applications (see Figure 14, B3) were rated by our experts as most useful (Q1) and applicable for education (Q4). However, two participants were frustrated with our interactive help system concerning the specific content of support feedback they received (Q4). The experts proposed more generic tips, similar to an extract of a mathematical table that supports alternative solution paths. In our math puzzle with substitutions, our HCI and educational experts suggested the additional support for touch input to reveal interim results, which our research platform already supports. Our participants commented that they sometimes felt uncomfortable to physically draw on a paper button and prefer touch interactions. Therefore, one HCI expert suggest the use of embossed or surface-treated paper buttons and mentioned as an example non-writable surface coats to support ink-free pen taps and sensory feedback for direct touch interactions in specific interaction regions. Furthermore, our educational experts contributed the idea of adjustable, personalized feedback options that can either be defined by the student or the teacher. Finally, we discussed our math live result checking. Overall, participants liked the technique and assumed that teachers can correct tests more quickly. Our educational experts value the idea of a correction assistant without losing control.

In general, our expert interviews revealed that our approach has been assessed as useful, intuitive and self-descriptive for several applications scenarios (see Figure 15, Q1+Q3). The most positive response received during these sessions was the promising potential for education as well as professional application contexts (Q6). In addition, all experts value the combination of natural paper properties with our integrated illuminations. Overall, participants liked the various interaction techniques that were realized, however, they also raised interesting questions and suggestions that need to be examined in a next iteration of our application cases.

LIMITATIONS AND CHALLENGES

We assume that paper-thin and flexible microprocessors will emerge and further display technologies will be made possible in the near future. However, our current research platform is limited in its form factor (dedicated clip), maximum addressable channels and even in the space-saving design of traces. We assume that next miniaturized and completely printed iterations will support a fully-integrated approach and the application of ILLUMIPAPER in more ubiquitous contexts.

Although the production costs of illuminated papers are much cheaper (cf. [46]) than emerging high-resolution OLED screens, their lifetime is actually shorter. Therefore, we currently recommend the conscious application of illuminated papers by using them for more long-term, recurring or important applications.

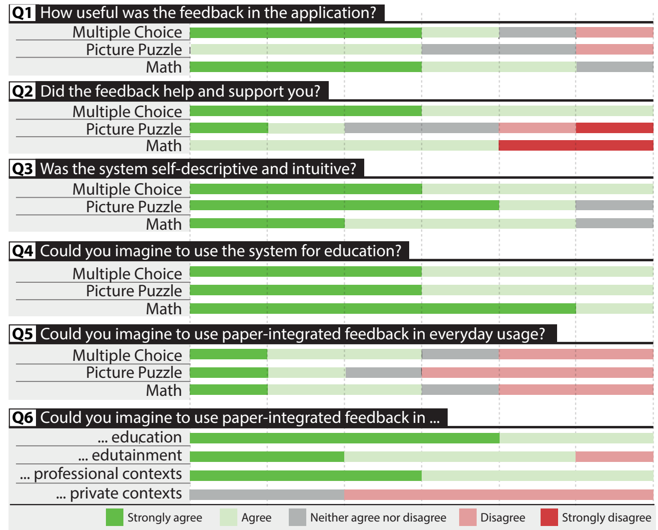

Figure 15. Survey results of questions scored on a five-point scale.

CONCLUSION AND FUTURE WORK

In this paper, we presented the idea of using emerging printed, segment-based display technologies to enhance PPUIs. We classified previous work along their used approaches for paper augmentation and positioned our own idea. As a main contribution, we introduced our concept of ILLUMIPAPER that seamlessly combines pen interactions with paper-integrated visual feedback. We described the essential design axes of position, visual type and feedback time for segment-based visual feedback and proposed a rich set of generic feedback components that address common interaction tasks in PPUIs. Starting from these interaction and feedback components, we have built a comprehensive, technical research platform that supports all of our introduced feedback components. Further on, we have shown the feasibility of our approach with several applications, which we have not only implemented, but also successfully reviewed in six expert interview sessions. Our observations and interviews let us suppose that our concept of ILLUMIPAPER has a sufficient potential to enhance several PPUIs for typical paper-related tasks and can bridge the gap between physical and virtual layers.

For future work, our ILLUMIPAPER system needs to be examined in additional studies, e.g. by comparing it to current on-pen feedback solutions. Furthermore, we would like to improve our existing paper sheets by using more sophisticated fabrication methods [24, 46] and investigate further thin-film technologies such as the integration of OLED segments. In addition, our prototypes need to be further miniaturized and technically extended (e.g., more addressable visual channels) to enhance user acceptance and to support more complex application scenarios. Finally, we plan to extend our set of applications and investigate them in a field study to confirm our promising results in professional application environments.

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