WatchPen: Using Cross-Device Interaction Concepts to Augment Pen-Based Interaction

Michael Hung
University of Calgary
Calgary, AB
myshung@ucalgary.ca

David Ledo
University of Calgary
Calgary, AB
dledomai@ucalgary.ca

Lora Oehlberg
University of Calgary
Calgary, AB
lora.oehlberg@ucalgary.ca

ABSTRACT

Pen-based input is often treated as auxiliary to mobile devices. We posit that cross-device interactions can inspire and extend the design space of pen-based interactions into new, expressive directions. We realize this through *WatchPen*, a smartwatch mounted on a passive, capacitive stylus that: (1) senses the usage context and leverages it for expression (e.g., changing colour), (2) contains tools and parameters within the display, and (3) acts as an on-demand output. As a result, it provides users with a dynamic relationship between inputs and outputs, awareness of current tool selection and parameters, and increased expressive match (e.g., added ability to mimic physical tools, showing clipboard contents). We discuss and reflect upon a series of interaction techniques that demonstrate WatchPen within a drawing application. We highlight the expressive power of leveraging multiple sensing and output capabilities across both the watch-augmented stylus and the tablet surface.

CCS CONCEPTS

Human-centered computing → Graphics input devices; *Pointing devices; Touch screens*

Author Keywords

Cross-Device Interaction; Pen Interaction; Smartwatch; Interaction Techniques

INTRODUCTION

Styluses and pens are used as direct input on digital screens for writing and/or drawing in lieu of a finger. While *passive* styluses conduct a user's natural capacitance (thus functionally acting as a finger), an *active* stylus utilizes onboard electronics to improve precision and expand the richness of interactions (e.g., grip sensing to switch tools [41]). The primary benefit of pen-based interaction is its use as a tool controlled by a precision-grip [31] which provides relatively precise direct input, especially when compared to touch.

MobileHCI '19, October 1–4, 2019, Taipei, Taiwan

ACM ISBN 978-1-4503-6825-4/19/10…$15.00
https://doi.org/10.1145/3338286.3340122

Figure 1. WatchPen is a prototype stylus which has been augmented with a smartwatch, thus providing rich cross-device capabilities to pen-based interaction.

While commercial active styluses typically focus on orientation and pressure sensing (e.g., Apple Pencil), these approaches generally treat styluses as an auxiliary or accessory input device to a mobile interactive surface (e.g., tablet or phone). We believe adding elements of self-contained devices (e.g., watches and phones) makes for an interesting exploration of how we can expand current pen-based interaction. We augment an active stylus by taking inspiration from the space of cross-device interaction. This simple reframing opens the design space of pen-based input to consider a more expressive symbiosis between people and their tablet-based interactions [5]. Thus, we contribute:

1. ***WatchPen, a prototype stylus consisting of a smartwatch attached to a stylus.*** Our prototype, shown in Figure 1, provides pen-based interaction with mobile sensors and continuous outputs, which can be combined to explore new interactions. The watch elevates the status of the pen to a cross-device interaction actor.
2. ***A series of interaction techniques*** that demonstrate the breadth and expressiveness of WatchPen.

WatchPen is a single platform that integrates multiple interaction modalities. The smartwatch's multiple sensors render WatchPen capable of replicating multiple prior work on stylus interaction, recreating existing physical interactions (e.g., airbrush) as well as introducing new ones (e.g., tonal brush). We envision a larger framework categorizing sensors and combinations as an interesting extension for future work.

WATCHPEN: EXPRESSIVE PEN-BASED CROSS-DEVICE INTERACTION

We created WatchPen by attaching a Sony SmartWatch 3 to a passive stylus (Figure 1), similar to past approaches of integrating mobile devices and passive objects to prototype new interactive systems [39, 24, 26]. With a smartwatch, it is possible to envision a stylus with more sensors and outputs available, and easily prototype these interactions. To define WatchPen in the context of cross-device interaction, we frame it within the broader taxonomy of this body of work [5]: (a) temporally *synchronous*; (b) *logical-distribution* configuration; (c) a *single-user (one-to-many)* relationship; (d) with *ad-hoc mobile* dynamics; (e) *near and personal* scale; and (f) in a *co-located* space.

BENEFITS

By using cross-device interaction as inspiration, we benefit from the following:

Awareness of state/parameters. Given the shift towards direct inputs such as touch and pen-based input, it is increasingly difficult to provide awareness to the user of the currently selected tool (e.g., brush), as well as its multiple parameter values (e.g., stroke thickness, hue, saturation, brightness). While this awareness was communicated to some extent in previous cursor-based interfaces simply by modifying the pointing cursor's appearance, it becomes possible for the stylus to communicate its current state and even more nuanced parameter values with an added display.

Dynamic changes of input values as they occur. Pen-based cross-device interaction provides opportunities for input from its many sensors. Changes can be rendered as the drawing is taking place. This tight communication back to the user reinforces the dynamic relationship between the augmented pen and tablet.

Increased expressive leverage and expressive match. Thanks to additional sensing, the stylus has a larger and more nuanced vocabulary of inputs. This can move pen-based interaction beyond traditional menus and open opportunities for interactions that could mimic real-world tools (e.g., an airbrush) or better communicate the effect of an action (e.g., showing copied clipboard contents on the pen's display).

RELATED WORK

We situate the work in this paper as a combination of pen-based interactions and cross-device interaction. This unique combination provides new sensing and output capabilities that can help push the boundaries of tablet interaction.

Pen-Based Interaction

A large body of work in Human-Computer Interaction has investigated the role of pens as input devices since as early as its use as a light-pen (e.g., [43]). In particular, many approaches explore how the digital pen might act more similarly to traditional pens (e.g., [8]), or how its role might be extended, such as through metaphors for colour picking [38], or context sensing to select tools [13, 16, 41] by understanding the user's grip. Indeed, Hinckley et al. reached a sensible design principle for pen-based interactions: *the pen writes, the touch manipulates* [16]. Thus, much of this work considers the relationship between the pen and the actions on the touch device, whether it is a bimanual action (e.g., [34]) or the pen is regripped to use touch input with that same hand [16]. These concepts can work in tandem with our augmented stylus in the same way.

WatchPen attempts to incorporate some elements of realism, such as input behaviour being closer to that of a real airbrush, or showing information about its current state (e.g., when using a coloured pencil one can tell the colour, the thickness of the stroke, etc. from the pencil's nib and shape). Given the present sensors on the smartwatch, it is also possible to replicate many of previous approaches, such as in determining pen orientation [20, 3, 44] and tapping [13] via the accelerometer and magnetometer with the smartwatch's sensors. We explore the use of additional sensors (e.g., microphone) and sensor-output combinations to increase the amount of possible expressions (e.g., colour selection by whistling).

Cross-Device Interaction

The space of cross-device interaction is by now well defined and explored [5]. We see WatchPen as highly related to cross-device interactions where one device is used in an auxiliary fashion, in particular: as a *context sensor*, as a *tool container*, or to provide *on-demand output.*

Device as a Personal Context Sensor

Mobile devices can be used as a means to understand context of use. This is a particularly strong application for smartwatches given their wearable nature. Systems such as Duet [7], WatchConnect [19], and Expressy [47] can tell when the hand with the watch performs actions on another display. In particular, Expressy [47] and Dynamic Duo [35] show that the external device can make live changes to objects of interest such as dynamically changing the size of a paint stroke as the person is drawing. Understanding some rough proximity information can allow actions such as "pouring" contents from one display to another [26], where the proximity can be sensed using magnetometers or simply through direct touch sensing [35]. To some extent, it is also possible to detect coarse pointing [18]. These types of actions also hold in the case of WatchPen given the integrated sensors, although they are now applied in the context of pen-based interactions.

Device as a Tool/Parameter Container

Many systems aim to declutter menus from the main workspace and shift their location towards an auxiliary device. The classic application is in extracting toolbars and tool palettes [2, 6, 7, 9, 19, 35, 45] as a means to distribute the workspace or provide individuals with their own personal tools [6]. This is different from contextual sensing approaches where the modification of tools is an explicit action. Additionally, while successful menu navigation is often measured in efficiency or speed, our focus on successful expressive endeavors require expressive range and adaptability (e.g., [21, 29]). Thus, our goal is to create interactions that can be reinterpreted and applied creatively.

Figure 2. The Airbrush tool mimics the grip and control of a traditional airbrush. (a) A traditional airbrush is shown for comparison against (b) WatchPen acting as an airbrush; (c) shows examples of how the angle and the control of flow via the touch sensor can change the quality of the paint.

Device as On-Demand Output

Mobile devices can also be used to provide on-demand output and augment the contents of another device, often in the form of a magic lens as demonstrated by systems such as Virtual Projection [1]. On-demand output is commonly used in information visualization, such as in work by Horak et al. [18] and Langner et al. [23]. Thus, mobile devices provide additional information without cluttering the workspace.

WatchPen leverages context sensing, as parameters within the tool change implicitly based on the user's action (e.g., the settings of the airbrush). The tool selection itself checks sensor values (e.g., stamp tool by orienting the pen perpendicular to the canvas). In the brush tool, the display acts as an on-demand output implicitly displaying the current tool's particular parameter settings (e.g., hue, saturation). Those settings can be modified either through sensor-based actions (as in colour changing by whistling) or by manually changing the sliders on the touch display.

INTERACTING WITH WATCHPEN

We designed and developed a series of interaction techniques that demonstrate the aforementioned benefits, while also showcasing the breadth of interesting inputs and outputs.

Context Sensing + Multi-Modal Techniques

Tool Selection. Given WatchPen's shape, it is possible to switch between different drawing modalities and tools based on the pen's orientation: regular/tonal brush, airbrush, a stamp, or an eraser. Each tool is activated using different orientations, sometimes with an implicit change in grip. Additionally, a short vibration occurs upon tool selection, providing tactile confirmation of the selection of a tool.

Airbrush. We replicated the level of expressive control found in a double action airbrush (Figure 2a). The artist can control the paint flow by pulling a continuous trigger on the pen's capacitive display – dragging the trigger towards the user increases the paint flow, whereas releasing it will cease the flow (grip shown in Figure 2b). By changing the inclination of the pen, it is possible to change how the paint scatters on the canvas. The colour of the paint is fixed and cannot be changed while the airbrush tool is active (Figure 2c).

Tonal Brush. When holding the pen with a traditional grip, the artist can use sound (e.g., whistling, humming) to change parameters within their brush: the frequency (pitch) controls the hue, while amplitude (volume) controls the thickness of the brush. This can be adjusted while drawing.

Eraser. Tilting the pen so that the display faces down switches to an eraser tool. As the artist erases the contents of the canvas, the watch vibrates. The length and strength of the vibration increases proportionally to the speed of the stylus' movement across the tablet screen while this tool is selected.

Tool/Parameter Containment Techniques

Brush Parameters. To provide awareness to the user, the watch display always shows the current values for the brush parameters (e.g., Figure 1): hue, saturation, brightness, and stroke size. The individual values for each parameter are shown as sliders, while their combination is represented as a circle. We wanted to provide the ability to work with both the implicit manipulation of parameters (as shown in the tonal brush), and explicit actions to adjust the parameter values (i.e. by manipulating the sliders).

On-Demand Output Techniques

Stamp. Holding the device vertically switches the current tool to a stamp (Figure 3). Touching the display with the pen captures a selection into the clipboard and shows it on the pen's display (Figure 3a). The artist can then execute a stamp action and create clones of that selection (Figure 3b). In the current version, switching to another tool clears the selection.

IMPLEMENTATION

The current implementation of WatchPen runs as a client-server architecture (based on Astral [28]). The server is a Surface Pro 4 running a WPF application which also acts as the drawing application. The smartwatch application consists of a Xamarin.Android client which streams all sensor data detected by the watch (e.g., touch events, microphone audio samples, accelerometer values, etc.) to the server via socket communication while also displaying the general interface containing the parameters of the currently selected tool.

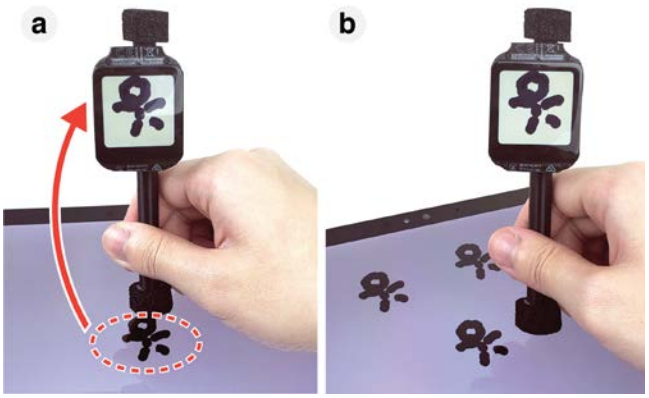

Figure 3. The stamp (a) copies a selection which can then (b) be pasted anywhere on the canvas by performing a stamp action.

To determine the active tool, we simply check whether the accelerometer's XYZ values fall within certain hardcoded thresholds. As for the airbrush tool, to determine the direction in which paint should 'spray', we interpreted magnetometer data from both the stylus and tablet and approximated the relative azimuth angle between them by calculating the difference between their respective detected North directions. From the touch point, we project an elliptical region within which pixels of paint are normally distributed; the shallower the incline, the further the projection; the further the airbrush's 'trigger' is pulled, the faster the ellipse is filled with paint. The ellipse's dimensions change dynamically based on these values.

REFLECTION & DISCUSSION

Thus far, we have demonstrated an instance of our vision of using cross-device interaction to inspire pen input and output via our interaction technique examples prototyped using WatchPen. We next discuss relevant design heuristics from Olsen [33] along with our own critical reflection on the strengths and limitations of our concept, as suggested by previous works in systems research evaluation [5, 27], with care to not fixate on specific implementation details [11].

Importance

For expressive and creative tasks, it is important to provide novel, organic, and flexible interactions as demonstrated by our drawing application examples. As a platform, WatchPen facilitates a range of new pen interactions. WatchPen mitigates workflow interruptions from tool configuration by directly controlling drawing parameters through sensor input. Additionally, WatchPen can display the active tool and parameter status while reducing menus and status displays, optimizing the tablet display.

Generality

While drawing is a clear application for a smartwatch-augmented stylus, we believe there are additional opportunities for WatchPen to apply to other application contexts. Having pen-based display output offers many advantages over traditional stylus interactions. For instance, tablet-based text editors could leverage the watch display to show stylus tools that are currently selected, similar to work by Brudy et al. [6]. Various applications such as text editors or web browsers might show clipboard contents on the WatchPen display, where the augmented stylus is used to perform selections and capture the contents (similar to pick-and-drop [35]). Thus, WatchPen can make the desktop ecosystem more like an annotative tool, as done by InkSeine [17]. The watch display can also act as an augmented hover, showing a magic lens [4] or provide additional detail pertaining to individual touchpoints on the tablet, ideal for information visualization and maps [18]. Additional pen sensor inputs can be used to perform three-dimensional manipulations, where touching the display acts as an explicit way to start manipulating the 3D environment [15]. In spite of the promise in different application domains, there are also potential complications of using the WatchPen, due to the added complexity of multiple sensors and outputs. Hinckley et al. [16] describe the roles of the pen and touch as *"the pen writes, the touch manipulates"*. With WatchPen's additional expressive power and nuance in manipulating objects on tablet devices, this distinction could become obscured and thus confuse people whom may still naturally gravitate to touch-based interactions for manipulation. Relying on multiple sensors and motion-based techniques at once can also lead to false-positives, as well as possible occlusion.

Discoverability

Our system uses the added display to its advantage to show the currently selected tool and parameters, bringing back awareness of state. Indeed, Doucette et al. [9] showed benefits of in-place toolbars. Yet, this approach relies on people's ability to know about possible interactions. Given the numerous sensors present in WatchPen, an end-user might have difficulty discovering interaction possibilities, depending on the extent to which designers communicate it. Similarly, it may not be straightforward to know what orientation triggers which tools. This could be remedied with feedforward and/or feedback from the tablet device.

Inductive Combination

While there are finite permutations of sensors, WatchPen can still produce wildly different interactions. Many previous pen-based interactions can be fairly easily reproduced using specific sensors on the WatchPen (e.g., accelerometer and gyroscope [13, 36, 44, 47], capacitive touchscreen [7, 19]). New dimensions could be added by combining additional sensor inputs (e.g., combining the tonal brush implementation with the airbrush).

Expressive Match

Thanks to the added sensors (e.g., microphone, capacitive touch), we can create interactions that more closely represent the real-world counterparts of these different drawing instruments (e.g., airbrush). The added display provides direct feedback on the state of the currently selected tool, as shown in our stamp technique.

Indeed, there is still room for careful and more novel interface designs – while the sliders serve as a solution to show all the parameters and their values at once they communicate the concept while perhaps not being the most appropriate representation on such a small display. “Fat finger” problems might arise when performing complex or minute touch interactions on the smartwatch screen itself. In the future, WatchPen could leverage previous research into menu navigation and selection [12, 21], rhythmic commands [10, 32] or approaches inspired by bio-acoustic sensing [25].

Scale

Because WatchPen uses the Android ecosystem, interactions with multiple tablet devices are plausible. WatchPen could also easily carry over custom tool configurations (e.g., paintbrushes and swatches for a drawing application) across multiple tablets without convoluted import processes. However, WatchPen is limited in the number of tools that it can represent; for example, a ‘rotary tool’ or an ‘airbrush’ may be indistinguishable from each other based on their sensor signals, even if the hand posture to use those tools differ.

Precision

While the current posture changing is sufficient for prototyping purposes, the technical implementation could be further improved. Users can accidentally trigger tool selection during regular usage because of the naïve usage of IMU sensors. This can be mitigated through two different ways. From a technical perspective, we could use machine learning and other means of recognition. Conceptually, we can enforce an additional explicit quasimodal action, as the ones done in Sensor Synaesthesia [15], for triggering tool selection (e.g., requiring thumb detection on the tablet screen [34]).

FUTURE WORK

There are many potential extensions of WatchPen both as a system and as a concept, which we describe next.

Applications. From a conceptual standpoint, it might be interesting to explore different application areas for WatchPen, such as the ones mentioned in our discussion section.

Interaction Techniques. In terms of our implementation, it would be worth exploring additional sensor and output techniques; for example, using the speaker or adding other physical controls (e.g., rotating the watch on the pen to change the brush size). We can also further improve the current physical model of WatchPen so that it is more comfortable to hold and improve its aesthetics.

Evaluating Usage. By making the prototype more robust, it is possible to investigate how people (e.g., digital artists) use WatchPen over an extended period. This would allow them to provide their impressions without fixating on minor usability. This would allow us to gather focused feedback on their interaction experience with WatchPen.

Authoring Environment. Given the flexibility and power in combination of the sensors in WatchPen, future work includes the development of an authoring tool to map and calibrate the parameters of input sensors to various outputs, allowing users to create their own tools as required.

CONCLUSION

By drawing inspiration from cross-device interaction into pen-based input, we created an augmented stylus with rich inputs and outputs as provided with a smartwatch. Our interaction techniques show interesting potential for pen-based computing: sensing and leveraging contextual information, containing tools/parameters to always show current state, and thus providing relevant on-demand output. Given our exploration, we show the value and expressiveness afforded by enhancing styluses with additional sensors and outputs.

REFERENCES

1. Dominikus Baur, Sebastian Boring, and Steven Feiner. 2012. Virtual projection: exploring optical projection as a metaphor for multi-device interaction. *In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, New York, NY, USA, 1693-1702. DOI: https://doi.org/10.1145/2207676.2208297
2. Xiaojun Bi, Tovi Grossman, Justin Matejka, and George Fitzmaurice. 2011. Magic desk: bringing multi-touch surfaces into desktop work. *In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems.* ACM, New York, NY, USA, 2511-2520. DOI: https://doi.org/10.1145/1978942.1979309
3. Xiaojun Bi, Tomer Moscovich, Gonzalo Ramos, Ravin Balakrishnan, and Ken Hinckley. 2008. An exploration of pen rolling for pen-based interaction*. In Proceedings of the ACM Symposium on User Interface Software and Technology*. ACM, New York, NY, USA, 191-200. DOI: https://doi.org/10.1145/1449715.1449745
4. Eric A. Bier, Maureen C. Stone, Ken Pier, William Buxton, and Tony D. DeRose. 1993. Toolglass and magic lenses: the see-through interface. *In Proceedings of the ACM Conference on Computer Graphics and Interactive Techniques*. ACM, New York, NY, USA, 73-80. DOI: https://doi.org/10.1145/166117.166126
5. Frederik Brudy, Christian Holz, Roman Rädle, Chi-Jui Wu, Steven Houben, Clemens Nylandsted Klokmose, and Nicolai Marquardt. 2019. Cross-Device Taxonomy: Survey, Opportunities and Challenges of Interactions Spanning Across Multiple Devices. *In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, May 4–9, 2019, Glasgow, Scotland UK. ACM, New York, NY, USA. https://doi.org/10.1145/3290605.3300792
6. Frederik Brudy, Steven Houben, Nicolai Marquardt, and Yvonne Rogers. 2016. CurationSpace: Cross-Device Content Curation Using Instrumental Interaction. *In Proceedings of the ACM Conference on Interactive Surfaces and Spaces.* ACM, New York, NY, USA, 159-168. DOI: https://doi.org/10.1145/2992154.2992175

7. Xiang 'Anthony' Chen, Tovi Grossman, Daniel J. Wigdor, and George Fitzmaurice. 2014. Duet: exploring joint interactions on a smart phone and a smart watch. *In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems.* ACM, New York, NY, USA, 159-168. DOI: https://doi.org/10.1145/2556288.2556955

8. Youngjun Cho, Andrea Bianchi, Nicolai Marquardt, and Nadia Bianchi-Berthouze. 2016. RealPen: Providing Realism in Handwriting Tasks on Touch Surfaces using Auditory-Tactile Feedback. *In Proceedings of the ACM Symposium on User Interface Software and Technology*. ACM, New York, NY, USA, 195-205. DOI: https://doi.org/10.1145/2984511.2984550

9. Andre Doucette, Carl Gutwin, and Regan L. Mandryk. 2010. A comparison of techniques for in-place toolbars. *In Proceedings of Graphics Interface*. Canadian Information Processing Society, Toronto, Ont., Canada, 35-38.

10. Emilien Ghomi, Guillaume Faure, Stéphane Huot, Olivier Chapuis, and Michel Beaudouin-Lafon. 2012. Using rhythmic patterns as an input method. *In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, New York, NY, USA, 1253-1262. DOI: https://doi.org/10.1145/2207676.2208579

11. Saul Greenberg and Bill Buxton. 2008. Usability evaluation considered harmful (some of the time). *In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, New York, NY, USA, 111-120. DOI: https://doi.org/10.1145/1357054.1357074

12. François Guimbretiére and Terry Winograd. 2000. FlowMenu: combining command, text, and data entry. *In Proceedings of the ACM Symposium on User Interface Software and Technology.* ACM, New York, NY, USA, 213-216. DOI: http://dx.doi.org/10.1145/354401.354778

13. Ken Hinckley, Xiang 'Anthony' Chen, and Hrvoje Benko. 2013. Motion and context sensing techniques for pen computing. *In Proceedings of Graphics Interface.* Canadian Information Processing Society, Toronto, Ont., Canada, Canada, 71-78.

14. Ken Hinckley, Michel Pahud, Hrvoje Benko, Pourang Irani, François Guimbretière, Marcel Gavriliu, Xiang 'Anthony' Chen, Fabrice Matulic, William Buxton, and Andrew Wilson. 2014. Sensing techniques for tablet+stylus interaction. *In Proceedings of the ACM Symposium on User Interface Software and Technology*. ACM, New York, NY, USA, 605-614. DOI: https://doi.org/10.1145/2642918.2647379

15. Ken Hinckley and Hyunyoung Song. 2011. Sensor synaesthesia: touch in motion, and motion in touch. *In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, New York, NY, USA, 801-810. DOI: https://doi.org/10.1145/1978942.1979059

16. Ken Hinckley, Koji Yatani, Michel Pahud, Nicole Coddington, Jenny Rodenhouse, Andy Wilson, Hrvoje Benko, and Bill Buxton. 2010. Pen + touch = new tools. *In Proceedings of the ACM Symposium on User Interface Software and Technology*. ACM, New York, NY, USA, 27-36. DOI: https://doi.org/10.1145/1866029.1866036

17. Ken Hinckley, Shengdong Zhao, Raman Sarin, Patrick Baudisch, Edward Cutrell, and Michael Shilman, Desney Tan. 2007. InkSeine: *In Situ* search for active note taking. *In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems.* ACM, New York, NY, USA, 251-260. DOI: https://doi.org/10.1145/1240624.1240666

18. Tom Horak, Sriram Karthik Badam, Niklas Elmqvist, and Raimund Dachselt. 2018. When David Meets Goliath: Combining Smartwatches with a Large Vertical Display for Visual Data Exploration. *In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, New York, NY, USA, Paper 19, 13 pages. DOI: https://doi.org/10.1145/3173574.3173593

19. Steven Houben and Nicolai Marquardt. 2015. WatchConnect: A Toolkit for Prototyping Smartwatch-Centric Cross-Device Applications. *In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, New York, NY, USA, 1247-1256. DOI: https://doi.org/10.1145/2702123.2702215

20. Sungjae Hwang, Andrea Bianchi, Myungwook Ahn, and Kwangyun Wohn. 2013. MagPen: magnetically driven pen interactions on and around conventional smartphones. *In Proceedings of the ACM Conference on Human-Computer Interaction with Mobile Devices and Services.* ACM, New York, NY, USA, 412-415. DOI: https://doi.org/10.1145/2493190.2493194

21. Ghita Jalal, Nolwenn Maudet, and Wendy E. Mackay. 2015. Color Portraits: From Color Picking to Interacting with Color. *In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, New York, NY, USA, 4207-4216. DOI: https://doi.org/10.1145/2702123.2702173

22. Benjamin Lafreniere, Carl Gutwin, Andy Cockburn, and Tovi Grossman. 2016. Faster Command Selection on Touchscreen Watches. *In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems.* ACM, New York, NY, USA, 4663-4674. DOI: https://doi.org/10.1145/2858036.2858166

23. Ricardo Langner, Tom Horak, Raimund Dachselt. 2017. VisTiles: Coordinating and Combining Co-located Mobile Devices for Visual Data Exploration. *In IEEE Transactions on Visualization and Computer Graphics*. IEEE: 626-636. DOI: 10.1109/TVCG.2017.2744019

24. Gierad Laput, Eric Brockmeyer, Scott E. Hudson, and Chris Harrison. 2015. Acoustruments: Passive, Acoustically-Driven, Interactive Controls for Handheld Devices. *In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems.* ACM, New York, NY, USA, 2161-2170. DOI: https://doi.org/10.1145/2702123.2702414

25. Gierad Laput, Robert Xiao, and Chris Harrison. 2016. ViBand: High-Fidelity Bio-Acoustic Sensing Using Commodity Smartwatch Accelerometers. *In Proceedings of the ACM Symposium on User Interface Software and Technology*. ACM, New York, NY, USA, 321-333. DOI: https://doi.org/10.1145/2984511.2984582

26. David Ledo, Fraser Anderson, Ryan Schmidt, Lora Oehlberg, Saul Greenberg, and Tovi Grossman. 2017. Pineal: Bringing Passive Objects to Life with Embedded Mobile Devices. *In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, New York, NY, USA, 2583-2593. DOI: https://doi.org/10.1145/3025453.3025652

27. David Ledo, Steven Houben, Jo Vermeulen, Nicolai Marquardt, Lora Oehlberg, and Saul Greenberg. 2018. Evaluation Strategies for HCI Toolkit Research. *In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems.* ACM, New York, NY, USA, Paper 36, 17 pages. DOI: https://doi.org/10.1145/3173574.3173610

28. David Ledo, Jo Vermeulen, Sheelagh Carpendale, Saul Greenberg, Lora Oehlberg, and Sebastian Boring. 2019. Astral: Prototyping Mobile and Smart Object Interactive Behaviours Using Familiar Applications. *In Proceedings of the ACM Conference on Designing Interactive Systems*. ACM, New York, NY, USA. DOI: https://doi.org/10.1145/3322276.3322329

29. Catherine Letondal and Wendy E. Mackay. 2007. The Paperoles Project: An analysis of paper use by music composers. *In Proceedings of CoPADD, the International Workshop on Collaborating Over Paper and Digital Documents*. London, UK. Retrieved from https://hal.archives-ouvertes.fr/hal-01299646

30. David Merrill, Jeevan Kalanithi, and Pattie Maes. 2007. Siftables: towards sensor network user interfaces. *In Proceedings of the ACM Conference on Tangible and Embedded Interaction.* ACM, New York, NY, USA, 75-78. DOI: http://dx.doi.org/10.1145/1226969.1226984

31. John Napier. 1956. The Prehensile Movements of the Human Hand. *The Journal of Bone and Joint Surgery*. British Volume 38.4: 902-913.

32. Ian Oakley, DoYoung Lee, MD. Rasel Islam, and Augusto Esteves. 2015. Beats: Tapping Gestures for Smart Watches. *In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '15)*. ACM, New York, NY, USA, 1237-1246. DOI: https://doi.org/10.1145/2702123.2702226

33. Dan R. Olsen, Jr. 2007. Evaluating user interface systems research. *In Proceedings of the ACM Symposium on User Interface Software and Technology*. ACM, New York, NY, USA, 251-258. DOI: https://doi.org/10.1145/1294211.1294256

34. Ken Pfeuffer, Ken Hinckley, Michel Pahud, and Bill Buxton. 2017. Thumb + Pen Interaction on Tablets. *In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems.* ACM, New York, NY, USA, 3254-3266. DOI: https://doi.org/10.1145/3025453.3025567

35. Tommaso Piazza, Morten Fjeld, Gonzalo Ramos, Asim Evren Yantac, and Shengdong Zhao. 2013. Holy smartphones and tablets, Batman!: mobile interaction's dynamic duo. *In Proceedings of the Asia Pacific Conference on Computer Human Interaction*. ACM, New York, NY, USA, 63-72. DOI: https://doi.org/10.1145/2525194.2525205

36. Jun Rekimoto. 1996. Tilting operations for small screen interfaces. *In Proceedings of the ACM Symposium on User Interface Software and Technology*. ACM, New York, NY, USA, 167-168. DOI: http://dx.doi.org/10.1145/237091.237115

37. Jun Rekimoto. 1997. Pick-and-drop: a direct manipulation technique for multiple computer environments. *In Proceedings of the ACM Symposium on User Interface Software and Technology*. ACM, New York, NY, USA, 31-39. DOI: http://dx.doi.org/10.1145/263407.263505

38. Kimiko Ryokai, Stefan Marti, and Hiroshi Ishii. 2004. I/O brush: drawing with everyday objects as ink. *In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, New York, NY, USA, 303-310. DOI: https://doi.org/10.1145/985692.985731

39. Valkyrie Savage, Colin Chang, and Björn Hartmann. 2013. Sauron: embedded single-camera sensing of printed physical user interfaces. *In Proceedings of the ACM Symposium on User Interface Software and Technology*. ACM, New York, NY, USA, 447-456. DOI: https://doi.org/10.1145/2501988.2501992

40. Dominik Schmidt, Julian Seifert, Enrico Rukzio, and Hans Gellersen. 2012. A cross-device interaction style for mobiles and surfaces. *In Proceedings of the ACM Conference on Designing Interactive Systems*. ACM, New York, NY, USA, 318-327. DOI: https://doi.org/10.1145/2317956.2318005

41. Hyunyoung Song, Hrvoje Benko, Francois Guimbretiere, Shahram Izadi, Xiang Cao, and Ken Hinckley. 2011. Grips and gestures on a multi-touch pen. *In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, New York, NY, USA, 1323-1332. DOI: https://doi.org/10.1145/1978942.1979138

42. Minghui Sun, Xiang Cao, Hyunyoung Song, Shahram Izadi, Hrvoje Benko, Francois Guimbretiere, Xiangshi Ren, and Ken Hinckley. 2011. Enhancing naturalness of pen-and-tablet drawing through context sensing. *In Proceedings of the ACM Conference on Interactive Tabletops and Surfaces.* ACM, New York, NY, USA, 83-86. DOI: https://doi.org/10.1145/2076354.2076371

43. Ivan E. Sutherland. 1964. Sketch pad a man-machine graphical communication system. *In Proceedings of the SHARE Design Automation Workshop*. ACM, New York, NY, USA, 6.329-6.346. DOI: http://dx.doi.org/10.1145/800265.810742

44. Feng Tian, Lishuang Xu, Hongan Wang, Xiaolong Zhang, Yuanyuan Liu, Vidya Setlur, and Guozhong Dai. 2008. Tilt menu: using the 3D orientation information of pen devices to extend the selection capability of pen-based user interfaces. *In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, New York, NY, USA, 1371-1380. DOI: https://doi.org/10.1145/1357054.1357269

45. Tom Van Laerhoven, Geert Vanderhulst, Kris Luyten, Frank Van Reeth and Karin Coninx. 2006. Using Device Federations to Enhance the Creative Process in a Distributed Interaction Environment. Technical Reports TR-UH-EDM-0603, EDM/UH, Diepenbeek, Belgium, 2006.

46. Daniel Vogel and Géry Casiez. 2011. Conté: multimodal input inspired by an artist's crayon. *In Proceedings of the ACM Symposium on User Interface Software and Technology*. ACM, New York, NY, USA, 357-366. DOI: https://doi.org/10.1145/2047196.2047242

47. Gerard Wilkinson, Ahmed Kharrufa, Jonathan Hook, Bradley Pursglove, Gavin Wood, Hendrik Haeuser, Nils Y. Hammerla, Steve Hodges, and Patrick Olivier. 2016. Expressy: Using a Wrist-worn Inertial Measurement Unit to Add Expressiveness to Touch-based Interactions. *In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems.* ACM, New York, NY, USA, 2832-2844. DOI: https://doi.org/10.1145/2858036.2858223

48. Xing-Dong Yang, Edward Mak, David McCallum, Pourang Irani, Xiang Cao, and Shahram Izadi. 2010. LensMouse: augmenting the mouse with an interactive touch display. *In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, New York, NY, USA, 2431-2440. DOI: https://doi.org/10.1145/1753326.1753695