Tilt-Responsive Techniques for Digital Drawing Boards

Hugo Romat[1,2], Christopher Collins[1,3], Nathalie Riche[1],
Michel Pahud[1], Christian Holz[1,2], Adam Riddle[1], Bill Buxton[1], and Ken Hinckley[1]
[1] Microsoft, Redmond, WA, United States <nath, mpahud, bibuxton, kenh>@microsoft.com
[2] ETH Zurich, Zurich, Switzerland, hugo.romat@gmail.com & christian.holz@inf.ethz.ch
[3] Ontario Tech University, Oshawa, Canada, christopher.collins@ontariotechu.ca

ABSTRACT

Drawing boards offer a self-stable work surface that is continuously adjustable. On digital displays, such as the Microsoft Surface Studio, these properties open up a class of techniques that sense and respond to tilt adjustments. Each display posture—whether angled high, low, or somewhere in-between—affords some activities, but not others. Because what is appropriate also depends on the application and task, we explore a range of app-specific transitions between reading vs. writing (annotation), public vs. personal, shared person-space vs. task-space, and other nuances of input and feedback, contingent on display angle. Continuous responses provide interactive transitions tailored to each use-case. We show how a variety of knowledge work scenarios can use sensed display adjustments to drive context-appropriate transitions, as well as technical software details of how to best realize these concepts. A preliminary remote user study suggests that techniques must balance effort required to adjust tilt, versus the potential benefits of a sensed transition.

Author Keywords

adjustable tilt display; posture; drafting table; micro-mobility

CSS Concepts

• Human-centered computing~Interaction techniques

INTRODUCTION

Display orientation—whether slightly inclined, vertical, or a diagonal posture in-between—strongly shapes people's behavior and expectations. A vertical monitor affords reading a document, but not writing on it with a stylus. Angled drafting tables in a design studio allow close engagement with one's ideas. But a vertically-oriented screen is better suited to present refined ideas to others. The problem is that no fixed display angle is best across all activities. It depends on the task and situation. This motivates techniques that sense and respond to display orientation, potentially improving interaction with adjustable displays, while offering new insights into tilt-responsive techniques.

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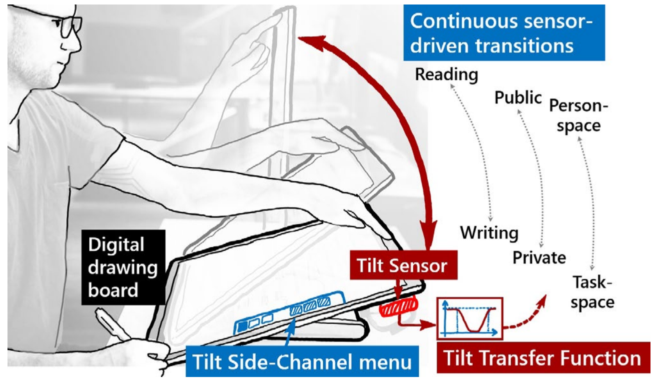

Figure 1. Tilting a digital drawing board from vertical to a low-angle posture transforms the current app's user experience via continuous, interactive, sensor-driven transitions.

We focus on *digital drawing boards* (Figure 1), which offer *continuously adjustable* and *self-stable* displays that hold their position when released. While well-suited for digital artists, we explore a range of applications because quick manual adjustments of display angle may benefit knowledge workers in general, e.g. for annotation [1, 64, 104], or for social flexibility via re-orientation [60]. The Samsung Space Monitor [57], Wacom Cintiq 22HD [97], and Surface Studio [100] offer recent examples of tilting screens—as do adjustable stands for tablets, such as the "floating cantilever" of the Apple Magic Keyboard [3], among others [22, 80]. Yet, none of these devices offer a user experience that senses and responds to shifting display angles—a lost opportunity to respond appropriately to the context-of-use, and thereby shift the burden of adapting the inputs, tools, modes, and UI layout from the user to the system.

To address this problem and explore a range of scenarios, we sense display postures and the continuous transitions in-between. Our approach is a pragmatic one. We require no "new" technology, beyond a tilt sensor and suitable software. But this simple idea opens up a rich new design space, where we contribute a range of context-appropriate transitions for knowledge-work applications, as well as technical software details on how to most effectively realize these concepts.

Specifically, we outfit a 27" Surface Studio (adjustable from 20-95°) with an off-the-shelf tilt sensor. This augments the Studio's existing input modalities, which include direct touch, pen, and an embedded front-facing camera. We then demonstrate various tilt-responsive interactions in a prototype window manager shell that hosts multiple experiences. These include transitions between shared task-and person-space in telepresence [15], reading vs. writing (handwritten annotations) [1], authoring vs. presenting, and other changes in an application's task focus based on display angle (e.g. Figure 2). Each scenario shows how continuously adjustable, self-stable, pen + touch digital drawing boards could sense and respond to transitions in display posture.

These transitions can involve input devices, tools and modes, or the layout of the interface. For example, in our telepresence scenario, as the display tilts we fade out the camera feed to let the user avoid unbecoming video angles. This also selectively focuses the remote audience's attention on a shared document, rather than the video-feed—in effect, a remote version of micro-mobility behaviors such as angling a paper document towards a collaborator [60].

We also contribute two techniques that extend the expressiveness of tilt responses. First, at motion onset, a *Tilt Side-Channel* menu fades in icons for generic actions, such as clutching, that can coexist with app-specific mappings of tilt. Second, a *Tilt Transfer Function* allows precise (relative, variable gain) tilt within a fixed (absolute, 20-95°) range of movement. This hybrid absolute/relative mapping [27] manipulates the device footprint (the motor space of physical movement [51]) to afford both small- and large-scale inputs.

Our application scenarios inhabit a continuum between *explicit* foreground interactions that directly use tilt as an input, versus *implicit* background sensing techniques [11, 52] that automatically adapt interface behaviors during natural display adjustments. Initial feedback suggests that users especially value implicit techniques that focus on occasional (not frequent/repetitive) use cases, and that strike a balance between the effort required to adjust display tilt, versus the potential benefits resulting from the transition. This balance is particularly favorable in situations where the user's task naturally prompts a shift in display orientation, such as angling the screen down to afford writing on it.

RELATED WORK

Previous work shows many ways that the orientation of a display—whether tablet, hand-held, electronic whiteboard, or tabletop—cues social norms and sets expectations of use. A continuously adjustable, self-stable digital drawing board can leverage such properties to support hybrid use-cases [63] and proxemic transitions [32, 56] via sensing techniques.

The Social Role of "Physical Artefacts"

The design of technology has proxemic consequences [56]. In social theory, *proxemics* concerns how people space their bodies to afford communication [31, 38]. But documents, physical artifacts, or displays are often at the center of such focused encounters [53]. People re-orient these objects to allow shared visibility, partial viewing, or even concealment. For example, a doctor might hold a medical record "close to the vest" at first, but then orient it towards the patient when ready to direct attention to particular areas of concern. This is known as *micro-mobility* of *physical artefacts* [60]. Beyond visibility of information, micro-mobility serves as a non-verbal and tacitly understood social cue, such as the ways in which people re-orient devices between public, semi-public, and personal roles [30]. These cues allow people to share physical *space* in nuanced ways, using artifacts to create a socially constructed *place* [40] in real-time as the task, activity, context, and mood demand [38].

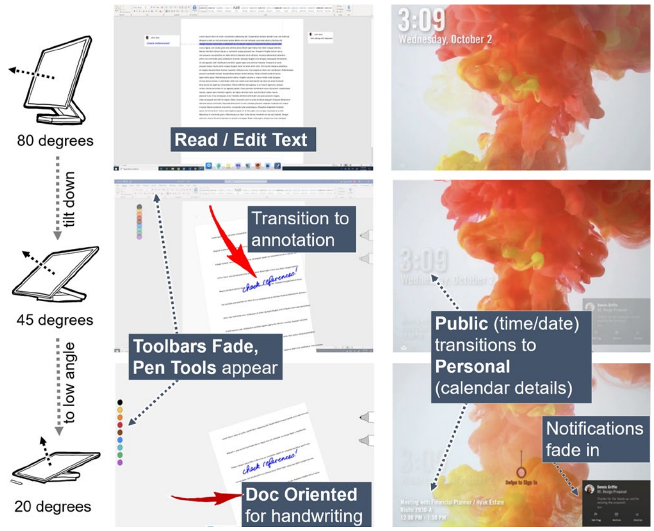

Figure 2. ***Left:*** **The Document app shifts from Reading to Writing annotations, based on posture.** ***Right:*** **At sign-in, the Lock Screen transitions from Public to more Personal views.**

Manually adjustable drawing boards offer a middle ground between easily moveable physical artefacts [60], and slowly actuated, furniture-like *semi-fixed features* [38] of a building or location. An angled drafting table, for example, reflects the collaborative norms of a design studio, whereas a vertical monitor breaks these social mores [13]. Such design properties invite certain actions, but implicitly discourage or signal the social inappropriateness of others [19, 40, 56]. And while actuation allows some degree of proxemic flexibility for large displays, in our experience (e.g. with a Surface Hub 2 on a Salamander stand [78]) this burdens users with indirect controls and a socially awkward delay while slewing to a new orientation. We thus focus on non-actuated displays.

Fixed Angle and Adjustable-Tilt Displays

Several early systems explore fixed-angle displays. The Memex [9] used a 45° display. ClearBoard [48, 49] is angled 35-45°, maintaining eye-contact with a collaborator while also showing natural hand gestures in reference to a shared whiteboard. The ActiveDesk drafting table [13] offers a pen for sketching, plus hand input [12]; it later supported several tilt positions [14], but didn't sense this angle or adapt the UI. Display orientation has been shown to influence touch input performance [69, 101, 103], the ergonomics of using a device [63, 88, 102], and other aspects of task activity. For example, a vertical display suits text entry, and reading electronic texts; yet users prefer low-angled surfaces for pen annotation, with higher prevalence of bimanual input [63].

The FLUX [59] pen + touch large display has a mechanical locking mechanism for adjusting between three stop angles for tabletop, drafting table, and whiteboard modes. The system senses these via an embedded accelerometer, and rotates displayed images, but does not demonstrate other UI adaptations. In Tilting Table [58], visual and audio outputs respond to the degree of tilt. ConnecTables [94] detect device proximity, and have adjustable display height and angle. But they do not sense or respond to display tilt/motion itself.

Sun et al. [89] explore sketching techniques based on orientation of a desktop display tablet. Tablet tilt between 0-90° moves between three discrete drawing layers, while tilting towards oneself reveals a private note space. Several of our techniques instead focus on *implicit* background-sensing techniques [11, 42, 52] that adapt the interface as the user works from different device postures [44, 105], while probing user experiences across a variety of scenarios.

Hybrid Devices and Proxemic Transitions

Curve [103], BendDesk [101], and Tilted Tabletops [65] explore workbenches with two displays in complementary orientations. Grønbæk et al. [32] explore an actuated hinged tabletop, emphasizing *proxemic transitions* that shift social expectations and opportunities for collaboration [56]. In the Agora [61] telepresence system, a horizontal display hosts a shared document in *Task Space*, while a vertical display shows the face-to-face video feed of *Person Space* [15]. While effective, such solutions require a large workspace with multiple displays; we instead explore sensing tilt as a natural way to automatically transition between Task Space and Person Space on a single adjustable display.

Interactions Driven by Mobile Device Tilting

Much previous work focuses on tilt for mobiles (e.g. [4, 39, 73]). TimeTilt [77] uses a "lenticular effect" to reveal layers, plus jerking to delimit tilting gestures. Our work instead transitions between contexts based on display angle, while using the onset of motion as an out-of-band signal to fade in our *Tilt Side-Channel* menu. Waggle [82] explores a software clutch mechanism, and applications such as direct 3D map viewing via tilting. We use our Tilt Side-Channel to reveal thumb-activated options (including a clutch) while tilting through a similar 3D map, among other app scenarios.

One crucial distinction is that mobile devices constantly move when carried. But digital drawing boards hold their orientation (self-stable). Hence, techniques that respond to a particular absolute orientation as an implicit background cue for context [11, 52] could work well on digital drawing boards, but may be less well suited to unsupported mobiles.

Counterbalanced and Self-Stable Displays

The Wacom Cintiq [97] and Samsung Space Monitor [57]—as well as the Apple Magic Keyboard [3], DraftTable [22], and Satechi [80] tablet stands—offer recent examples of tilting displays. The "poseable" iMac G4 [21] flat-panel provides self-stable (but not sensed) adjustability in 2D. Examples that are continuously tracked in 3D include the Boom Chameleon [95], palm-top VR on an articulated arm [25], and the actuated Hover Pad [86]. Our work instead emphasizes sensed transitions between application states.

We use a manually adjustable Surface Studio pen + touch display, plus an external sensor for tilt. The display is not actuated, but a light touch quickly and easily moves the screen; four-bar linkages generate sufficient internal friction & torque to stabilize and counterbalance the display [100]. The display adjusts from vertical (95°) down to a minimum 20° tilt. This gives the display a distinct preferred orientation, so it does not afford tabletop-like experiences [83]; in the future, a fully horizontal mode would be valuable to explore.

Summary of Related Work

While much previous work explores tilt and motion sensing, there are few examples of interaction techniques that take advantage of orientation changes on continuously adjustable tilt displays. Furthermore, because such an interaction surface is self-stable, both absolute and relative mappings of orientation become feasible. This fosters design choices that diverge from mobile techniques—and that lead to a novel design space especially well-suited to digital drawing boards.

DESIGN SPACE OF DIGITAL DRAWING BOARDS

The following table (Figure 3) situates our work in relation to many of the devices and techniques discussed above. The rows consist of three main categories, with terminology co-opted from social theory. At the high end of the mobility scale we have full *micro-mobility* [60]. Next come *semi-fixed features* [38] that are only partially moveable or adjustable. Finally, we consider immobile *fixed features*, such as bulky furniture, that have angled but non-adjustable displays.

			1dof tilt / angle	**2dof** poseable	**3+dof** spatial
Full Micro-Mobility	Sensed	Discrt.	TimeTilt [77] app layers Codex [44]		Storeboard planes [41]
		Contin.	Waggle [82] Tilt me! [39] Tilt scrolling [4, 42]	Waggle [82] Tilt to share [62] Throw and Tilt [18]	Tilting operations [73] TabletInVR [90] Foldable3D [8]
Semi-Fixed Feature: self-stable & adjustable	Sensed	Discrt.	FLUX [59] Drawing layers at 30 / 45 / 90° [89] **THIS**		
		Contin.	**PAPER**	TiltingTable [58]	PalmTop VR fig 9 [25] Boom Chameleon [95]
		actuated	ImmersaDesk2 [17, 79] Salamander [78] Proxemic Transitions [32]		HoverPad [86] Shape-changing displays (e.g. [50, 66, 71, 91]
	Not sensed	Discrt.	ActiveDesk: Arnott version [14] DraftTable stand [22]		
		Contin.	Wacom [97], Samsung [57], Satechi [80] ConnecTables [94] Surface Studio [100]	iMac G4 poseable display [21]	Fully articulated monitor arms
			1-Display Tilted fixed tilt angle	**2-Display Workbenches** fixed-angle Horizontal + Vertical displays	
Fixed: non-adjustable		0°	tabletops (e.g. [20, 83])	Agora [61] (Horizontal task/document space + Vertical person-space displays)	
		12°	metaDesk [96]		
		30°	ActiveDesk [12], Bricks [26]		
		35°	ClearBoard-2 [49]	Tilted tabletops fig 4 [65] (low-angled + high-angled displays)	
		45°	ClearBoard [48], ImmersaDesk [17]		
		75°		Curve Desk [103] (Horizontal + 75° Vertical)	
		90°	wall displays ([23, 37])	BendDesk [101] (Horizontal + 90° Vertical)	

Figure 3. Design space of oriented displays, organized by social aspects of mobility (main rows) by number of dof's (columns).

Across these categories, only a subset of previous work considers interactions where display orientation is *sensed*. Otherwise, angle is *not sensed* by the device or technique.

For micro-mobile and semi-fixed devices, interaction techniques can interpret display orientation in a *discrete* or *continuous* manner. However, there are few examples of interaction techniques for semi-fixed displays with a sensed tilt angle, particularly in the continuous category. Our work contributes a rich set of application experiences that explore a range of discrete and continuous mappings for tilt.

In the design space's columns, we consider the degrees-of-freedom (dof) of movement possible. Despite the simplicity of focusing on a single degree-of-freedom, our work reveals a range of interesting tilt-responsive app scenarios with novel interactions in this portion of the design space. This hints at classes of similar techniques for 2-dof and/or multi-dof displays (e.g. mounted on armatures). Meanwhile, the commercial availability of suitable 1-dof adjustable digital drawing boards, which can easily be augmented with off-the-shelf sensors, offers a pragmatic choice for our present work.

IMPLEMENTATION

Our system consists of a prototype window manager and shell. It probes the role of display orientation across various task scenarios for tilt-responsive digital drawing boards.

Hardware

Our system runs on a Surface Studio 2. Applying a light but intentional force smoothly pivots the display to a new angle. The display holds its angle when released. There is no manual lock or motors. Four-bar linkages within the hinge mechanism produce the friction and torque necessary to counterbalance the display [100], making it self-stable.

To sense display angle, we currently use the inertial motion sensors of a wearable device (Microsoft Band) affixed to the back of the display, and streamed to the host via Bluetooth. The Surface Studio does not currently include a tilt sensor, presumably because suitable experiences that sense display posture (and the nuanced transitions in-between) are lacking. We thus probe a range of plausible techniques in this space.

Software

A C# module samples the sensors and implements signal conditioning, including our *Tilt Transfer Function*. Samples (at 62.5Hz) transmit via UDP to a Node.js webserver, which forwards to a web client through web socket. The client is a JavaScript web application that uses the React framework. We implement multi-layer rendering for handling input, annotations, and application content. On top, a transparent SVG layer captures touch, pen, mouse, and keyboard, with app content and various UI controls below.

The experience starts with a tilt-responsive Lock Screen, with each app accessible after swipe-up. The user can tap on the App Bar at the bottom of the screen (Figure 4), or a window in our Desktop View, to switch app scenarios. The user can then Sign Out from our prototype window manager when finished with their session.

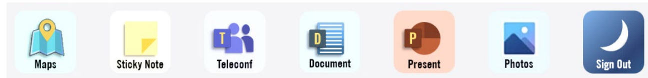

Figure 4. The App Bar (at bottom center of screen) lets users tap to switch between various task scenarios in our prototype.

TiltVideoPlayer

We prototyped and partially implemented several of our user experiences by playing back video files interactively, proportional to tilt. That is, the current angle indicates which frame of the video to display, allowing interactive non-sequential access, forward or backwards, as the user adjusts the display. We found this powerful as a rapid prototyping vehicle, because any quick screen recording or video mock-up could be used to quickly try out ideas, reflect-in-action [81] on working prototypes, and pilot-test various interactive responses to tilt. This also allowed us to use stock time-lapse videos in our experiences, with UI elements rendered on top.

Because currently available web video players do not support randomly accessing a video frame out of sequence, we implemented our own video player. This segments a video into individual frames that we then display on a Canvas.

Tilt Transfer Function—Hybrid Absolute / Relative Control

Considered as an input device, a tilt sensor returns an absolute angle. Many of our techniques respond to large-scale transitions in this absolute value. After all, the affordances (or social signals) communicated by a display depend on the user's perception of absolute orientation—whether low-angled, vertical, or some diagonal in-between.

But for a continuous response to exhibit stability, precision, and nuanced control, small tilt motions must have controllable effects. This implies a variable gain factor—movements within a few degrees are magnified, so the user can make fine adjustments. As Jellinek & Card [51] observe, gain does not change performance, but does optimize device footprint—the physical range over which a device moves. Hence the hybrid absolute/relative nature of our Tilt Transfer Function allows response to both small-scale and large-scale tilting motions. This wouldn't be possible with a fixed gain across the full 75° footprint of tilt between the Studio's fixed limits of motion (20-95°). In effect, our resulting transfer function is an automatic transmission for tilt.

To realize this, we revisit high-precision touchscreen input techniques of Sears et al. [84, 85], and adapt them to stabilize tilt. In particular, we divide the motor space of changes in tilt into A, B, and C regions which apply a deadband, relative control, and absolute control, respectively (Figure 5).

The input mapping works as follows. From an initial resting center, the sensed tilt angle moves away. Within a region A close to this center, a deadband is applied, so the resulting (virtual) angle used by applications does not change. As the screen tilts into region B, a proportional gain yields enhanced control. But if the screen tilts further away into region C, the virtual tilt angle re-centers by jumping to the absolute tilt angle. The A/B/C regions also recenter whenever the virtual tilt angle remains in region B while the display is motionless (i.e. the change in tilt falls below a critical time-motion threshold). See Figure 6 for pseudocode.

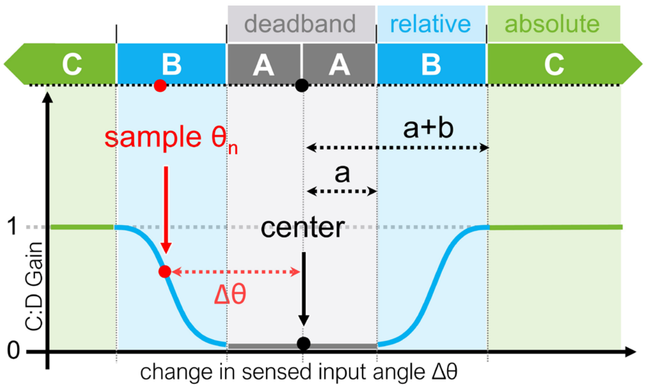

Figure 5. Our Tilt Transfer Function uses deadband, relative, and absolute control regions depending on change in angle Δθ.

```
// Time-weighted pre-filtering of raw (absolute) tilt sample
ω = 0.7; // weighting factor for past samples
θn = Absolute_Tilt_Sensor_Sample();          //current raw sensor value
θn = ω * θn-1 + (1.0 – ω) * Tn;              // time-weighted pre-filter

a = 0.7; b=5.0; // width of A and B regions; C region is > (a + b)

// θ is absolute tilt angle, S(θ) is stabilized virtual tilt
Δθ = θn – center;

S(θ)n = {
   if |Δθ| < a     : S(θ)n-1;                // A: deadband, don't move

   if |Δθ| < (a+b): ƒ(S(θ)n-1, Δθ);          // B: relative, variable gain
                    if (moving==false)       // < time-motion threshold?
                        center = S(θ)n;      // recenter to relative tilt

   if |Δθ| ≥ (a+b): θn;                      // C: absolute mode
                    center = θn;             // jump center to abs. tilt
}
// Function ƒ returns value between 0 and 1 with ease in / ease out
// based on proportion of distance (a+b) that Δθ represents.
define ƒ(S(θ)n-1, Δθ) {
   return S(θ)n-1 + ease_in_ease_out(Δθ / (a+b), a+b);
}
```

Figure 6. Pseudocode for Tilt Transfer Function, with smooth transition from relative to absolute control as the screen tilts further and further away from its initial resting center position.

Animated Transitions with Hysteresis

Many of our scenarios explore interface transitions when the screen tilts from near-vertical to a low angle, or vice versa. Unless noted otherwise these transitions happen near 45 degrees. Once an animated transition begins, it continues until completion. Furthermore, we implement these transitions with several degrees of forgiveness (hysteresis) so that the system will not chatter between two states, for example, due to sensor noise or mechanical wobble. Furthermore, stopping a tilt adjustment "in the middle" does not lead to ambiguous states; indeed, with the continuous mappings we use for some scenarios, the intermediate states are often interesting and lend richness to the experiences.

APP SCENARIOS AND INTERACTION TECHNIQUES

Figure 7 summarizes the role of display orientation across our app scenarios, input modalities, and interaction techniques. Our goal was to explore both *continuous* and *discrete* mappings of *sensed* tilt for *self-stable & adjustable* digital drawing boards, per the design space of Figure 3. We also wanted to probe how tilt adjustment could respond to a range of use-cases that people might encounter on a day-to-day basis. The resulting experiences demonstrate a variety of roles that orientation can play, as well as how input modalities might change their behavior with display angle.

App Scenario / Technique	Role of Display Orientation		
	Low Angle	***transition***	**High Angle**
Lock Screen (sign in/out)	**Private / Detail**	*Interactive time-lapse; Fade in / fade out details*	**Public / Holistic**
Desktop View	**Freeform**	*Animate between layouts*	**Organized**
Document	**Writing** (handwritten annotations)	*Show pen tools vs. toolbar Call-outs vs. in-line notes Adapt orient. & line spacing*	**Reading** or Editing Text
Teleconf	**Task Space**	*Zoom to task/person space Fade in/out camera view*	**Person Space**
Map	**Overhead View**	*Continuous perspective based on angle*	**Skyline View**
Sticky-Notes	**Messy / Personal**	*Show/hide personal content*	**Tidy / Public**
Presentation	**Authoring**	*Slide-sorter vs. single slide Pen writes vs. spotlights*	**Presenting**
Live Photos	**Start**	*Continuous interactive browsing through timeline*	**End**
ROLE OF INPUT DEVICES AND MODALITIES			
Pen	**Handwrite / Sketch**	***Partially Available*** *ergonomics limits pen input*	**Spotlight**
Touch	**Bimanual** pen+touch	***Partially Available*** *suitable for intermittent use*	**Unimanual** touch or pen
Mouse	**Available**	***Available***	**Available**
Mechanical Keyboard	**Not Available**	***Partially Available*** *display takes up desk space*	**Available**
Camera (front-facing)	**Not Useful** aimed up	***Partially Useful*** *camera view aimed off-kilter*	**Useful** aimed at user
SYSTEM-WIDE INTERACTION TECHNIQUES			
Tilt Transfer Function	*Hybrid absolute / relative mapping for tilt*		
Tilt Side-Channel	*Options appear for thumb input at onset of tilt; fades away slowly when screen motionless*		

Figure 7. Role of display orientation across app scenarios, input devices, and modalities. System-wide interaction techniques extend the expressiveness of tilt across all scenarios.

Lock Screen—Personal vs. Public, Hedonic vs. Utilitarian

Our prototype launches to a "lock screen," displaying a time-lapse video of colorful ink clouds in water (Figure 2, right). As the user tilts the device, we show individual video frames, forward or time-reversed, according to the current tilt. This serves both hedonic and utilitarian purposes [47].

On the utilitarian side, the display shows only time/date when vertical—holistic information suitable for this public display posture. As the user starts to tilt the screen down, the time/date slides down with the colorful ink clouds and starts to fade away. Then as the screen reaches a low angle, this reveals detailed private information such as notifications, and specifics of one's next meeting. Tilting the display back up, to vertical, reverses this sequence and starts to fade out personal details while the time/date rise back up, along with the time-lapse video of the colorful ink clouds.

But we also had hedonic design values in mind—the demo is fun to play with. We hoped this would reward the user for making small adjustments to tilt, eliciting a sense of delight that might foster a greater sense of personal attachment to their "digital possession" [5, 67, 68]. We also speculated that this might help reveal the concept, likely unfamiliar, that the display responds to tilt. Immediate, real-time sensor feedback of this sort has been shown to help users discover force-sensitive inputs [29], for example. But, with test users unable to actually try out this technique due to COVID-19, these design values remain hypothetical at present.

Desktop View—Freeform vs. Organized

The Desktop View (see our accompanying video) serves as a workspace and window manager. Here, a low angle offers a Freeform layout where users can employ multi-touch to directly manipulate windows in an overlapping and unconstrained manner—much like the arrangement of work-in-progress in a "spatial holding pattern" [54] on a physical desk. These windows include blank canvases ("scraps of paper") for capturing fleeting thoughts [74] with a digital pen. Tapping on a window switches to that experience.

Tilting up, to vertical, transitions to an Organized view, which animates windows to a Swiss-grid-like arrangement, with non-overlapping windows. Since touch is less convenient in this posture, and non-overlapping windows may not fit on a single screen, the user can employ the mouse wheel to scrub through this organized view of all windows. Tilting the screen back down, to a low angle, recalls the freeform arrangement, animating the windows back to their previous locations. This allows users to easily transition between personally meaningful informal arrangements [2, 55, 75] and more structured views of their current windows.

Document App—Reading vs. Writing (Annotation)

The Document App (Figure 8 & Figure 2, left) supports fluid transitions between the reading vs. writing tasks typical of active reading [1, 63, 87]. In particular, the user can *read and edit text* with the display in the canonical vertical "desktop" orientation. Tilting down then lets the user *handwrite or annotate* with ink, directly on their document, from a convenient display posture. Not only do the ergonomics differ, but also the features required to support each activity. To support this transition, and to better support the r*ead / edit* vs. *handwrite / annotate* subtasks of "active reading," the Document App makes multiple accommodations:

Pen tools vs. Toolbar. When annotating the document, the standard toolbar at the top of the window disappears. Tools geared towards pen-based annotation then fade in along the edges of the window (Figure 8, left), which affords bimanual thumb + pen interaction to switch pen modes [28, 70, 98].

Line Spacing. To make more room for ink-based mark-up, the line spacing expands when transitioning to a low angle for annotation. The user can pan the current page via touch to access any text pushed off-screen by this expansion. This is a sensor-mediated way to create space, unlike related gesture-based techniques such as TextTearing [104].

Document Orientation. People naturally orient a page with the nonpreferred hand while handwriting [36], but the optimal orientation for reading differs from that for writing [88], especially for left-handed users [35]. Hence, at the low-angled display posture, users can manipulate the document with the nonpreferred hand, via multi-touch, to rotate the page to their preferred writing angle. But when going vertical, the document rotates back to the canonical (non-rotated) reading orientation. Tilting back down again re-orients the page to the user's preferred writing angle.

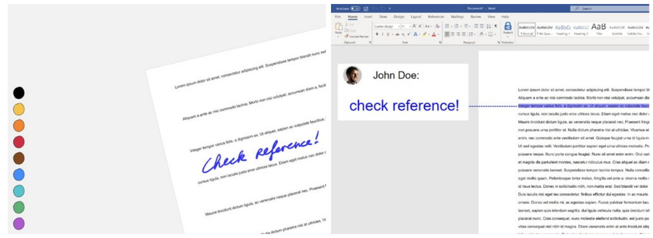

Figure 8. Document App details. *Left:* The low-angled posture affords handwritten annotation. *Right:* Tilting up to the vertical posture transitions to reading and editing. Here, the text is canonically aligned and spaced, standard toolbars return, and comment boxes in the margin call out annotations.

Call-out vs. In-line: In the vertical posture, we automatically call out in-line handwritten notes (made in the low-angled posture) as comments that appear in the margin of the formatted text document. By default, the call-out displays the original ink, but users can select a check-box to optionally convert hand-written notes to recognized text (Figure 8).

Changes in Modality: Pen, Touch, Bimanual Input. The role of input modalities also changes. When vertical, the mouse and keyboard edit text; but touch is only suitable for infrequent, single-handed (unimanual) taps. By contrast, a low angle affords handwriting and annotation via the pen, and bimanual input via multi-touch [63]. Yet as the screen tilts down, it slides out, covering the desk real-estate where the keyboard normally resides—making it inaccessible.

Teleconf App—Person Space vs. Task Space

Commercially available telepresence applications support both Person Space and Task Space [15], yet typically this involves a heavyweight mode entered via a command such as *Share Screen* or *Share Document*. But the problem is that this transition requires cognitive and attentional resources that distract the user from their demanding foreground task: human-human communication.

For example, Agora [61] places the "talking head" of Person Space on a vertical display, while the Task Space (shared document) appears on a horizontal display. But this requires a specific multi-display set-up, and is socially ambiguous as to which of the two spaces a participant should attend to.

Embody Person vs. Task Space via Tilt. Our Teleconf App (Figure 9, left) explores a solution that uses the display tilt to transition between Person Space and Task Space. When vertical, the display emphasizes Person Space. Tilting down then transitions to Task Space, where the user can mark-up a shared document or whiteboard. This embodies the two spaces in a direct physical motion, allowing users to switch between Person vs. Task Space in a way that minimizes disruption to the conversation itself.

Avoid Unbecoming Video Angles. This technique serves a second purpose. For mark-up of shared documents, users want to use the pen—and a low screen angle. But as they tilt the screen away from vertical, the front-facing camera moves off-kilter with it. Users then find themselves streaming an unbecoming camera angle to their audience. Hence, as the camera moves off-kilter, our technique starts to fade out the camera feed—and completely hides it before the user tilts the screen all the way to the low-angled posture for mark-up.

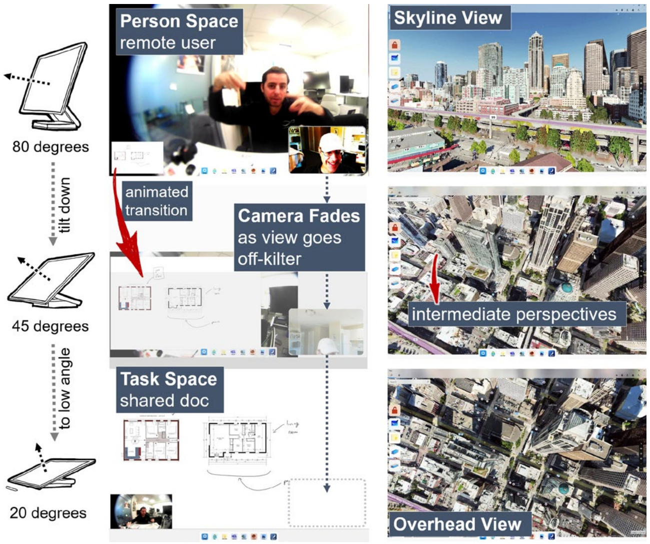

Figure 9. ***Left:*** **The Teleconf App transitions between Person Space (for face-to-face video) and Task Space (for mark-up of shared content, at a low screen angle).** ***Right:*** **Maps transitions between Skyline (vertical) and Overhead (low-angle) views.**

Focus the Remote Audience's Attention in the Right Place. As the user tilts the screen away from vertical, our technique also expands the shared document (or a blank shared whiteboard) to fill most of the screen. This lets the user adjust the screen tilt to dynamically steer the focus of a remote audience's attention onto their mark-up of the shared document, or back to the face-to-face conversation, as the topic and situation require. Thus, this technique may offer a compelling remote manifestation of the *micro-mobility of physical artefacts* [60] observed in co-located collaboration.

Maps App—Skyline vs. Overhead View

The Maps application (Figure 9, right) uses tilt to control a perspective view of a city. At vertical, the screen shows the Skyline, as if looking through the screen onto a miniature cityscape. As the user tilts down, the view of the city rotates, until reaching an Overhead View. The perspective shift stops about 5° short of the lowest tilt angle, after which tilting further gradually reveals icons for local points-of-interest.

We do not claim the Maps app as especially novel. Past work has shown closely related experiences [18, 58, 82]. But it showcases our Tilt Transfer Function well and also illustrates how *continuous* tilt control fits in with our other techniques. Furthermore, during large hands-on demos of an early version of this experience, we found it drew participants to the tilt display—and when actually trying it, they seemed to find the tight coupling of tilt and perspective compelling.

Sticky-Notes App—Messy / Personal vs. Tidy / Public

The Sticky-Notes app (Figure 10, left) provides a space for handwritten information-scraps [6] where, in the low-angled posture, the user can jot notes on yellow, blue, and orange stickies. These can be left lying around the screen, like a messy desk. In this scenario, the color of the stickies designate a few categories, with orange for personal info.

Your Boss Barges In. If a boss or co-worker barges in, you can angle the display vertical. This automatically tidies up this information-scrap space, and hides personal information, making the display more suitable for public or semi-public viewing by others. The orange, more personal, stickies quickly fade away while the yellow and blue stickies animate to a small and tidy thumbnail view, sorted by color. The user can later tilt the display back to revert to the "messy" layout.

Asymmetric Transitions? In this scenario, the Personal-to-Public transition triggers automatically. But its reverse—a Public-to-Personal transition where private information could be made visible to others—perhaps should not. We did not implement this or other asymmetric transitions, but this theme would be interesting to explore in future work.

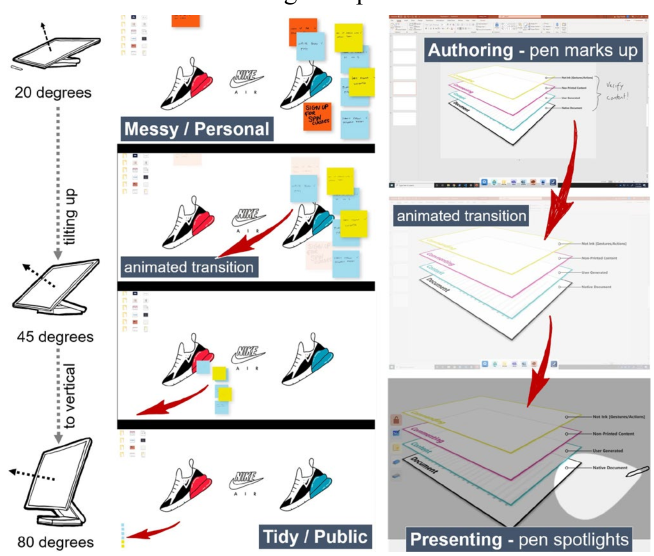

Figure 10. ***Left:*** **Sticky-Notes hide Messy, Personal information by automatically switching to a Tidy, Public view when the user tilts the screen up—such as when one's boss walks in.** ***Right:*** **The Presentation app shifts roles when the screen goes vertical, from Authoring to Presenting, where the pen acts as a spotlight.**

Presentation App—Authoring vs. Presenting

The Presentation App (Figure 10, right) provides an example where the intended use of the software—authoring or presenting—can shift with the display orientation.

The Social Mores of a Transition to Vertical. If the user is in the slide-sorter view, authoring or marking-up slides, they can tilt up to vertical. Per the social mores of a vertical display, this transitions to presenting the slides, e.g. in the context of a small-group setting.

From Mark-Up to Spotlight. At a low angle, when Authoring, the user can employ the pen to make private notes or mark corrections directly on the slides. These marks disappear when the screen angles up for presenting, and the unmarked slide expands to fill the display. In this presentation view, swipe gestures flip through the slides via direct touch. The pen also changes roles, acting as a spotlight to call out details or otherwise direct a colleague's attention to particular portions of the slide. The user can point the pen in different directions to cast the spotlight on the desired area of the screen, proportional to the pen tip's angle and pressure. The spotlight effect fades out quickly when the user moves the pen away from the screen.

Malleability and Flexibility via Clutching. By tapping the Clutch icon (via the Tilt Side-Channel, detailed below), The user can Clutch the display to freeze it and freely adjust the screen without triggering any transitions in role or view. This leaves users in control if they want to drive a presentation from the low angle, author while the screen is vertical, or anything in between. This reflects design sensitivities of Malleability and Flexibility [32, 33] articulated by recent work. Here, we use clutching to allow users to override tilt sensing based on their particular needs, task, or social situation. Note that the UI remains stable when the user releases the clutch—it does **not** snap into a new state until the user again adjusts the screen to a different posture.

Live Photos App—Continuous Navigation through Time

Modern devices capture short video sequences with every photo. Our Live Photos app explores a continuous mapping of tilt as a way to enliven these photos, letting users browse this extra dimension of time in an embodied manner. Unlike the standard tap-and-hold technique, which can only play video snippets forward in time, here one can tilt the display forward-back, forward-back, to seesaw playfully through time. The merit of this whimsical interaction is embodied and hedonic, rather than some utilitarian notion of "efficiency."

Via our Tilt Transfer Function, fine motions can key in even on a single specific frame of these short video clips. In our accompanying video, which shows children hand-feeding some friendly birds, this allows the user to dial in on a single "lucky shot" frame of the video where the bird can be seen perched on the child's hand, with wings extended.

Live Photos currently only implements tilt control, but as a practical matter standard controls, such as swipe or scrub touch gestures, would be desirable to add for high-frequency actions. If tilting were necessary for all video browsing and control, for example, we expect it would quickly become tedious rather than an *occasional* playful interaction.

Sign-Off—Fade Personal Details to Black

The Sign Off experience transitions to a different version of the *Lock Screen* experience discussed earlier, but for Sign-Off we show a time-lapse of conifers rustled by the wind as a starry night sky rises above them. And again, as the user tilts their screen vertical, personal details fade while a prominent display of the time/date rises in the night sky along with the Pleiades star cluster. See the conclusion of our accompanying video for an illustration of this experience.

Tilt Side-Channel—System-Wide Menu via Motion Onset

To support a few generic tilt-responsive actions that can span all of our application scenarios, we devised a technique to multiplex tilt for app-specific vs. system-wide uses.

The Tilt Side-Channel (Figure 11) is a novel mechanism that uses the onset of display motion to surface command options. These appear as icons along the side of the screen, suitable for thumb input with the non-preferred hand [70, 98]. Since users typically grip the bezel to adjust the display angle anyway, it offers a convenient spot to reveal commands via motion—for the user to confirm, if desired, by touch [46].

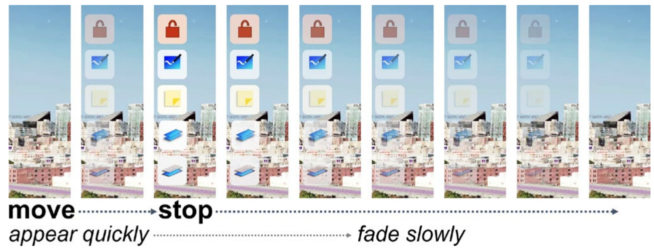

Figure 11. Time sequence for the Tilt Side-Channel technique, which appears at the edge of the screen to allow thumb input. The icons *appear quickly* at motion onset. They then *fade slowly* when motion stops. Touching an icon activates it, even if fading.

The Tilt Side-Channel responds to relative motion, rather than absolute angle. As such, there is no "gesture" associated with the Tilt Side-Channel *per se*. By design, we allow any significant motion to surface it. This makes it easy to bring up. If the user does intend to use it, it appears quickly, and the user can then tap the desired option with their thumb.

But if the user has no intention of using the Side-Channel, or adjusted tilt for other reasons—which could be considered a form of false-positive activation—then once the display stops moving, the Side-Channel simply disappears. It slowly fades away, withdrawing from attention. This makes the "cost" of appearance low (even if unintentional), with no further action required to dismiss. These design choices allow the Tilt Side-Channel to coexist with our other applications, despite their varied uses of tilt.

In particular, the Side-Channel starts fading in—with a 500ms animation to full opacity—at the onset of motion (defined as an adjustment exceeding 20°). When motion halts (staying within ±2° for 3 seconds), the Side-Channel fades out slowly with a 3s animation. Even if the Side-Channel has started to fade away, touching any icon returns the menu to full visibility, where it remains as long as the Clutch (or other commands) are engaged. This gives the user a grace period of at least 6.5 seconds (500ms fade-in + 3s of no motion + 3s fade-out) to engage the Side-Channel.

Example Tilt Side-Channel Commands

Side-Channel commands include Clutching as well as invoking a general-purpose Annotation Layer. Other icons are for additional, currently experimental, features such as ink strokes associated with specific tilt angles.

Clutching. Tapping on the Clutch turns off tilt response. This freezes the current screen, as indicated by the lock icon closing and turning bright red. The clutch stays on until the user taps this icon again to unlock. This gives the user full control and flexibility to override application responses to tilt sensing, as desired, for ergonomic or other reasons. As mentioned earlier, unlocking the clutch doesn't snap to a new state; the UI only updates when the user again re-adjusts tilt.

Annotation Layer. This creates a vellum-like transparent layer over the screen, and can be used in combination with the Clutch. For example, the user can clutch, tilt down to a comfortable angle for handwriting, and then invoke the Annotation Layer on the still-frozen screen to mark it up.

REMOTE SURVEY AND INTERVIEW

Given social distancing requirements of the Rona Pandemic, we could not conduct in-person studies. Nor was it feasible to deploy our custom tilt-responsive digital drawing board remotely for people to try our user experiences hands-on.

Instead, we conducted a remote survey of 12 people who currently own a Microsoft Surface Studio, self-selected via a recruitment message sent to a mailing list of designers. The survey focused on prevalence and context of screen angle adjustments; 58% of respondents self-reported they adjust their screen daily or more frequently, 17% occasionally, and another 25% only rarely—but with 0% responding "never."

We then recruited 5 of these participants—selected to give us a diverse sample based on their survey responses—for in-depth interviews. The interviewer showed participants the accompanying video of our techniques (with narration off), and gathered participants' impressions and feedback on each scenario illustrated. Several themes became apparent:

The most compelling experiences leverage *implicit tilting*

Participants gravitated to our *Document* and *Teleconf* apps as the most compelling experiences. Both of these scenarios evoke situations where users would already implicitly adjust their screen angle, typically driven by use of the pen to mark-up content. Techniques that respond to tilt to automate certain options or settings on behalf of the user in such situations offer a potential benefit "for free" during a display angle adjustment that the user needed to make anyway.

Teleconf App. For example, in the context of a *Task Space vs. Person Space* transition—from face-to-face video to a shared document—P3 stated that during their experiences with status quo interfaces, "*we stumble to it [the shared whiteboard].*" Hence, for P3, automating this transition would be "*something really positive. Quickly able to share whatever you are drawing.*" P4 also remarked that "*I usually draw on some document or image. And I put the screen back up to copy paste to email or presentation. [The Teleconf app] could automate something for me.*"

Participants made many positive comments about disabling the camera when tilted or horizontal. In addition to removing unbecoming video angles, P5 articulated the benefit of focusing the remote audience on content: "*It does two good things: on the video front, it makes it clear to people on 1:1 that I want you to listen to me and not be distracted and look at the screen content. And in tilted mode it gives a clear signal to focus on the content and what is going to happen with my pen. A physical notification almost.*" This echoes our hoped-for role for tilt in *remote* micro-mobility [60].

Document App. Our *Reading vs. Writing* transition offers a better writing angle and more space for handwritten annotations, but also implicitly leverages the tilt adjustment necessary for pen use. Participants especially valued these enhancements to the digital inking experience, e.g. P5, "*As a user I'm forced to use my pen on what was made for mouse and keyboard.[…] It's hard for me today, everything feels too tiny.*" As another example, P1 commented that they perceived tilting as less effortful to automatically call-out comments, and recognize handwritten ink as text, versus navigating the many UI commands and options typical of current practice in productivity apps.

Perceived Effort. Participants mentioned similar difficulties with current telework user interfaces to find whiteboards (P3) and document sharing (P1) during video calls. This suggests that when the UI responds appropriately, implicit uses of tilt can also lower the perceived effort to access certain program functionality—even though tilting the screen likely takes more time (but perhaps *less attention*) than tapping an on-screen button or clicking through a menu. Users perceive locating a button as an extra step that can be eliminated by doing the right thing, automatically, in the course of a natural display adjustment.

Experiences must dovetail with user's existing practices

We received mixed responses to our Lock Screen and Presentation app experiences. Responses were only positive if the experience dovetailed with a user's existing practices:

Lock Screen. For example, heavy pen users often go directly to a low tilt angle when starting a session. For such users, tilting down to move through the lock screen "*would put me in a state that is more conducive to pen input. That is interesting*" (P1). This experience also offers *"a more personal focused mode, it would be helpful to me"* (P5). But for users who typically put the screen vertical, the Lock Screen as shown in the accompanying video did not suit their needs; to address this, the "Swipe to Sign In" prompt should also appear when the user adjusts their screen upwards.

Presentation App. The *Authoring vs. Presenting* transition, and the change in role of the pen, elicited positive reactions from participants who sometimes present to other people using their Studio. For example, P5 explained the need to focus individuals coming into their office on specific parts of the screen, where using the pen as a spotlight would drive attention: "*I always think about this. What should I be focusing on. I would use the flashlight a lot*" (P5). However, for a user who never makes such informal presentations in their office, automatically switching to presentation mode when tilting vertical would not be useful: "*For me, it is still the same work, down or up does not change*" (P2).

Desktop View, and One Size May Not Fit All. We garnered similar reactions to the *Freeform vs. Organized* transition of the Desktop View—the "desktop cleanup" was appealing to some but "the window organization stuff" received a lukewarm response from others. These observations suggest that one size may not fit all for these particular tilt-responsive experiences. What is compelling to some users may not be to others, depending on how well it fits their natural workflow. This suggests that selectively enabling some tilt features, or surfacing them as suggestions on tilt motion (in a manner that could perhaps be integrated with our Tilt Side-Channel), may be interesting directions to pursue in future design iterations.

Design tradeoffs of tilt as an explicit control mode

A number of our experiences, including the Maps and Live Photos Apps, required explicit tilting. Here, tilt input acts as a continuous, intentional control. These experiences contrast sharply with implicit tilting, where screen adjustment serves some other human-centered task or ergonomic need. It was difficult to remotely assess these explicit uses of tilt because participants could only watch—not actually engage hands-on with these demos. The contrasting reactions of people who tried an early version of our Maps scenarios during hands-on demonstrations—versus the mixed reactions of our remote participants who could only watched this experience on video—hints that much of the potential value of such techniques arises from the embodied nature of interaction.

For Hedonic Design Qualities. For example, participants noted the entertaining aspect of experiences such as Maps ("*It's cool and I like it but I don't know if I would use it often,*" P5). Reactions to the Lock Screen's colorful ink clouds playing in sync with tilt (*"it could be nice for people who spent a lot of money to have a magical thing*," P2) also resonated with the hedonic design intent of this experience.

For Utilitarian Design Qualities. When considered as a control mode—that is, as an efficient and utilitarian means to an end—participant's reactions to explicit tilting were divided. For example, if tilt were the only way to change the Maps view, or scrub through the short video sequences in the Live Photos app, P3 commented "*You do it and you are delighted by it, but in practice you may just do it regularly and hit a button.*" (P3). Clearly, if the interface requires frequent and repetitive tilting for explicit control, that could be problematic. Explicit continuous mappings might also interfere with ergonomic considerations: as P2 stated, "*I change the screen because my physical body hurts not because I want to see that content differently.*"

Overall Summary of User Reactions

While our inability to test these techniques in hands-on fashion at present limits the conclusions we can draw, our remote interview study with current Surface Studio owners strongly suggests that such techniques can be compelling. In particular, the Teleconf and Document apps both manage to co-opt implicit tilting motions to automatically refine the user interface. And both do so along multiple dimensions, serving both practical issues with the devices and technology (such as off-kilter camera angles) as well as human considerations, such as steering attention alternatively to a shared document, or back to face-to-face videoconferencing. Yet, the merit of some other concepts we explored is less clear, and hints that some degree of personalization (or surfacing certain transitions as suggestions rather than automatically-enacted changes in state) may be desirable.

DISCUSSION

Here, we reflect on a few higher-level design considerations of the scenarios and techniques we implemented, as well as various limitations inherent in our work so far.

Meta-Level Design Considerations

Dualities from the Literature. Many of our specific designs are motivated by dualities of knowledge work in the literature. In active reading [1, 63, 87]—often translated into practice via multi-display [7, 34, 44] and pen interfaces [45, 74, 88]—these dualities include reading/writing, freeform/ organized, and detail/overview. The CSCW literature raises further dualities such as public/personal, solo/collaborative, semi-fixed/mobile, and person-space/task-space [15, 30, 60, 61]. As well, we draw from the input devices literature [10, 16, 43] to reason about absolute/relative, continuous/ discrete, and other properties of tilt as an input channel.

Cost/Benefit. As noted earlier, transitioning a user interface in response to sensed context can have costs as well as benefits. Here, the cost might be several seconds of manual effort to tilt the display to a new orientation. The possible benefit is the elimination of extra steps, mode-switches, or rearranging the UI layout to suit the new screen orientation.

Manual Effort vs. Attention/Cognition. Pure time-motion efficiency offers one potential benefit, but maintaining cognitive focus on a task, or visual attention on a social exchange, may be more important considerations for users. Our most successful techniques, such as bringing task-space to the fore in our Teleconf app, offer significant such benefits while overlapping much of the time-motion cost with a tilting motion that the user needed to make anyway.

Stimulus-Response Compatibility. In our explorations, we noticed prototypes that "feel natural" usually provide a strong vertical component of optical flow, thus maintaining stimulus-response compatibility [24] with the up/down axis of tilt. But the direction of movement also appears to depend on whether the user adopts a *camera-in-hand* or *scene-in-hand* mental model [99]. At times, either can work: Maps and Live Photos still feel natural if the polarity of motion is reversed—an issue of design convention not unlike scrolling interfaces, which use either viewport-in-hand (with indirect scroll bars), or document-in-hand (with direct touch [72]).

Limitations

Specific Design Properties. Our work leverages digital drawing boards with 1-dof, continuously adjustable, self-stable displays. But Surface Studio lacks other properties: it is not poseable in 2D, nor can it flip past vertical for face-to-face consultation [76]; and it can't tilt below 20°, precluding horizontal collaboration. Further work is needed to explore, adapt, and extend tilt-responsive techniques to devices that offer these and other, perhaps subtly different properties.

Display Posture vs. Body Posture. Our techniques make the pragmatic choice to sense only the tilt of the display. But what about the people around it? To support richer notions of public/private, solo/collaborative, and various nuances in-between, we would need to sense the presence and proxemic relationship of persons nearby. Much might be gained, as well, by conditioning interface transitions on various sensed aspects of the user's body posture (e.g. sitting vs. standing; leaning in vs. leaning back; looking towards or looking away from the display; or even simple head motion parallax). This suggests an interesting space of sensing techniques that explore and reconcile further aspects of "posture" [105].

Other Limitations. Our work still leaves many questions unaddressed. For example, our Lock Screen's interactive time-lapse of colorful ink clouds provides playful, real-time sensor feedback that might help to reveal the concept of tilt responsiveness, but it remains unclear how users can discover and understand varied roles of device orientation in multiple applications. Further, our system currently lacks mechanisms to override, customize, or adjust the sensitivity of tilt responses. Does the infrequent nature of display adjustments mean that standard controls must also be provided for high-frequency actions? Should transitions first appear as semi-automatic, mixed initiative suggestions? What sort of sensed transitions might benefit the specific workflows of domain experts, such as data analysts or digital artists? These interesting questions are left to future work.

CONCLUSION AND FUTURE WORK

Our exploration of tilt-responsive interactions across a variety of user scenarios for digital drawing boards reveals an intriguing class of techniques that sense and react to dynamic tilt adjustment. Along the way, we have contributed designs, techniques, and system-wide interactions that help to get the most out of tilt as a sensor and input modality.

Yet much remains to be explored. For example, we would like to devise lab or field studies that can more fully unpack the cost-benefit tradeoffs inherent in automatic or semi-automatic responses to tilt (and other sensors). Unpacking more deeply the human cognitive, perceptual, attentional, and sensorimotor aspects inherent in such transitions could improve existing designs, or open up new possibilities.

From a technology standpoint, our work could clearly be extended to other form-factors beyond digital drafting tables. Exploring other form-factors, possibly even ones with subtly different properties, could deepen our understanding of designing such techniques. This also hints that similar but heretofore overlooked design spaces of sensor-responsive techniques may exist for other specialized classes of devices. These could include motorized stands [17, 78, 79], shape-shifting displays [32, 92, 93], or foldables [8, 44], to enumerate just a few of the many exciting possibilities.

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