Interstices: Sustained Spatial Relationships between Hands and Surfaces Reveal Anticipated Action

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ABSTRACT

Our observations of landscape architecture students revealed a new phenomenon—interstices. Their bimanual interactions with a pen and touch surface involved various sustained hand gestures, interleaved between their regular commands. Positioning of the non-preferred hand indicates anticipated actions, including: sustained hovering near the surface; pulled back but still floating above the surface; and resting in their laps. We ran a second study with 14 landscape architect students which confirmed our observations, and uncovered a new interstice i.e. stabilizing the preferred hand while handwriting. We conclude with directions for future research and challenges for designers and researchers.

CCS CONCEPTS

• **Human-centered computing** → *Empirical studies in HCI*;

KEYWORDS

Bimanual interaction, pen and touch, hover gestures

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1 INTRODUCTION

Recent commercial pen and touch devices [2, 36] offer opportunities to more directly involve the hands in digital design tools. Correspondingly, HCI research has developed many bimanual pen and touch techniques [16, 20, 22, 35, 37, 47, 49]. These techniques prescribe interaction based upon Guiard's [14] principles of asymmetric coordination between the hands, found in human interaction with physical objects.

As we incorporate techniques into larger systems, mixing Guiard-based approaches with symmetrical ones (e.g., two finger stretchies [28]), questions arise about how the techniques, Guiard's principles, the tasks performed, and the user's expertise affect interaction behavior. Prior work investigates usability of these techniques, typically conducting studies involving novice users performing controlled tasks in isolation [6, 20, 35, 37, 47, 49]. However, unlike controlled study tasks, real-world activities are not planned out and then performed, but rather are situated and ad-hoc [42]. Users improvise and adapt as their goals change. Even so, few studies capture the bimanual interaction behavior associated with these improvisations, particularly as users become more experienced with each system.

This paper investigates the bimanual behaviors of expert visual designers during real-world situated use of a pen and touch system. We begin by reviewing related work. Next, we present a technology probe with landscape architecture students. We report empirical findings that identify a phenomenon in the sustained spatial relationships between hands and interactive surfaces. We then validate our findings with a larger study involving less experienced students and more diverse tasks. We conclude with directions for future research and challenges for designers and researchers.

2 RELATED WORK

We discuss related work on bimanual interaction, specifically approaches based upon Guiard's principles and those involving above and around surface interaction.

Bimanual Interaction

HCI has a long history investigating bimanual interaction [3–7, 16, 21–23, 29, 30, 40, 43]. One of the earliest examples, Sketchpad [43], enabled interactions with a light pen in the preferred hand (**PH**) modified by button presses with the non-preferred hand (**NPH**). By instrumenting both hands with pointing devices, such as trackballs and mice, movements of both hands became part of interaction. For example, Toolglass enables positioning a see-through tool with the NPH for interaction with a cursor controlled by the PH [5].

With both hands instrumented, studies of bimanual interaction investigated the benefits of dividing interaction between the two hands. Interaction techniques that assign different roles to the hands can improve user efficiency at performing compound tasks [7, 30]. For symmetric interactions where both hands are given the same role, users still perform the tasks with some asymmetry [4]. Latulipe et al. found symmetrical techniques outperform asymmetrical ones for spline curve matching [29]. Brandl et al. found that bimanual tasks are performed more quickly using combined pen and touch compared to both hands using either touch or pens [6]. While these studies show improvements in user efficiency at specific tasks, we lack further explorations of bimanual behaviors as users become more experienced, particularly at transitioning among different roles assigned to the hands. This research provides such an investigation.

Beyond controlled experiments, field studies of public displays uncover user behaviors towards bimanual interaction in real-world social settings [23, 24, 26, 39]. Users begin with single-touch interactions [39] and build up to multi-fingered and bimanual gestures [26]. However, with non-traditional interfaces, users gestures become more multi-fingered and bimanual [24]. Further, the interaction context and social context influence what gestures are performed [23].

Guiard-abiding Interaction

Guiard derives a theory of human bimanual activity that explains asymmetric coordination between the hands [14], exemplified by Toolglass. Guiard presents several principles for describing this asymmetric division of labor in certain bimanual tasks, such as writing with pen and paper. These principles describe (for the right handed) how left-hand actions tend to precede those of the right. The left hand defines a reference frame for the actions of the right.

Interaction Techniques. Guiard's work has widely influenced the design of pen and touch and multi-touch interfaces [3, 16, 22, 35, 37, 44, 47, 49]. Hinckley et al.'s pen+touch approach builds on Guiard, using contextual NPH gestures to define frames of reference for actions of the pen in the PH [22]. Webb et al. derive the phrase, *Guiard-abiding bimanual interaction*, to designate approaches that adhere to Guiard's principles [47]. Xia et al. use Guiard-abiding interaction to integrate element selection with action on digital whiteboards [49]. Others use edge-constrained regions, where NPH gestures specify the operations performed by the pen in the PH [16, 35, 37]. Wagner et al. showed how to take advantage of how users grip tablet devices to support Guiard-abiding bimanual interaction when the NPH holds the device [44]. Avery et al. use NPH gestures to specify transient pan and zoom that can easily be undone by lifting NPH touches [3].

Evaluation. Earlier work focused on informal lab studies to evaluate Guiard-abiding surface interaction [22, 35, 37, 47, 49]. These studies typically gather subjective experience data from surveys about individual techniques from around ten (typically novice) participants. This methodology uncovers usability issues, through novices performing controlled, but artificial tasks. It does not capture data about involvement of the hands beyond what participants report.

In contrast to studying novices, Hamilton et al. studied pen and touch interactions with expert gamers playing a real-time strategy game [16]. They reported user experience findings from surveys. While they collected video data of the hands, they did not present an analysis of this data.

Our review of prior work found few studies that investigate the improvisational behaviors that arise as users situate their real-world activities with Guiard-abiding interfaces. This suggests the need for studies of "between-interaction" behavior.

Above and Around Surface Interaction

Freitag et al. define levels of engagement for surface interactions, establishing liminal pre-input and post-input phases that precede and follow surface contacts [11]. Wilkinson et al. describe a model for expressive touch interaction, beginning with the intention phase prior to touch, followed by the enrichment phase during touch, and concluding with the follow-up or recovery phase [48]. These two models are reflected in the interaction design of prior techniques that make use of hovering hand gestures before and after surface contacts [1, 9, 10, 13, 19, 34, 50]. These models and techniques center around surface contacts. Through sensing around surface gestures, Pohl and Murray-Smith develop casual interactions which do not require direct attention or contact with surfaces [38]. Our findings expand these models, revealing new between-interaction phenomena that impact design choices for both above and around surface gestures and provide potential benefits for supporting expert use.

Emmâ: Bimanual Pen and Touch System to Study

Webb's dissertation [45] develops *Emmâ*—a bimanual pen and touch system with Guiard-abiding interactions that supports early-stage visual design. In our study, we use Emmâ to probe aspects of bimanual activity. Emmâ contains bimanual interactions for both edge-constrained and contextual gestures, each initiated with the NPH. Emmâ provides an opportunity—not available in commercial design tools—to study the effects of Guiard-abiding interactions on bimanual activity, particularly when users must transition between edge-constrained and contextual gestures.

3 STUDY 1: TECHNOLOGY PROBE

We conducted a qualitative investigation of the bimanual behaviors of landscape architecture students using Emmâ. While we created a laboratory space to facilitate capturing data, we employed Emmâ as a technology probe [25] to uncover real-world behaviors that arise through the plans and situated actions of participant's actual design tasks. The goal was not to inform design of Emmâ or other pen and touch systems, but to gather empirical findings on bimanual behaviors of experienced designers using such systems.

Participants. We recruited three female masters students (G1-G3), all right handed (RH), in a landscape architecture design studio, *Professional Study*. In this studio, students work on projects initiated by industry sponsors for real-world sites. These participants were in the early stages of their design processes for their projects.

Hardware. We created a studio / laboratory space with four workstations. Each workstation had a Wacom Cintiq display with pen and touch sensing capabilities. Each display was angled (~60-75 degrees) on an adjustable, articulating arm.

Software. Participants used Emmâ [45] to perform early-stage design tasks on course assignments. Emmâ uses the medium of free-form web curation [32, 46] to enable users to collect, spatially assemble, and sketch amidst visual media in a zoomable canvas.

Emmâ provides an edge-constrained chorded gesture area, called the *Hotpad*, in which the user can change the function of the pen, activating quasimodes [18] for lasso selection and adjusting image opacity and blending depending on the number of touches. Emmâ provides contextual gestures for selecting ink properties, drawing straight lines, duplicating elements, and applying perspective transforms.

Procedure. We conducted three sessions with each participant, each lasting 1-1.5 hours, over two weeks. In this open-ended study, we did not define a specific task. Instead, we asked participants to work on any significant design project task, which they considered productive in their own work.

Data collection. We positioned two cameras at each workstation—one overhead and one profile—to ensure that at least one will show an unobstructed view of the hands. We produced a *bimanual activity recording* of each participant's session, capturing synchronized views of the Emmâ canvas and the two cameras.

Analyzing Bimanual Activity Recordings

We performed in-depth analysis of bimanual activity recordings for G1-G3 using a visual grounded theory approach [27, 32]. Rich data gathered for grounded theory typically consists of field notes and interview transcriptions [8, 41]. Visual grounded theory shifts the primary source from textual to visual data [27]. Video data provides a visual version of an event, but resists, at first, reduction to categories and codes [17]. Yet, through selective and interpretive transcription, focusing on aspects related to research questions, the present research applies visual grounded theory methods, e.g., coding and categorization, to video data.

We first transcribed 10.35 hours of recordings, looking for phenomena involving bimanual activity. Through discussions within the research team, we identified interesting behaviors between surface interactions. These behaviors became the focus of our coding process. We performed an initial open coding, which captured hand positions in relation to activities performed. We then performed a more focused coding, deriving 5 codes for hand position (lap, hover, chin, float, desk). The transcription and initial coding were performed by two researchers. We discussed codes and phenomena. Once a specific set of codes was defined, one researcher performed focused coding.

4 STUDY 1: FINDINGS

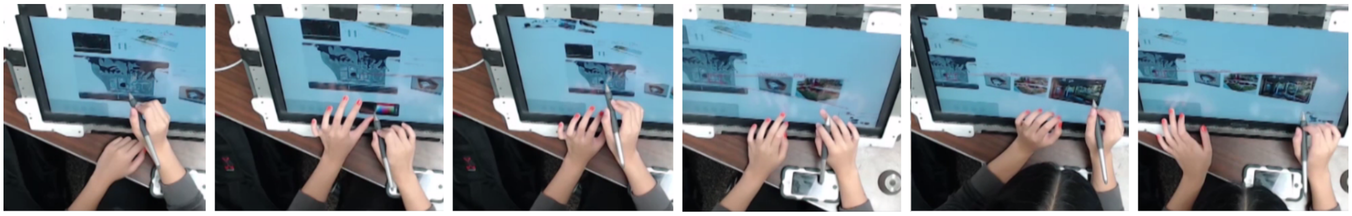
Our analysis shows that participants adopt specific hand gesturing, particularly for the NPH, between their use of commands. This anticipates their future command use.

Interstices

We identify *interstices*—sustained spatial and kinesthetic relationships between hands and surfaces that arise in the periods between input and reveal the user's anticipated future actions. Interstices reflect engagement and anticipation, rather than commands or direct manipulation of objects.

Types. We observed three types of interstices:

- **`Hovering`**—the hand hovers in close proximity to the surface with fingers extended outward, ready to engage in touch input at any moment (Figure 1).
- **`Away`**—the hand floats in-air, pulled away from the surface; it is removed from the immediacy of interaction, but able to quickly engage with light effort (Figure 2).
- **`Rested`**—the hand is disengaged from interaction and in contact with a non-interactive object, such as the desk or the participant's lap (Figure 3).



(a) (b) (c) (d) (e) (f)

Figure 1. `Hovering` interstice sequence: (a) LH rests on the desk (`Rested`); (b) LH lifts and performs a gesture (activate ink properties tool); (c) LH is `Hovering` near the surface without contact, RH draws ink strokes; (d) LH and RH bimanually zoom and pan to situate interaction; (e) RH draws additional ink strokes, LH is `Hovering`; (f) LH swipes on the Hotpad to undo an erroneous ink stroke.

Interstices of the Non-Preferred Hand

All three participants performed all three interstices with their left, non-preferred hand (LH).

`Hovering`. When participants expect to reuse the left hand for an upcoming interaction, they hover it near the surface (Figure 1). The `Hovering` interstice occurs between interactions and involves one or both hands. As with all interstices, this is sustained behavior, in contrast to the brief hovering between post-input and pre-input phases in a sequence of commands. Even as their right hand interacts, the left hand remains hovering near the surface, well placed for a subsequent action. We lack measures of the exact distances observed, but estimate that participants hovered their left hand within three centimeters of the surface. Further, we suspect this distance varies slightly by participant and per occurrence. When `Hovering`, participants extend their fingers outwards, towards the surface. This too reveals anticipation.

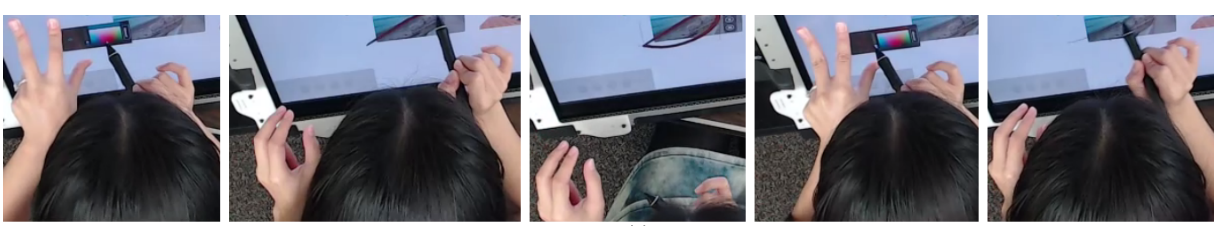
Specifically, G2 hovered her left hands in proximity to the Hotpad (Figure 1c and 1e). A `Hovering` interstice allowed her to quickly do all of the following with her left hand: (a) undo actions with swipes on the edge-constrained Hotpad; (b) perform contextual gestures, such as activating ink property selection; and (c) zoom in and out bimanually. She regularly panned and zoomed to keep her work area near the Hotpad, constraining her active work space. G3 exhibited a similar behavior near the middle of the surface when assembling elements. She hovered her left hand, periodically using it to perform bimanual zoom when switching between micro and macro views for fine-grained transformations and high-level organization, respectively.

`Away`. When participants are less certain about future actions, they pull back. The `Away` interstice removes the hand from immediately touching the surface and leaves it floating in the air, still ready if an anticipated interaction arises.

For example, G1 floated her left hand in the air after using it to activate the ink property tool while sketching (Figure 2). As she sketched with her right hand, the left remained `Away`. At times, she would interact with her left hand; other times, she would not. She would then rest her left hand, whether it was used or not, when switching to an activity other than sketching. G2 similarly used a `Away` hand when sketching over images. She would periodically use her left hand to activate the ink property tool, then return her hand to `Away`. The `Away` interstice is an uncertain state that often appears when participants transition from `Hovering` or `Rested`.

In a particularly salient example, G2's left hand was `Away` before interacting with the surface. Afterwards, she began returning her hand to `Away`, but briefly hesitated and brought her hand back towards the surface in a `Hovering` position. Her left hand was then used in a subsequent action.

`Rested`. When participants do not expect to need the left hand in upcoming interactions, they rest it on their lap or the desk (Figure 3). This was most evident when G1 and G3 were sketching. They sketched for significant periods without changing ink properties or undoing ink strokes. During these periods, they rested their left hands in their laps or on the



(a) (b) (c) (d) (e)

Figure 2. `Away` interstice sequence: (a) LH activates ink property tool; (b) RH selects ink style while LH remains in-air; (c) both hands are `Away`; (d) both hands manipulate ink properties; (e) RH sketches, while LH remains `Away`.

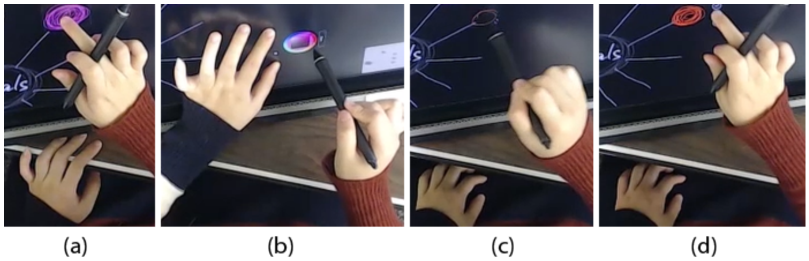


Figure 3. `Rested` interstice sequence: (a) LH rests lightly on the desk with tips of fingers; (b) LH lifts off the desk to perform a gesture (activate ink properties tool); (c) LH returns to her lap, RH sketches with new ink style; (d) LH continues to rest in her lap while RH performs additional actions.

desk. When they did use their left hand to swipe on the Hotpad or activate the ink property tool, they immediately returned the hand to a `Rested` position after use (Figure 3c).

NPH Interstices by Participant and Task

We see individual differences in how often each interstice is performed (Figure 4). G1 used `Away` the most, closely followed by `Rested`. Her tasks focused primarily on sketching over collected images. She used her left hand to undo ink strokes with the Hotpad and activate the ink property tool. These actions were interleaved with significant unimanual sketching. G2 used `Hovering` the most, followed by `Rested`. Her tasks focused primarily on a mixture of assembling visual content and sketching over images. She used her left hand to undo assembling operations and ink strokes, activate the ink property tool, apply perspective transforms to images, and zoom bimanually. G3 used `Rested` the most, followed by `Hovering`. Her tasks focused primarily on sketching and assembling diagrammatic elements. She used her left hand to undo ink strokes, activate the ink property tool, and unimanual pan and zoom.

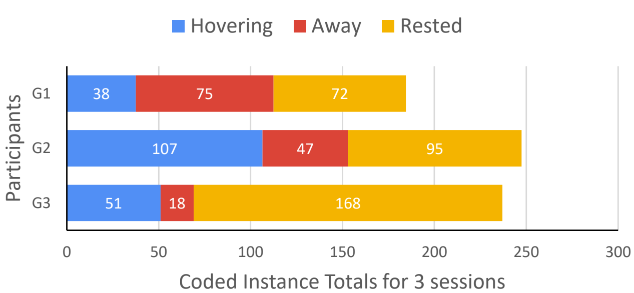


Figure 4. Distributions and total counts of NPH interstices by participant. All participants used all three interstices. G1 favored `Away`; G2 favored `Hovering`; and G3 favored `Rested`.

Interstices of the Preferred Hand

For all participants, the right, preferred hand hovers directly above the surface between contacts. Most interactions involve the right hand. `Hovering` lets participants quickly engage in compound tasks, such as repeatedly transforming an element with two-finger stretchies.

The right hand is not always `Hovering`—participants sometimes bring it back towards their body (`Away`). G2 held her right hand near her face (26 instances in 2.5 hours), seeming to reflect upon her work before deciding what to do next. When assembling elements with her left hand, G3 pulled her right hand back, leaving it hovering in the air (14 instances in 2 hours). From this position, she could quickly interact again with her right hand.

Participants tuck the pen in their right hands when not using it (Figure 5). Hinckley et al. describe how pen grips in tablet interactions affect which fingers point toward the surface [20]. G1 used a palm grip—wrapping the middle, ring, and pinky fingers around the stylus barrel—with her index finger and thumb pointed towards the surface. G2 and G3 used a tuck grip—resting the stylus barrel on the thumb and middle finger while the index finger wraps over top, with the middle, ring finger and thumb pointed towards the surface. This forms a variation of the pinch pose, where the thumb and middle finger, rather than index finger, can perform pinch gestures. Once or twice, participants passed the pen, from the right to left hand, to facilitate precise touch interaction with the right hand.

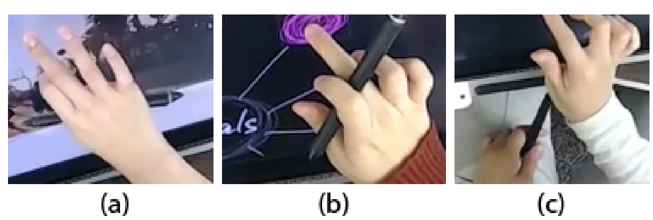


Figure 5. Examples of pen grips: (a) palm grip; (b) tuck grip; (c) passed to NPH.

Interstice Qualities: Spatial, Temporal, Kinesthetic

We observe spatial, temporal, and kinesthetic qualities of interstices, each of which reveals aspects of anticipation. The spatial relationships of interstices reflect different levels of engagement between hands and surfaces. A `Hovering` hand is close to the surface, ready to immediately interact.

Conversely, a `Rested` hand is down, removed from the immediacy of interaction. An `Away` hand is spatially between these two—pulled back but still above the surface.

The spatial relationships do not by themselves reflect anticipation. For example, a hand, returning to rest in the lap, does not represent a `Hovering` interstice while close to the surface in the post-input phase. Interstices involve a stationary hand that sustains the spatial relationship. It is this temporal quality of interstices that demarcate its beginning and end. The hand is held, waiting to act. A hovering hand waits in expectation of interaction; a rested hand waits without intending to act.

Interstices reveal anticipation through varying levels of kinesthetic tension, represented by the physical effort of holding hands up and extending fingers outward. Both `Hovering` and `Away` involve holding a hand aloft, requiring sustained physical effort. An arm with a `Hovering` hand is extended more outward from the body than one with a `Away` hand. This requires additional physical effort to sustain, while a `Rested` hand has little-to-no kinesthetic tension when laying in the participant's lap. When `Hovering`, the fingers spread outwards towards the surface (Figure 1c), anticipating future action. When `Away`, the fingers tuck inwards away from the display (Figure 2c), retaining the possibility of interaction.

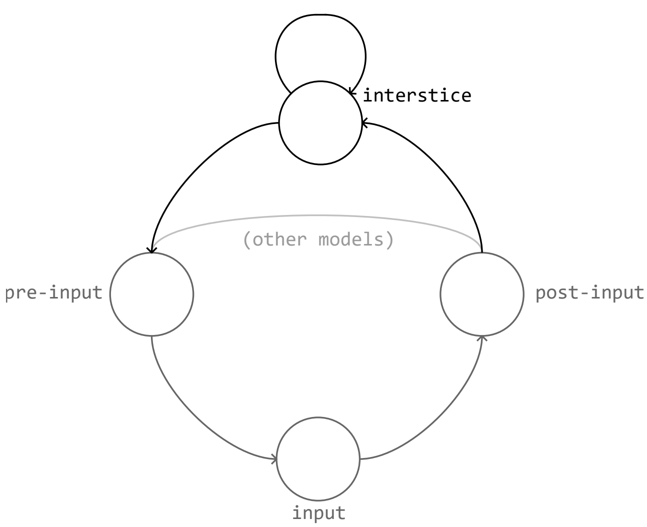


Figure 6. Surface interaction model extended for interstices. The existing model (in gray) represents an interaction cycle where post-input directly joins pre-input. We add an interstice phase between post-input and pre-input phases (in black). Since the hands can transition to different interstitial positions, the interstice state feeds back into itself. For simplicity, we present only the interaction cycle. States representing user approach and disengagement that connect to pre-input and post-input, respectively, are not pictured.

Interstices in Freitag's Surface Interaction Model

Interstices represent sustained behaviors between input that are not part of pre-input or post-input phases in surface interaction models. We extend Freitag's [11] model to include interstices (Figure 6). The existing model directly connects post-input with pre-input. Interstices represent an additional path between these liminal phases.

5 STUDY 2: VALIDATING INTERSTICES

Given the small sample size in Study 1, we wanted to see if interstices obtain in other situations. We conducted a larger study with undergraduate landscape architecture students performing design tasks in the context of course assignments.

Participants. We recruited 14 participants, all right handed: 10 students (7 female) from the upper-level undergraduate course, *Landscape Construction I*; and 4 students (2 female) from the undergraduate studio, *Landscape Design IV*.

Hardware and Software. Same as Study 1.

Procedure. We conducted 13 individual sessions with *Landscape Construction I* participants (C1-C10). Three (C1, C2, C10) participated in a second session. Each session lasted 45-60 minutes, except for one (C3, 150 minutes). Participants sketched over photos of their campus to analyze aspects of landscape construction, such as the suitability of seating areas in relation to pedestrian paths.

We conducted two sessions with *Landscape Design IV Studio* participants (D1-D4). The first session lasted 2.5 hours, and the second session lasted 1.5 hours. D3 left the first session early and did not participate in the second session. Participants analyzed existing sites in order to develop design solutions for a real-world site. Participants D1, D2, and D3 worked individually to analyze different design aspects in the first session. In the second session, D4, with assistance from D1, integrated and assembled their separate analyses into one product.

Data collection. Same as Study 1.

Phenomena-Specific Coding. We used codes specific to interstices from Study 1 to perform focused coding, avoiding an initial round of open coding. The coder was able to introduce new codes for interstitial behaviors that did not fit with existing ones.

Coding video data is time intensive. Rather than perform in-depth coding on the entire data set as we did in Study 1, we instead focused on a specific phenomenon: the interstices performed with the non-preferred hand. We sampled 30-minute blocks from the middle of each participant's video. We selected the middle to ensure that we analyzed design activities and avoided learning stages and wrap-up activities.

6 STUDY 2: FINDINGS

The results support our findings from Study 1, revealing interstices for `Hovering`, `Away`, and `Rested`. We also identified a new interstice that emerged from a task performed infrequently by participants in study 1.

Validation of Interstices from Study 1

We observed similar distributions of NPH interstices compared with those from Study 1 (Figure 7). Again, participants varied in their uses of interstices. Eleven participants favored `Rested`, followed by `Hovering`. Three participants—C2, C5, and D1—favored `Hovering`.

`Hovering`. As in Study 1, all participants exhibited `Hovering`. Again, participants anticipate future actions by hovering their left hands. Participants engaged in interactive sequences similar to those described in Figure 1, where the left hand remains closely hovering, even when not being used. This hovering was sustained across interactions with the right hand, such as drawing ink strokes with the pen.

Similar to G2 in Study 1, C2 and D1 hovered their left hands in the bottom half of the surface near the Hotpad in order to quickly execute various commands. While this constrained where they worked, like G2, it enabled them to develop a certain expertise at performing bimanual interactions in Emmâ.

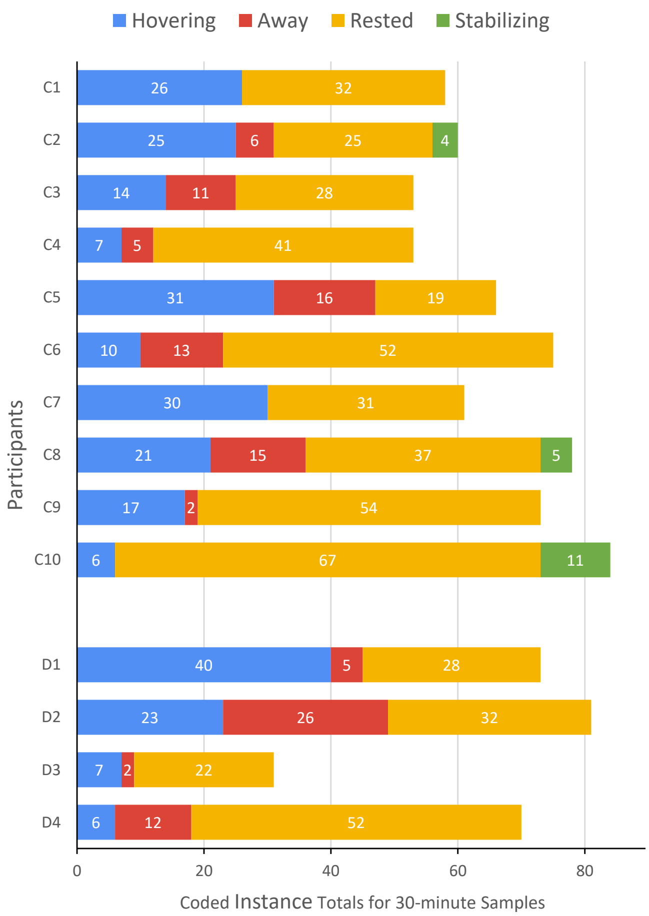


Figure 7. Distributions and total counts for NPH interstices by participant. All participants used `Hovering` and `Rested`. Three participants (C1, C7, and C10) did not use `Away`. C2, C8, and C10 used the newly identified interstice, `Stabilizing`.

`Away`. All but three participants—C1, C7 and C10—exhibited `Away` in the 30-minute sample. Of the three exceptions, both C1 and C7 used `Hovering` nearly as much as `Rested`, while C10 almost exclusively used `Rested`. While all three performed similar tasks, C10 demonstrated minimal anticipation of the left hand's subsequent actions, preferring instead to primarily use the right hand, even for undoing actions with swipes on the Hotpad—an action all other participants performed almost exclusively with their left hands. Conversely, C1 and C7 showed clear anticipation towards left hand use. They never used `Away`, the more uncertain interstice. Instead, they rested their left hand when it was not needed and hovered it near the surface when it was.

`Rested`. All participants in Study 2 engaged in `Rested`. As opposed to Study 1, we observed several participants almost exclusively use `Rested` with their left hands (C4, C10, D3). Participants from Landscape Construction I primarily performed unimanual activities, such as sketching over images with a single color and handwriting. This is reflected in their use of `Rested`. In particular, C10 rarely used his left hand to access the Hotpad. Instead, he would bring his right hand over with pen tucked.

`Stabilizing`: New Interstice when Handwriting

We observed an additional interstice by Landscape Construction I participants that we call: `Stabilizing`. A `Stabilizing` hand aids the actions of the other hand by providing physical assistance, such as holding a forearm to support precise interaction. Participants C2, C8, and C10 grabbed their right forearms with their left hands (Figures 8b and c) when producing ink with the pen, particularly when handwriting. C10

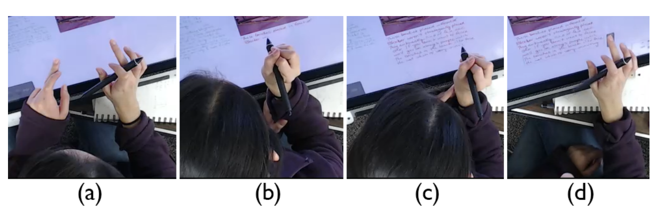


Figure 8. `Stabilizing` interstice sequence: (a) bimanual zoom and pan; (b) handwriting with RH, while LH stabilizes; (c) LH continues to stabilize RH; (d) LH rests in lap upon handwriting completion.

grabbed near her wrist, while C2 and C8 grabbed closer to the elbow. They used this interstice to help stabilize the right hand as they wrote and sketched. Kinesthetic tension for `Stabilizing` involves LH fingers grabbing the right forearm or wrist, suggesting no near-term interaction. Participants from Landscape Design IV did not significantly engage in handwriting. They did not exhibit this interstice.

7 DISCUSSION

Study 1 identified three interstices and how they reveal anticipation towards subsequent actions. Study 2 verified these three interstices, while identifying a new one. We further break down differences in NPH interstices by task and examine the effects of Guiard's principles on interstices.

Interstices Differ with Task

Table 1 breaks down interstices by task for all participants from both studies. We see differences between tasks that are explicitly bimanual versus those that are unimanual or involve a mixture of the two.

For bimanual tasks, such as blending images via the Hotpad or drawing straight lines, the majority of NPH interstices involved `Hovering` (50-71.88%). Participants usually sustained `Hovering` after a bimanual task (82.81-94.44%). The left hand was not always used in an upcoming task, but remained hovering in close proximity with the surface, until it was used for another interaction.

For unimanual tasks, `Rested` comprised a majority of NPH interstices (51.16-67.27%). Yet, for panning, where participants shift their perspectives with single- touch drags, the left hand was often `Hovering` (41.86%). Panning and zooming typically precede or interleave other tasks, such as two-finger manipulations. Again, by hovering their left hands close to the surface, instead of resting, participants reveal anticipation towards future actions. Not surprisingly, for handwriting tasks involving only the right hand, the left hand was rarely `Hovering` (17.27%).

We analyzed how often participants maintained the previous interstice following a command (Table 1, Maintained). Participants predominantly maintain their NPH interstices (82.81%-94.44%). This too reveals anticipation. We see variations in interstices by task, but these interstices are primarily maintained. Participants do not return to a single specific interstice after every command, nor do they return to random ones. Instead, they adopt and maintain particular interstices to support situated action.

Effects of Guiard-abiding Interaction Design

Use of Guiard's principles in Emmâ seemed to influence interstitial behaviors. Emmâ combines global, edge-constrained gestures with more specific, contextual ones. Participants performed spatial transitions with the left hand, back and forth between the edge and a context. The three participants that hovered their left hands near the Hotpad minimized this transitional distance, improving their efficiency when performing operations.

Of the four solely bimanual tasks reported in Table 1, only bimanual zoom is not asymmetric and Guiard-abiding. The left hand was `Rested` more often after bimanual zoom (30%) than the other bimanual tasks (16.67-21.43%). The left hand stayed in a more actionable position (`Hovering` + `Away`) for Guiard-abiding tasks (78.57-83.34% vs 70.0%).

Hands	**Tasks**	**Gestures**	**% of Part.**	**`Hovering`**		**`Away`**		**`Rested`**		**Maintained**
Unimanual	Panning	Contextual	93.75%	41.86%	(36)	6.98%	(6)	**51.16%**	(44)	91.86%
	Handwriting	Contextual	62.50%	17.27%	(19)	15.45%	(17)	**67.27%**	(74)	88.18%
	Unimanual Zoom	Contextual	93.75%	26.19%	(22)	19.05%	(16)	**54.76%**	(46)	84.52%
	Collecting elements	Edge	56.25%	27.78%	(20)	18.06%	(13)	**54.17%**	(39)	83.33%
Bimanual	Image transform	Edge	25.00%	**50.00%**	(7)	28.57%	(4)	21.43%	(3)	92.86%
	Bimanual Zoom	Contextual	87.50%	**60.00%**	(30)	10.00%	(5)	30.00%	(15)	90.00%
	Straight-line drawing	Contextual	43.75%	**71.88%**	(46)	9.38%	(6)	18.75%	(12)	82.81%
	TSR multiple elements	Both	31.25%	**66.67%**	(12)	16.67%	(3)	16.67%	(3)	**94.44%**
Mixed	Free-form sketching	Both	**100.00%**	26.29%	(51)	14.95%	(29)	**58.76%**	(114)	89.69%
	TSR single element	Contextual	93.75%	37.44%	(82)	19.63%	(43)	**42.92%**	(94)	86.30%

Table 1. Percentage breakdowns by task of NPH interstices (`Hovering`, `Away`, `Rested`) collected from 30-minute samples of all participants across both studies. A majority of bimanual tasks involved a `Hovering` NPH, while a majority of unimanual and mixed tasks involved a `Rested` NPH. Participants primarily maintained the same NPH interstices after performing a command. Max values presented in bold. Instance counts presented in parentheses.

Between the two tasks that mix unimanual and bimanual interaction, only free-form sketching involves Guiard-abiding gestures. Unlike with bimanual tasks, participants rested their left hand more often when sketching (58.76% vs 42.92%). We attribute this to the action of sketching, which only requires one hand with the pen to make marks. Guiard-abiding interactions only occur when the participant needs to change ink properties. In most cases, this happens once initially. In cases where `Hovering` occurred, participants were sketching with different ink styles, which required frequent activation of the ink property tool.

Limitations

While we argue that the phenomenon of interstices extends broadly to interaction as a whole, the ones we observed are situated in a Guiard-abiding pen and touch interface on a slanted desktop surface. We find that `Hovering`, `Away`, and `Rested` represent a common set of interstices for Emmâ. We observed tens of hours as participants performed different tasks: all three interstices occurred repeatedly. We expect these three are present in the broader context of bimanual touch interaction, but lack empirical data to verify this. We also expect more interstices to exist in other contexts. For example, a user may position their NPH hand to the side of a Wacom surface for accessing modifier buttons or position a finger over a line of text to temporarily mark the location while attention is drawn elsewhere. The interstices presented in this research are not intended to inform design beyond this context. Interstices will certainly vary for other input modalities, types of interaction, and orientations, such as vertical whiteboard displays or horizontal tabletops. Further investigation is needed.

8 FUTURE RESEARCH

Discover More Interstices

Our findings revealed four interstices performed by landscape architecture students using bimanual pen and touch interactions. Future research should investigate interstices in other input modalities and contexts. We encourage investigating traditional HCI modalities, such as mouse and keyboard, but additionally more embodied ones, in which the user's body movements execute commands or directly manipulate digital objects. For pen and touch, contacts with the surface clearly demarcate input. This demarcation is less clear for embodied sensing modalities, such as those supported by the Microsoft Kinect, where all movements within range of the sensor are sensed as input. What constitutes an interstice in these modalities is equally less clear. Even so, identifying and understanding existing interstices across user practices with these modalities could motivate new approaches for delimiting gestural input.

Investigate Different Form Factors

This research investigated desktop surfaces with a slanted orientation. Future research should investigate interstices for other surface form factors. In particular, we are interested in small mobile devices and large collaborative surfaces, two ends of the surface interaction spectrum.

Mobile Surfaces and Grip. Our findings, along with prior work, identify different forms of pen grips when the pen is stowed in-hand for touch input. Users adjust their grips to facilitate their intended interactions. Further, we posit that the user's grip of a mobile device, such as a tablet or smartphone, is an interstice. For example, using the finger tips to hold the edges of a smartphone with both hands provides stability, allowing for quick adjustments of position and angle, and avoiding finger occlusion of the camera. Hinckley et al. demonstrated ways to use grip of a mobile device to present context-appropriate interfaces during pre-input [19]. We seek to expand this understanding by considering grip, not just as a precursor to touches, but as a sustained behavior that emerges and evolves as users become more experienced with their devices. In co-located collaborative contexts, the micro-mobility [31] of mobile surfaces and associated grips likely result in varied interstices affected by aspects of social interaction and proxemics [12, 15].

Digital Whiteboards and Tabletops. Large collaborative surfaces, such as digital whiteboards and interactive tabletops, provide modalities for investigating interstices in computer-supported cooperative work. While devices, such as the Microsoft Surface Hub, make use of edge-constrained interfaces, we anticipate that users will not exhibit the same hovering behaviors employed by our participants to more efficiently command. The physical constraints and interference by other users will potentially prevent such behaviors. Conversely, on tabletops, we anticipate seeing similar behaviors, as users primarily work in personal spaces near the edges.

9 CHALLENGES FOR DESIGN AND RESEARCH

Our findings highlight the complex nature of human bimanual activity. We do not prescribe a set of universal behaviors consistent across all participants and tasks. Instead, these findings reveal interstices as subtle, emergent behaviors—the cumulative result of interaction design, input modality, expertise, and user task. We posit that interaction designers and researchers who account for interstices can better facilitate expert use. However, they face numerous challenges.

Designing Techniques with Above-Surface Gestures

We identify that interstices constitute a time and space for above-surface gestures. Prior work develops new interaction techniques that make use of above-surface gestures, such as hovering. They understandably seek to take advantage of the seemingly unused space above the surface to make it interactive. However, we find that users already make use of this space through interstices. We argue that prior work has inadvertently affected interstitial behaviors. Thus, we encourage interaction designers and researchers to identify and respect users' existing interstitial gestures in the space above and around surfaces.

Support Expert Use with Interstices

How can interaction designers support expert use? While initially novice users of Emmâ, the participants quickly learned individual interaction patterns, and developed experienced practices involving interstices. Interstices reflect user adaption to and improvisation with interfaces, rather than the intended behaviors specified by interaction design. We argue that interstices can support controlling interactive systems by experts, not through developing new pre-input and post-input gestures, but through sensing already-present interstitial behaviors.

A key challenge lies in how to address individual interstitial behaviors that emerge in expert use. As users adapt to and improvise with interfaces, so too must the interfaces adapt to interstitial behaviors. Co-adaptive interfaces [33] that change with expertise as the user adopts particular interaction patterns are necessary. For example, an interface could transition from supporting novice use through feed-forward mechanisms that reveal possible commands to supporting expert use by providing quick access to frequently-used commands. Different interstitial gestures become associated with different commands changing which ones are presented for quick access. These co-adaptive interfaces must be contextualized by tasks and interaction design. In our studies, we observed differences among interstitial behaviors with regards to tasks. Guiard-abiding interaction design influenced where the hands were positioned during interstices.

Sense Subtle Interstices

Interstices are subtle behaviors, unlike command gestures with distinct movements to facilitate recognition. An interaction designer does not prescribe interstices; rather, they emerge through use. Thus, sensing interstices raises certain challenges. Our findings tease out spatial, temporal, and kinesthetic qualities of interstices. Still, we need methods that map these qualities to recognized interstices. Yet, qualities of interstices appear highly individualistic. For example, the proximity to a surface at which a hand is considered `Hovering` varies from user to user and user to surface, depending on their hardware setup, physiology, and comfort levels with input devices. We need sensing methods that adapt to and possibly learn from individual user behavior.

Derive and Sense Quantitative Metrics

Our qualitative methodology revealed an interesting phenomenon that would not have emerged in logged interaction data. Still, coding video is time-intensive. Designers and researchers would benefit from quantitative metrics for interstices. These metrics will need to sense spatial, temporal, and kinesthetic qualities of interstices. This may require varied sensing technologies. For example, computer vision sensors, such as the Leap Motion, afford sensing spatial qualities, while physiological sensors, such as the Myo armband afford sensing kinesthetic qualities. Quantitative metrics will help further validate qualitative findings and more easily support comparisons across techniques, tasks, and input modalities.

10 CONCLUSION

We identify a between-interaction phenomenon that we call *interstices*, in which users position and orient their hands between actions to situate their activities with interfaces. Interstices reveal anticipation towards future action. Prior models of surface interaction lack representations for the subtle behaviors that users exhibit between post-input and pre-input. As a result, interaction designers miss out on opportunities to take advantage of these behaviors. They may even inadvertently influence or disrupt emergence of these behaviors as users become experts with systems. Our participants adopted experienced interstitial behaviors to more efficiently perform interactive sequences in Emmâ. These behaviors arose, in part, because their actions are not planned out and then performed; they are situated and ad-hoc [42]. Interstices are a result of the improvisation in real use, emerging as users become more experienced. We anticipate that interstices continue to develop and evolve as users transition from novices to experts. We encourage further studies of interstices in other contexts and modalities.

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