Understanding Multi-Device Usage Patterns: Physical Device Configurations and Fragmented Workflows

Ye Yuan[*]
University of Minnesota

Nathalie Riche
Microsoft Research

Nicolai Marquardt
Microsoft Research, UCL

Molly Jane Nicholas
University of California, Berkeley

Teddy Seyed
Microsoft Research

Hugo Romat
Microsoft

Bongshin Lee
Microsoft Research

Michel Pahud
Microsoft Research

Jonathan Goldstein
Microsoft Research

Rojin Vishkaie
Arizona State University

Christian Holz
ETH Zürich

Ken Hinckley[†]
Microsoft Research

Figure 1: Seven different configurations of multi-device workspaces from the corpus of 156 photos.

ABSTRACT

To better ground technical (systems) investigation and interaction design of cross-device experiences, we contribute an in-depth survey of existing multi-device practices, including fragmented workflows across devices and the way people physically organize and configure their workspaces to support such activity. Further, this survey documents a historically significant moment of transition to a new future of remote work, an existing trend dramatically accelerated by the abrupt switch to work-from-home (and having to contend with the demands of home-at-work) during the COVID-19 pandemic. We surveyed 97 participants, and collected photographs of home setups and open-ended answers to 50 questions categorized in 5 themes. We characterize the wide range of multi-device physical configurations and identify five usage patterns, including: partitioning tasks, integrating multi-device usage, cloning tasks to other devices, expanding tasks and inputs to multiple devices, and migrating between devices. Our analysis also sheds light on the benefits and challenges people face when their workflow is fragmented across multiple devices. These insights have implications for the design of multi-device experiences that support people's fragmented workflows.

[*]yuan0191@umn.edu
[†]kenh@microsoft.com, surface-fleet@microsoft.com

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CCS CONCEPTS

• **Human-centered computing** → **Empirical studies in HCI**; **Empirical studies in ubiquitous and mobile computing**.

KEYWORDS

multi-device, cross-device computing, distributed user interfaces

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1 INTRODUCTION

Everyday interaction with information technology increasingly involves more than one device: reading documents on a tablet while writing on a laptop, using the camera of a laptop while streaming audio from a phone during video conferencing, or moving slide decks across devices for best editing access. This shift towards personal multi-device ecologies, an existing trend likely accelerated by the change to remote work during the COVID-19 pandemic, reflects how people have adapted their homes to function as ad-hoc workspaces by adding work devices to other co-opted devices and furniture in the home.

Research on cross-device interaction and multi-device use explores designs and techniques for a variety of device configurations [11]. These include novel interaction techniques [31, 40, 43, 67] and application scenarios [8, 27] for distributing content and applications across devices. While such techniques often inspire new research directions, they frequently presume particular device arrangements — such as pinching across touchscreen devices that are closely juxtaposed at an identical screen angle, or having a large empty tabletop on which one can arrange a plurality of identical tablets [31, 33, 44, 52] — which may differ sharply from users' actual work practices and which are not representative of people's real-life device configurations.

Rather, as our observations will reveal, during the pandemic people have tended to employ highly heterogeneous device ensembles that they use on small or cluttered desks, co-opted dining tables, or other locations in their dwelling driven by task needs, comfort, ambient noise, and all the other emergent necessities of work-at-home while dealing with home-at-work. This adds observational depth and detail to a general reflection raised by Brudy et al. on cross-device research [11]: *"While many of the technical contributions re-envision and push the boundaries of interaction possibilities, they are often disconnected from findings using empirical studies."* To bridge this divide, and arrive in this new future of remote work, we need to better understand current use and people's interactions across devices.

Several studies that predate the pandemic — often from much earlier stages of adoption of mobile, tablet, wireless, and laptop devices — investigate people's multi-device activities. For example, Oulasvirta et al. [54] highlight information workers' challenges of synchronizing content across devices. This echoes Dearman et al.'s finding [22] that data access is challenging to manage with multiple devices. Other studies further unpack use-cases and practices, such as the spectrum of sequential-parallel and related-unrelated use of multiple devices, and how users choose between them [41]. Other work identifies key roles of multiple devices and workflows [61], or how attention switches in multi-device setups [57]. These studies suggest there remains much potential for designing cross-device interactions, but also many points of friction that could discourage multiple-device use and undermine their perceived benefits. However, beyond previous studies e.g., of multi-monitor use [30] or how people organize paper documents on desks [1, 9, 46], our study is the first to investigate more deeply how users physically arrange multiple devices in their physical workspaces. Our work also seeks to document practices during the work-from-home shift and analyzes people's *physical device configurations* as well as how they leverage them in *recurring patterns of multi-device use* that relate to—and which indeed appear to be at least partially embodied by—these physical configurations.

Our observations of multi-device interactions and physical device configurations draw from a study of 97 participants from diverse backgrounds. We collect and analyze photographs of people's workspaces, detailed information on their devices, and open-ended answers about their everyday tasks and workflows. Our qualitative analysis offers insight into not only the wide diversity of people's work-at-home device setups, but also some of their recurring multi-device usage patterns. Indeed, people's real-world multi-device use often leads to *fragmented workflows*, with tasks, content, interactions, and attention split across diverse sets of devices. We characterize physical workspace configurations, including number of devices used, diversity of form factors (whether homogeneous or heterogeneous), and common sets of devices used together (e.g., companion devices used alongside a primary device, or multiple laptops employed in parallel). Workspaces vary greatly; we observe many small and constrained workspaces, oft-cluttered work surfaces, and ad-hoc working locations improvised at places and locations around the home. We also categorize device *arrangement*, *orientation*, *fixation*, and *reachability*; for example, we found that when people use devices together, they are not always placed directly next to each other, depending on whether the use reflects partitioning of information or separation of concerns. Nor did we observe use of devices flat on a tabletop (in sharp contrast to many proposed cross-device techniques for tiling tablets or phones together [29, 44, 56]).

Complementing this categorization of physical device configurations, from survey responses we synthesized five patterns — and pattern combinations — of common multi-device usage (expanding on [41]): *integration* (e.g., device capabilities complementing each other), *cloning* (e.g., facilitating collaborative sharing), *expanding* (e.g., increasing screen real estate), *partitioning* (e.g., for unrelated parallel tasks), and *migrating* (e.g., continuing interrupted tasks later on another device). We contextualize these patterns by explaining motivations, perceived values, and challenges behind using multiple devices, and discuss how within fragmented workflows there are not only states, but also transitions — that is, combinations of patterns — such as the sequential flow from integration to partitioning pattern.

Finally, these grounded observations of multi-device usage patterns and physical configurations that actually exist in real-world user practice lead us to identify a number of opportunities for researchers and practitioners to both reflect on existing solutions for cross-device experiences and to generate novel ones. In particular, we propose a better matching of specific physical configurations to any of the five usage patterns, and we provide an overview of these links in the context of users' values. We also suggest better transitioning between usage patterns and reflect on the link between our findings to previous empirical multi-device studies.

In summary, we contribute the following:

- **A detailed analysis of people's real-world multi-device setups and physical configurations**, including categorizations of device ecologies (number of devices, diversity of form factors, common sets of devices), physical configuration (arrangement, orientation, fixation, and reachability of devices), workspaces (size, clutter, and places/locations), and use of other physical artefacts.
- **Documentation of five common multi-device usage patterns**: *integration*, *cloning*, *expanding*, *partitioning*, and *migrating* — with explanations of user's *values* behind their multi-device use, common *challenges*, and *combinations* of device usage patterns.
- **Design implications and research opportunities derived from our qualitative analysis**, such as how particular physical device configurations might facilitate certain multi-device usage patterns, or how to support better transitions between patterns.
- **Access to our full data corpus** of 97 survey responses featuring 866 textual descriptions and 156 photographs with the corresponding codebook, allowing others to expand on our analysis.

Taken together, our observations establish and detail usage patterns that characterize people's fragmented workflow across multiple devices. The overall goal of our analysis is to provide the cross-device community as well as the wider HCI community with a frame-of-reference for higher-level motivations, in-practice patterns, and resulting opportunities that we synthesized from data of real use-cases. Our insights shed light on people's real-world multi-device working practices during the transition to remote work driven by the pandemic. But since this new future of remote work appears to be here to stay, these observations also reveal opportunities for future technology design to better support people's fragmented workflows, and contrast the trend of innovative cross-device techniques with the grounded perspective of realistic user scenarios, working practices, and their surrounding context in people's lives.

2 RELATED WORK

Considerable research in the human-computer interaction community focuses on designing novel cross-device and multi-device interactions and technologies. The *Cross-Device Taxonomy* [11] characterizes over 500 related publications over multiple axes, coining the term *cross-device computing* to designate the substantial body of research on the topic. In this section, we introduce this existing body of literature to contextualize our work.

2.1 Supporting Cross-Device Computing

A large number of research papers introduce techniques to support simultaneous usage of multiple devices. For example, many techniques enable distributing content across multiple devices [4, 35, 42, 58, 60], or gestures to enable interactions across multiple devices [33, 52, 53, 59]. Systems such as Webstrates [43], Conductor [31] or Panelrama [67] provide technological solutions to distribute user interfaces across multiple devices [3, 24]. Rather than building a new system, our efforts are focused on understanding existing cross-device workflows, and broader patterns of people's behaviour with multi-device usage.

Researchers have also delved into specific multi-device configurations such as dual-screen or multi-screen (e.g., [32, 39, 50]), tablet formations (e.g., [13, 47]), companion devices such as mobile phones (e.g., [2, 12, 21, 28, 45]), or large screen displays (e.g., [4, 16, 51, 63, 66]). Prior work has also explored categories of application design techniques, including *migratory* interfaces [5, 6, 8] and *migratable* applications [26, 27, 64], which are asynchronous usage patterns related to the "*migrate*" pattern discussed by [11]. Other researchers have explored how changing form factor and interaction modality can be supported by responsive or adaptive user interfaces (e.g., [7, 38, 67]).

These technological research papers often support their advances via formative or evaluative studies with users (e.g., [12, 19, 34, 62]). Yet, most focus on specific aspects of multi-device usage, and on introducing entirely novel interaction paradigms rather than studying people's existing workflows. Our work represents a bridging of the gap between this ongoing research agenda with empirical studies, identified by Brudy et al. [11], that help ground future research projects in existing behaviour and contribute to *"a frame of reference to compare and evaluate cross-device techniques and systems"*.

2.2 Understanding People's Multi-Device Workflows

Multiple studies attempted to gain such broader view of people's workflows when working with multiple devices, including understanding multi-device utilisation [17, 18, 22, 39, 54] and challenges [55], in both individual [30, 61] and collaborative settings [37, 68]. Within this body of informative work, a number of previous studies [22, 54, 61] highlighted motivations for people using multiple devices. Oulasvirta et al. [54] focused on information workers owning multiple laptops and smartphones, attempting to understand interactions with files and data across multiple devices in early 2007. While insightful, it's clear the landscape of technology and user experience design has changed dramatically since then. For example, Oulasvirta et al.'s participants described needing to manually synchronize their smartphone with their laptop, tracking which was the master copy and which was the "view-only" reference, a technique that no longer applies to the current technological landscape. Dearman et al. [22] studied researchers in academia and industry, providing insights on the challenges for people needing to manage and access data across multiple devices. Santosa et al. [61] identified the roles that different devices can play in a field study from 2013. Rashid et al. investigated patterns in attentional switching across multi-display setups [57].

From this collection of prior work, we know that people use different devices depending on the *task* — such as requiring more computing performance, specific software, or data — the *physical context* — such as the ability to use extra monitors, or the need to be mobile — the *social context* — such as using a smaller inconspicuous device during a gathering, or one with a large display for collaborative work — or *unexpected factors* — such as lack of battery, or connection interruption. Our work seeks to go one step further and identify motivations behind the use of specific sets of devices for specific types of tasks.

2.3 Understanding People's Multi-Device Usage Patterns

Prior research revealed patterns and key behaviors in multi-device usage (e.g., [30, 41, 61]). Grudin observed that people tend to *partition* tasks and information between multiple monitors [30]. More recent work identified multi-device usage patterns with different perspectives: Santosa and Wigdor used the lens of device roles and usage parallelism to uncover usage behaviors in distributed workspaces [61], Jokela et al. examined the patterns through their connections with temporality of usage (sequential or parallel) and the relatedness of accomplished tasks (related or unrelated), and Houben et al. emphasized the importance of task transitions (in-task and between-task) in multi-device usage [36]. Our research builds on this knowledge and delves deeper, identifying multiple recurrent patterns of multi-device usage through a similar framework of task relatedness, temporality [41], and transitions [36]. Our work also expands this prior research, identifying specific user values and motivations behind these patterns of multi-device configurations.

We share motivations from prior studies [41, 61] to understand how different professionals (beyond the technology-savvy and researchers) currently use multiple devices in order to reveal broader research and technological opportunities. The global shift to remote work, during the COVID-19 pandemic, offered a unique opportunity for this research. It gave us the possibility to study how technology-naïve or even technology-adverse people use multiple devices at hand to accomplish their tasks, and associated costs and values. This context also offered the opportunity to study rather unique situations such as multi-user multi-device practices, involving families for example, juggling between work and remote education with their children.

Our aim is to expand the knowledge on how people use multiple devices to accomplish their tasks, drawing connections with the physical arrangement of their devices, attempting to understanding how they fragment their workflow across these. The overarching goal is to provide task patterns, configurations, and scenarios of reference that practitioners and designers can leverage when building novel technologies or test against when evaluating them.

3 METHODS

Our survey was administered through Qualtrics during the summer of 2020, where we collected both photos and textual responses about people's multi-device usage during the time when most people had shifted to remote work or online learning from home during the COVID-19 pandemic.

We took a qualitative approach to investigate our research questions. We decided to use a qualitative survey to collect data through online platforms as such a methodology let us reach a relatively large and diverse group of participants, compared to other qualitative methods (e.g., interviews). And with a careful design of survey questions, we were able to collect in-depth data on people's work-from-home setups and tasks they performed on multiple devices. This decision on survey methodology was also driven by the constraints posed by the COVID-19 pandemic when in-person visits and interactions were restricted (i.e., observations and contextual inquiry studies became challenging in the remote format). In the following section, we provide more details on our data collection process, our participants, and our analysis process.

3.1 Data Collection

The survey contained 55 questions, asking 10 open-ended textual answers and 14 multiple-choice or Likert scale ratings (others are demographic questions and prompts for uploading photos). We structured it around five different themes on multi-device usage and experience. The first section consisted of demographic questions. The second part centered around the devices they use and their (multiple) arrangements in space. We asked participant to list and characterize the devices they use or own and to upload a photograph of their most common physical setups. The third set of questions dealt with the tasks and activities they perform using multiple devices. The fourth set inquired about aspects they value as well as pain points and challenges encountered during their tasks. The final category probed into what they felt was missing or needed to improve their experience, as well as the ideal environment for the future. Among the valid responses, the median of completion time was 45 minutes, including idle time, with a small number of responses (14 out of 97) taking over 120 minutes to complete. The survey was advertised on social media channels and active for 4 weeks. Participation was not compensated.

3.2 Participants

Our participants were people who self-selected to respond to our survey posted on social media channels. 588 people started answering the survey and 101 finished it. We included a screening question at the beginning of our survey to filter out responses from people who did not use multiple devices and hence could not provide insights for our research questions. We also manually removed meaningless or partial entries. The final data analyzed consisted of 97 unique responses. Our participants live in various locations around the world, including Asia, Australia, Europe, and South America, with the majority residing in North America (69 participants, 71%). Their ages range from 18 to 74: about a half of them (48 participants) are between 25 and 44 years old. Most of our participants identify as male (80 participants, 82%) and the rest identify as female (11) or non-binary (5). Our participants represent diverse occupations, including student, professors, IT professionals, researchers, creative professionals, marketing professionals, legal professionals, and executives.

Table 1: Ninety-seven Participants' detailed background information (age, gender, region, occupation, and number of devices owned).

Category	Information Details	Number of Participants (%)
Age	18-24 years old	8 participants (8%)
	25-34 years old	23 participants (24%)
	35-44 years old	25 participants (26%)
	45-54 years old	19 participants (20%)
	55-64 years old	17 participants (18%)
	65-74 years old	4 participants (4%)
	Prefer not to answer	1 participant (1%)
Gender	Female	11 participants (11%)
	Male	80 participants (82%)
	Non-binary	5 participants (5%)
	Prefer not to answer	1 participant (1%)
Region	Asia	6 participants (6%)
	Australia	1 participant (1%)
	Europe	18 participants (19%)
	North America	69 participants (71%)
	South America	3 participants (3%)
Number of Devices Owned	2-4 devices	15 participants (15%)
	5-9 devices	42 participants (43%)
	10+ devices	40 participants (41%)
Occupation	Architecture and engineering	3 participants (3%)
	Arts, design, entertainment, and media	6 participants (6%)
	Business and financial operations	11 participants (11%)
	Community services	2 participants (2%)
	Computer and mathematical	27 participants (28%)
	Education and training	7 participants (7%)
	Legal	1 participant (1%)
	Management	21 participants (22%)
	Office and administrative support	5 participants (5%)
	Research	5 participants (5%)
	Student	5 participants (5%)
	Retired or unemployed	4 participants (4%)

3.3 Data Analysis

We analyzed a total of 156 photos following the approach of content analysis and 866 textual entries following the approach of thematic analysis. Through the analysis on the photos, we developed insights of participants' multi-device setups and configurations from visual content. Through the analysis on the textual responses, we generated descriptions on participants' common multi-device usage patterns, as well as their motivations and challenges behind these usage patterns.

To analyze the corpus of 156 photographs, we developed a codebook to understand different physical configurations people commonly use from home. We started this codebook from prior work [11, 48], and iteratively refined it through the discussion among a subset of the authors during joint coding sessions. The final codebook (Appendix A) included 43 individual codes to describe device configuration, input and output modality, workspace setup, and environment. Then, two coders independently coded 20 photos to compare codes with each other to resolve any differences in interpreting the codebook. The two coders also separately coded the same 39 photos (25% photos randomly selected from the set) to ensure consistency. Inter-rater reliability (IRR) for these 39 photos was 0.805, which was calculated using Cohen's kappa, suggesting a strong level of agreement between coders [49]. The two coders then discussed all disagreements in this set of photos' codes to ensure accurate coding, before proceeding to code the remaining photos.

To analyze the set of 866 textual responses from 10 open-ended questions, we followed the guidance of the reflexive thematic analysis approach [10], with a combination of deductive and inductive coding. Three authors independently familiarized themselves with the data and met remotely during a weekly meeting to converge around a set of pre-determined codes from our research questions and related literature (e.g., usage patterns identified by prior work, the relatedness between tasks performed by the multi-device setup). Following the discussion, one author led the coding process for all textual responses, using *a priori* coding and open coding, to identify participants' multi-device usage patterns, motivations and pain points. The same author also led the clustering process, to organize codes into themes, generating insights about participants' values and challenges behind their usage patterns. Over 700 codes were generated from the coding process, and four additional memos chronically document emerging themes and topics.

4 MULTI-DEVICE PHYSICAL CONFIGURATIONS

In this section, we present a set of dimensions to characterize participants' physical device configurations. We analyzed the data from textual descriptions of the survey pertaining to number, types and sets of devices used by participants as well as the corpus photographs of their physical setups. Summary and visualization of the survey is available at our online repository[1], which also includes access to the full corpus and the corresponding codebook. Figure 2, 3, and 4 depict the key dimensions surfaced from our analysis, illustrated by examples from the corpus.

4.1 Summary of Device Ecologies (Figure 2)

Figure 2a depicts the number and types of devices reported by our survey respondents (textual descriptions) and shows devices found in their most common physical setups (uploaded photos). Note that most people took pictures with their phones to upload to the survey so these devices do not necessarily appear in the photo corpus. While we counted devices labelled as shared use of family devices, we did not count devices labelled as being used by a different person than the survey respondent.

Participants own more than 10 devices on average. We found that the average number of devices per person was more than 10, which was higher than we expected. Yet it is important to note that this number greatly varied between participants, the minimum being 3 devices while the maximum was 26 (see graph in the lower right corner of Figure 2a). In addition, 25 participants also reported devices belonging to others in their household, or not currently in use, which we excluded from our count. This means that *most participants have a large number of devices at their disposal, perhaps as many as a dozen* if we account for household devices.

In fact, almost half of the participants (46) reported owning the entire range of form-factors (phone, tablet, laptop or desktop, and TV). Assuming that everyone has a TV, which we strongly suspect, this would amount to about 76% of our participants. *Not only do participants have many devices, but most have the full range of device form-factors.*

[1] https://devicesathomestudy.github.io/devicesathomestudy

Participants never use their entire device ecology together. When analyzing the descriptions of physical setups and the corpus of photos, we could not find a single participant using their entire set of devices together for any activity. Instead, *participants describe using multiple sets of devices* (averaging 3 sets per person), often associated with certain rooms in their home. It is interesting to note that *most participants (89) tend to use devices with similar form-factors together* as our scale of homogeneity indicates.

Participants also do not think of TVs as devices. Over two thirds of participants (63 of 97) omitted to report their TV, although in about half of these cases, we added a count of at least one TV when they reported it later in the survey, or mentioned streaming devices or gaming consoles. As P40 states *"I would have loved to turn my large TV into my computer monitor while Zooming from home during this pandemic remote life." There is an opportunity to help people better leverage these (often) large devices around them.*

Participants have vastly different device ecologies and physical configurations. Photos and textual descriptions reported vastly different device ecologies both in number, form-factors, and physical arrangements. Figure 1 gives an idea of the variety of setups reported in the survey. We report a few of the most commonly found sets of devices used together below. Yet we want to note that physical arrangements, even for similar sets of devices, often vary between participants.

Classic laptop or desktop with external or large monitors are in dedicated work areas. Mentioned by 67 participants (and counted 69 times in the photos; Figure 2c), this classic setup is prevalent in dedicated home offices. However, *all of these participants also described using their devices from other places, not always taking advantage of these large or additional monitors.* Almost a third of the participants (30) do not own any additional monitors.

As one might expect, **all participants had at least a phone, and most (93) reported to have at least a laptop or a desktop**. While few photos of physical configurations exhibit the presence of both a phone and larger device, nearly all participants reported carrying the phone with them at all times and often using it with their other device. A surprising finding is that over two thirds of the participants (74) reported at least one tablet. The data suggests that tablets are often paired with larger devices to act as a companion. *This suggests the emergence of larger form factors such as tablets used as companion devices.*

Another interesting recurrent set of devices participants report using are dual laptops. *Almost half of the participants (41) reported using at least two laptops together* and photos frequently showed them side by side in physical setups.

4.2 Device Arrangement and Orientation (Figure 3)

The majority of our participants submitted the photo of their fixed and larger setups (e.g., dedicated home office), although they described textually other configurations, often more mobile, with a smaller subset of devices. Overall, we noted a wide range of diverse physical setups.

Participants do not necessarily place their devices next to each other. In fact, half of the participants (47) had one or more devices relatively far away from each other (Figure 3d). We also

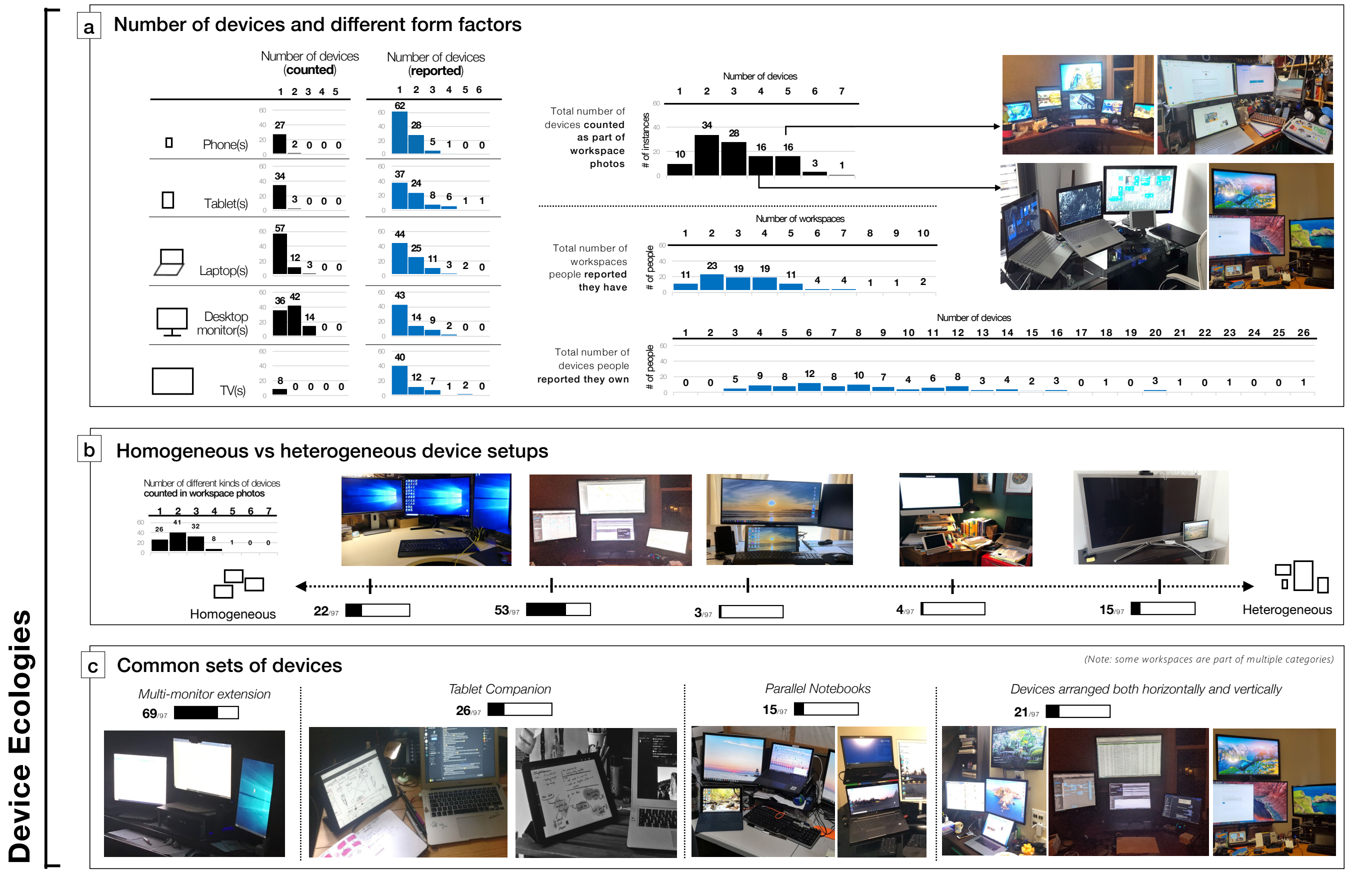

Figure 2: Physical multi-device configurations – Part 1: Characterizing the device ecologies used by our participants.

found instances where participants were stacking or overlapping devices. In some of these cases, participants had their phone (likely temporarily) propped up on a device. However, in some other cases, it appeared at a more permanent overlapping setup (see example in Figure 3d overlapping).

Participants do not use devices flat on their desk, even tablets. Few devices are actually depicted flat on the work surfaces, apart from their phones (probably temporarily placed on their desk when not in use) — summarized in Figure 3e. Most tablets were found in a tilted position, even ones we could identify as pen-enabled tablets. This may suggest that participants optimize the angle for screen viewing by default in their multi-device setups, rather than for hand touch or pen interaction. We also found that the large majority of devices participants used is within arms' reach (Figure 3g). This may explain the large number of concave arrangements found in the photos, placed around the user.

Participants want to integrate their mobile devices better in their setups. A relatively large number of the mobile devices (tablets, laptops) were positioned in semi-fixed setups (i.e., on a stand). Participants appeared to position these devices with additional stands or flexible mounts, at higher positions or at a tilted angle, likely for better viewing; or to align them with different devices in a more continuous manner (Figure 3f). Yet, the semi-fixed nature of these setups and the textual comments describing other physical arrangements indicate that participants want to retain the mobility of these devices.

4.3 Multiple Workspaces at Home (Figure 4)

Multiple workspaces (an average of 3) are reported — which often include one or more fixed setup or mobile ad-hoc workspaces. As P53 put it, they have a *"Home Office [with a] windows computer, 33" screen. All other devices float around the house."* Note that our photo corpus is likely to be incomplete as 67 participants submitted a single photo, usually of their fixed setup or dedicated workspace, while describing multiple physical setups in the textual answer.

Participants tend to work on small surfaces. Given the relatively large number of devices participants own, it is an interesting finding that about half of the participants (47) used rather small work spaces with low clutter, even in dedicated office areas (Figure 4h and 4j). In fact, three participants did not identify any work surface: *"I just pile them all on the couch at once"* (P74). Several participants explained that different spaces in the house were assigned to different household members. Sharing spaces with others and migrating between spaces may be factors for more compact work spaces with low clutter.

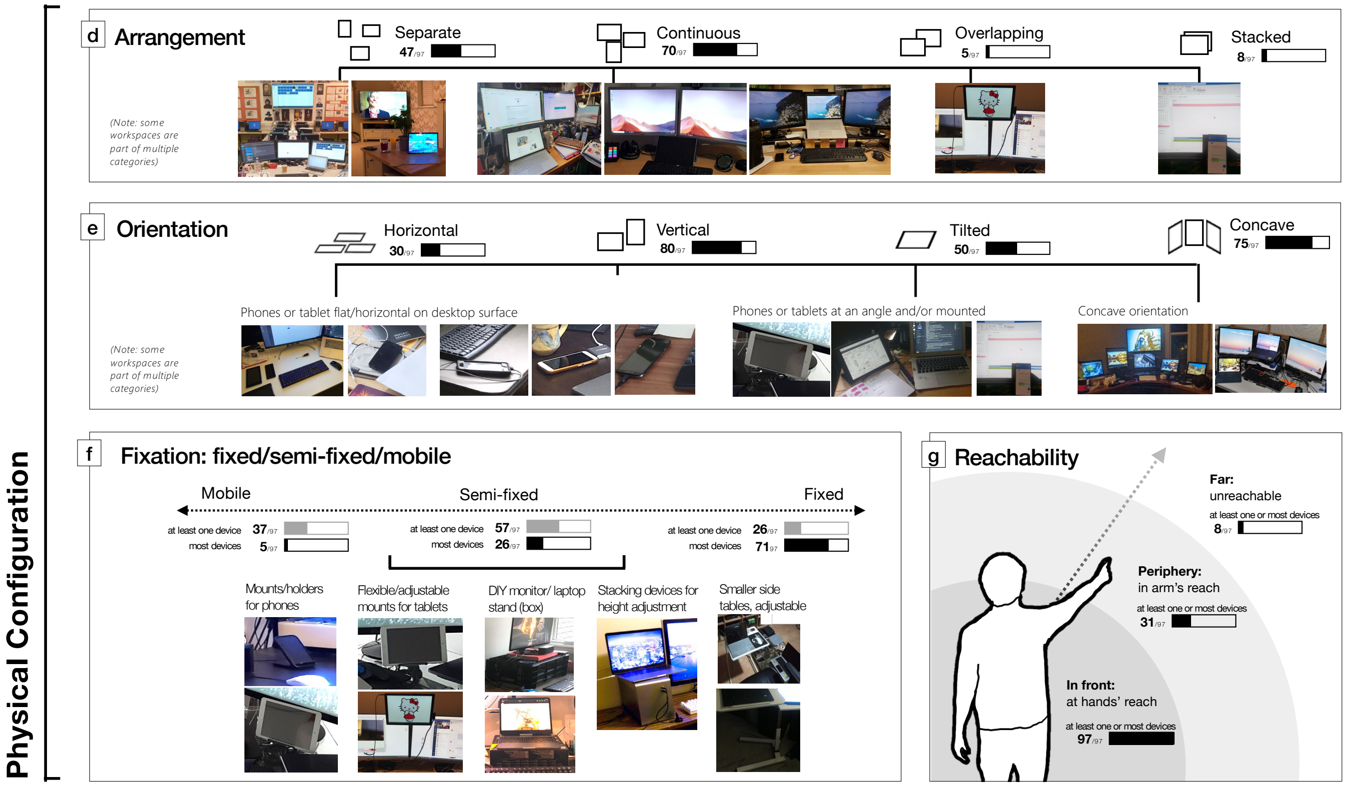

Figure 3: Physical multi-device configurations – Part 2: Device arrangement, orientation, fixation, and reachability.

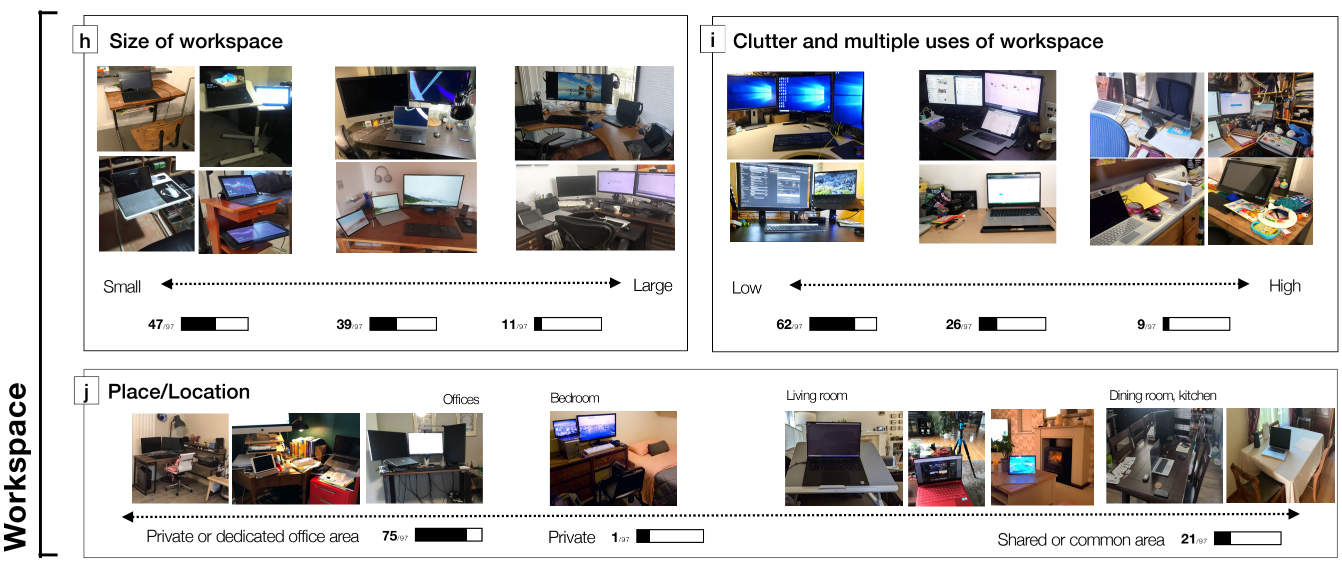

Figure 4: Physical multi-device configurations – Part 3: Size of workspaces, clutter and multiple uses, and places/location.

Participants migrate between workspaces. A theme that often came back in participants' description of their different workspaces is the migration over the course of the day. For example, P53 explained: *"We use devices wherever we are during the day. In kitchen for breakfast to see news, at deck for breakfast, on deck during lunch, on sofa in evening for relax and streaming movies."* Participants commented positively on the ability to move their setups around their house *"[physical location] Changes constantly - kind of the point"*

(P52). All of the participants noted that they worked at least in two locations in their homes. P6 labelled theirs as *"a roving physical setup,"* describing using an adjustable metal stand, the kitchen table, an outdoor table, or the couch, depending on their mood and social context. A recurrent theme is participants moving to specific larger desk spaces to have better ergonomic posture, or because they require extra space for hard keyboards or to take advantage of a larger fixed screen, for example. *"Macbook Pro - email, websurfing, website upkeep, MS Office - dining room / will go to office if need large monitor"* (P94).

Participants often have to step away from their dedicated optimal fixed setups. Participants also often reported moving around their house because of other members in their households. For example, P16 commented that *"with kids at home I cannot always be sat at my desk working [...] I need to be able to do work and interact with my kids."* Conversely, participants also reported needing to isolate themselves from others. For example, P57 noted *"I work outside a lot because the noise from my baby or wife working as a piano teacher will be too loud to cancel out."* Comments indicate that, in many situations, people have to step away from their "optimal" work spaces, which may explain the number of semi-fixed setups we observed in photos.

To mitigate this, a few participants created mobile multi-device workspaces enabling them to **migrate their entire multi-device setup**. For example, P19 described theirs: *"When I work I use a rolling laptop stand. One of my work PC's sits on the main shelf. I use my Surface 3 Pro on the side shelf as a second display."*

5 MULTI-DEVICE USAGE PATTERNS FOR DIFFERENT TASKS

In this section, we present five different multi-device usage patterns that emerged from our data. For each pattern, we provide example activity scenarios from participants then we describe user values and motivations behind different multi-device usage as well as current user challenges.

5.1 Common Multi-Device Usage Patterns

People work on multiple tasks in their everyday work and life. Especially when after transitioning to working from home, they often need to manage tasks from multiple sources (e.g., work, family). Participants described a wide range of tasks they accomplish with multiple devices such as writing reports and creating slides, attending meetings, remote teaching, developing software, sharing media content, and discussing family budget. Our analysis on the subset of 253 entries submitted by participants to describe their top three activities led to 170 unique combinations of tasks. We first attempted to cluster these by their nature such as communication or content generation. Yet, we could not identify salient connections with regards to multi-device usage. Instead, we took a different perspective, abstracting the nature of each task to instead focus on their relatedness (i.e., whether tasks are related to each other or not), and their arrangement in time (simultaneous or sequential) [41]. This perspective led to the identification of five categories of multi-device usage patterns: *integrate*, *clone*, *expand*, *partition*, and *migrate*. Some of these identified usage patterns echo the patterns identified by prior work (e.g., *integrate*, *partition*, and *migrate* [30, 41, 61]). These patterns reflect the different recurrent ways people arrange their devices, associating each with a different set of values and challenges. Figure 5 situates these usage patterns in the context of task relatedness and time ordering. We then describe each and provide example scenarios from participants.

5.1.1 Participants ***integrate*** devices that are suited for the tasks.

Different devices have different strengths related to performing various tasks. This usage reflects the computing vision suggested by Weiser, that computing devices have different capabilities to serve different task needs [65]. For example, using a high quality camera for a video call, a touch screen for small search tasks, or a large screen for tasks that require a lot of visual space. This recurrent pattern also echoes usage identified by prior work: borrowing resources from other devices for a single task or using multiple devices for the same task [41]. With multiple related tasks, each of them might have different requirements of a device. For example, in an online lecture scenario, taking notes requires a digital pen with a tablet while viewing lecture content requires a laptop screen for better viewing experience with larger screens (e.g., P28, P70). P22 also talked about distributing tasks that need more computing power to a desktop and keeping other related tasks on another laptop when working on rendering tasks for 3D models. Sixty-two participants discussed the way they *integrate* the strength from different devices to work together for completing related tasks simultaneously. Figure 5a illustrates an example from P57 demonstrating integrated device usage for joining an online meeting. In this setup, he used the tablet to access the digital collaborative whiteboard with digital pen, smartphone for internet audio for the meeting, and laptop for large screen view and web camera.

5.1.2 Participants ***clone*** tasks to other devices.

Whether it is the entire workspace or a single application, we saw that people duplicate the tasks to all their available devices to interact with their application from any device when needed. Twenty-two participants provided examples of this device usage from two contexts. When collaborating with other co-located or remote people, participants needed to *clone* their entire workspace to another screen to share their tasks (e.g., P31, P77). For tasks that needed to be monitored throughout the day (e.g., checking emails, playing music, checking calendar schedules), participants would like to have the task duplicated on all available devices so they could pick up any device to interact with the task at any time (e.g., P6, P29, P63). P48 described an example of cloning a laptop workspace to a TV through a wireless display setup, for sharing media content, web pages, or YouTube videos with family members (illustrated in Figure 5b).

5.1.3 Participants ***expand*** tasks to all devices.

Several participants (7) provided examples of *expand*ing tasks to multiple devices to have more screen space for the data set they needed to work on (P50) or *expand*ing the same set of input to interact with related tasks between devices (e.g., P32). This usage lets people have an *expand*ed device screen or input space to accomplish tasks. P76 provided an example of expanding input to multiple devices that is depicted in Figure 5c. In this usage, he set up an application that allows him to use one set of keyboard and mouse to interact with tasks from two computers connected to three monitors. With this

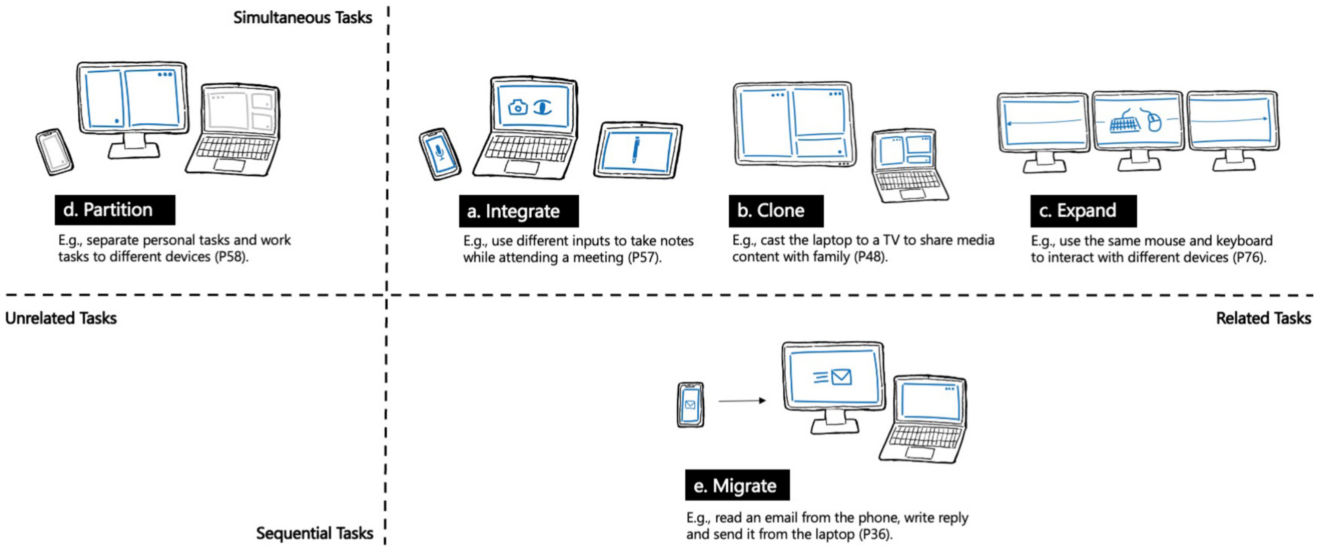

Figure 5: A summary of five multi-device usage patterns with example scenarios in the context of task relatedness and order: a. *integrate*, b. *clone*, c. *expand*, d. *partition*, and e. *migrate*.

expand setup, he could move task content between devices tied by one set of input.

5.1.4 Participants ***partition*** *tasks onto different devices.* When working on unrelated tasks or tasks that are independent of each other, people tend to distribute them across different devices to keep them separated from each other. Forty-six participants *partition* their tasks in their multi-device activities. Grudin identified a similar pattern in his prior work investigating people's multi-monitor usage [30]. He found that people like to distribute their secondary tasks, either related or unrelated to their primary tasks, to secondary monitors. Our *partition* usage only focuses on the scenario of working on unrelated tasks with multi-device setup. This usage is common when participants work on personal tasks and work tasks at the same time (e.g., P14, P69, P79), work tasks with different contexts (e.g., P10, P31), or attending a remote meeting while working on a separate task (e.g., P3, P16, P92). Figure 5d shows an example of *partition* usage from P58. In this usage scenario, he used the laptop for primary work and video conferencing, the tablet for watching media, and phones for checking messages or browsing social media.

5.1.5 Participants ***migrate*** *tasks from one device to another.* Due to outside interruptions and other reasons, people often have to change their working environments but need to continue their tasks. In such contexts, 22 participants talked about migrating tasks from one device to another device to complete their tasks when they need to switch their workplaces in their daily work and life. A similar pattern in migratory interfaces and devices has been identified by prior work (e.g., [11, 41, 61]) and we follow a similar definition to describe this category of multi-device usage (i.e., migrating between devices to work on related tasks). For example, participants described how they check and read emails from their mobile phones when they wake up in the morning, and then *migrate* to their laptops or desktops to reply to these emails (e.g., P22, P66, P91). Figure 5e provides an illustration of this usage scenario (P22). P36 also talked about starting a collaborative document from the laptop but later *migrate*d to the phone to continue editing and to view discussion from the car.

5.2 Values Behind Multi-Device Usage

In this section, we analyze the ways in which multiple different patterns serve the same high-level need, articulating the values that people gain from working with multiple devices. These insights are extracted from the thematic analysis of textual answers to five questions of the survey prompting participants to articulate the benefits of working with multiple devices to achieve their tasks.

5.2.1 Use all devices together for various task needs. When people work on a set of related tasks, these tasks often have different requirements on device capabilities [65], including required computing power, larger screen real estate, or preferred input modality. The *integrate*d usage allows people to compose "a super device" for the tasks taking the strength of different devices. As both P22 and P30 commented, because "*some devices are more powerful than others*" and "*the feature need that could only be used on certain devices*", participants wanted to distribute tasks to devices that have the most appropriate form factor for completing those tasks. This could mean picking the device with the best performance for completing a computationally heavy task (P91), using the camera on the mobile device to scan a document for its better suited form factor (P19), or writing notes with a digital pen during an online lecture (P40). As P36 commented, "*each device has its strength and features, using multiple devices lets people get the most out of each device*". Having multiple devices also allows people to have a non-disruptive primary task environment, when unrelated side tasks pop up that people need to attend to. With the *partition* usage pattern, people can keep the primary task on one device and complete unrelated side tasks from another device without one blocking the other (P18). *Expanding* a single input to multiple devices also let participants tie multiple devices together. The transitions between devices became more seamless and would not be disrupted by switching input devices (P32). Each pattern may involve very different redistribution techniques, but all to serve the same purpose of leveraging the most important aspects of a device to achieve a specific task.

5.2.2 Separate devices with different purposes. Grudin [30] identified patterns in the way that people use multi-monitor setups. Building on that work, we found that people take a similar approach to their multi-device setups, often assigning different roles and purposes to devices. *Partitioning* tasks into devices with different assigned roles lets people better separate and manage tasks from different categories. Many participants drew the distinction between work and personal devices (e.g., P3, P29, P43), and discussed splitting work and home related tasks between work and personal devices. This separation helped keep private and personal information away from work devices and draws the line between work and personal life when people were working from home during the pandemic. As P9 mentioned, "*I do want to keep work mostly separate from home though, so I don't want to use my work device after hours.*" In addition, some devices might be shared among family members. Keeping work tasks away from those devices helped participants better manage their work tasks when they were at home. P31 discussed another scenario within his work when *partitioning* unrelated tasks to different devices could be helpful. As he often needed to work on tasks for different clients, "*keeping them on different devices*" was the easiest way to achieve separation between these tasks. This pattern supported people's needs to compartmentalize different aspects of their life when working from home.

5.2.3 Augment primary tasks with multi-device usage. Using multiple devices allows people have more space for their primary and related tasks. Several participants mentioned that with more screen space from multiple devices, they could "*preserve the status of primary tasks on [one] device while having access to more information [on other devices]"* (P38). P41 specifically mentioned the online meeting scenario: multi-device usage allows them to maintain contact with other meeting attendees while having the flexibility to reference a document under discussion. This device usage is not only helpful in work contexts; P32 mentioned that *integrate* usage was also common outside working hours, for example, during movie watching. Having an extra device to look up related information without entirely disrupting their immersive entertainment experience supplemented the activity with more context . The *expand* usage also provides more space for the primary tasks when needed. For example, P50 mentioned that expanding a task which required more screen space to multiple devices provided "*more visibility, more flexibility, and more live data*". Often times, the ability to leverage devices with more screen space with *cloned* workspace helps provide shared context and facilitate the collaboration process. Several participants provided the examples from family context, when they cast media content from their laptops to TVs for sharing with other family members (e.g., P48), or duplicate their tablet screen to another laptop to discuss family budget planning with their partner (e.g., P36). The ability to *clone* a workspace also helps facilitate the collaboration process in remote settings, as P60 mentioned that the ability to see "*what each other to make sure they were not at cross-purposes*" is really important when working with others. These patterns helped device users to augment their own work processes, and collaborate with others, especially in online settings.

5.2.4 Support flexible work environments. People need to juggle between different responsibilities and tasks when working from home (e.g., work, child care). This often requires people to be able to work from any place and any time throughout the day. Having various devices with different form factors (e.g., portability) allows people to *migrate* tasks between devices, or pick up any device with *cloned* tasks to work from. Many participants discussed the importance of mobility in their work, either going outdoors to work (e.g., P16, P68), or attending family and children's needs during the work hours (P25). As P36 discussed, "*different devices are best suited to the physical location and level of intrusion*". In addition, having the same set of tasks *cloned* on all available devices provided participants with the flexibility to choose any device to work from. Having communication tasks *cloned* to all available devices helped demonstrate participants' presence and availability during the workday, so they "*could be reached and could reach others at any time and any place*" (P69). The flexibility to choose any device to interact with the tasks can also be helpful outside of work settings. For example, P6 commented on the experience with having *Spotify* on multiple devices, that he could change the song or the volume on "*any of the devices and it would happen right away*".

To summarize, our work provides insights on user values and motivations behind recurrent usage patterns that categorized our participants' work-from-home multi-device workflows: using appropriate device capabilities for different tasks, separating personal tasks from work tasks for privacy needs, borrowing additional space from other devices for sharing, and choosing device form factors for mobility during work. These different values and trade-offs between them drive our participants' device usage. As our participants switch between tasks and contexts, their values and priorities also changed, and often times could lead to transitions between usage patterns. In the following section, we present insights into participants' hybrid multi-device usage.

5.3 Hybrid Multi-Device Usage

Two third of the participants (61) reported more than one usage patterns. In this section, we describe some common combinations of individual usage patterns and provide examples scenarios associated with these combinations.

*5.3.1 Combine **clone** with **integrate** or **partition**.* One of the popular combinations of usage is clone and integrate or partition patterns (16 participants). The tasks involved in the *clone* usage can often be characterized as "background tasks" [15], such as watching concert, listening to music, monitoring emails or messages. P36 provided an example scenario with both *clone* and *partition* usages at the same time, that he mirrored live stream concert from his phone to the TV for watching with his partner while engaging in side conversations with his friends over the laptop (illustrated in

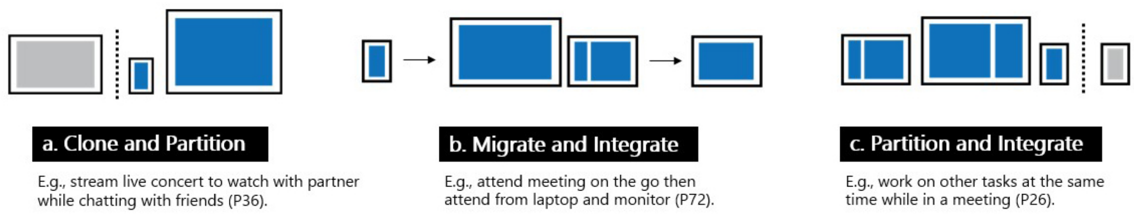

Figure 6: Illustrated examples of hybrid device usage patterns: a. combine clone with partition, b. combine migrate with integrate, and c. combine partition with integrate.

Figure 6a). Participants often involved in other tasks at the same time, both related and unrelated to the primary tasks performed with *clone* usage. And these tasks involved other device usage pattern like *partition* or *integrate* to provide more context for the other task or make sure the tasks do not block each other. P7 also talked about monitoring emails while watching videos. Depending on whether devices were occupied by other tasks or not (such as browsing websites related to the video), he would pick the device that is more available for checking emails.

5.3.2 Combine **migrate** with **integrate** or **partition**.

When working from home, people often need to move from one place to another, as well as migrating their workplaces. Our participants commented on taking advantage of devices with different forms factors to be able to work from difference places at home or going outside. However, as people moving between workplaces, they would still like to use multiple devices simultaneously in a *partition* or *integrate* setup when the work environment allows (e.g., having a dedicated working area, having enough surface space for multi-device usage). We identified 13 participants who had hybrid usage of *migrate* and *integrate* or *partition* patterns for their everyday tasks (e.g., P45, P72, P69). P72 provided an example from his multi-device experience with online meetings (illustrated in Figure 6b). When he was away from the desk, he often joined the meeting from the smartphone. And when he moved to the desk, his desk workspace had multiple laptops and monitors set up to "*push the performance*" for working while attending the meeting.

5.3.3 Combine **integrate** with **partition**.

When primary tasks require more resources, people might transition from *partition* usage to *integrate* usage for their changed task requirements. Such transitions are more common when people have similar physical device setups for their *partition* and *integrate* usages. We found 23 participants engage in both *partition* and *integrate* patterns with their multi-device usage. P26 provided an example of this transition (illustrated in Figure 6c). While attending a meeting from his laptop, he might also send messages with people who were not involved in the conference call, take meeting notes, or do quick online searches, regardless of whether the tasks were relate to the meeting or not. Participants often dedicated these non-primary tasks to devices that were more mobile, such as tablets or smartphones, as these devices had the flexibility to quickly transition to a different setup for different task needs. P95 also talked about an example usage during cooking, that he used one of the devices both for timing and streaming music that were not related to cooking (besides another device he used for looking up recipes).

5.4 Current Challenges with Multi-Device Usages

Many challenges exist with current multi-device experiences. In this section, we describe the challenges reported by participants resulting of the analysis of textual entries to five questions.

5.4.1 Effort to manage multiple devices.

Our participants had on average over 10 devices at home, and managing all of these devices could be tedious. Managing devices is a particular challenge for multi-device setups. We identified three particular categories of management challenge: configuration, power management, and synchronization. Previous studies also identified similar challenges in energy management and data synchronization with multiple devices (e.g., [41, 61]). In our work, these challenges were especially associated with *partition* and *integrate* patterns, when participants needed all their devices to be ready and work together for their tasks. Keeping track of multiple devices, charging them and managing different devices' power needs (i.e., some devices might have a shorter battery cycle), organizing all the cables and chords attached to devices, or keeping all devices up to date could make the multi-device experience frustrating and prevent people from using all of their devices. As P35 mentioned, it was frustrating *"when one device is updated but [an]other refuses to get the latest sync"*. More effort in configuration or re-configuration is needed, when people want their devices to work together. P92 mentioned that much effort is needed to position devices in the correct places every time for his multi-device setups. The configuration process can also be challenging when people need to manage different configuration requirements with multiple devices. For example, some devices can only be placed on a flat surface, or some devices must need to be placed on a stand (P87). **Once participants configured their devices to work together, substantial effort was required to change their setups**. This resulted in a lack of fluidity in changing the configurations like switching monitor sources, or reconnecting input devices (P98). All these efforts are a barrier for people hoping to fully utilize their multiple devices.

5.4.2 Compatibility and consistency between devices.

Challenges like cross-device interface inconsistency and incompatibility across devices also become barriers in people's multi-device experience. Sometimes multiple devices are not easy to interface together, often because of compatibility issues between different platforms. Similar challenges associated with diversified device ecosystems were identified by prior work in understanding people's multi-device experiences (e.g., [23]). Our participants mentioned such challenges that services or applications which are supported on one device but not fully supported on another device. P35 also mentioned the difficulty of integrating one device with another operating system into their existing device ecosystem. **Most of our participants stated that they expected multiple devices to work together as easily as if connecting multiple external monitors**, without worrying about compatibility issues between different platforms or the need to explicitly migrate content to cloud storage. Some participants needed to figure out work-around to get their devices together and rely on additional service. The incompatibility between devices increases the challenge of debugging or addressing issues as they come up. For example, P87 mentioned that he needed to go through an external hub for the sensors at his house to interface to an Amazon Echo, and if something breaks in this connected multi-device systems, it often "*takes a while to debug the issue*". Even an application or service is fully supported across different device platforms, the experience might be inconsistent from one platform to another. In some of the *integrate* and *migrate* usage examples, participants discussed how inconsistent experiences (e.g., different shortcuts) could become barriers in their multi-device usage, when they needed to remember and spend time adjusting to different platforms' experiences (e.g., P36, P43, P93).

5.4.3 Repetitive actions with the same application across devices. When people use the *clone* pattern to distribute tasks to multiple devices, participants often need to interact with duplicated information on devices multiple times for one single action. For example, several participants (e.g., P4, P30, P70) mentioned the repetitive effort involved when marking notifications as read on multiple devices with their messages and emails, because the "marked" notification status was not shared between devices. P11 also mentioned that "*it was frustrating to touch multiple times on multiple devices for one single action*" when the action such as marking notification was not shared between devices. Participants sometimes also spent repetitive effort when *migrating* tasks from one device to another. As P77 mentioned, when transitioning between devices, the context of the task built on one device was often lost during the transition (e.g., launch the main application, open up the reference documents to support the task). **Participants often need to rebuild the task context on multiple devices, taking time and effort for something they expect should just work**. As P70 puts it: *"I should be able to drag running applications between *devices* and have them just work."* All these challenges increase people's effort and the cost in utilizing multiple devices for task completion.

6 DISCUSSION

We first summarize insights we gained and how they expand the knowledge we had from prior studies on the topic. We then reflect on how to bridge the gap between empirical findings and novel technology, describing how a multi-device usage-centric perspective outlines opportunities for design. Finally we discuss limitations of our study.

6.1 Building Empirical Knowledge on Multi-Device Experiences

Prior work unpacked the roles that different devices may play for a given user's setup [61]. We augment these earlier findings by also considering the way physical layout affects these roles. Where Santosa and Wigdor identified patterns of device usage, our work additionally identifies strategies people have for managing these device usage patterns. For example, the"Producer-Consumer" pattern identified by Santosa and Wigdor (where contents or an application from one device is transferred to another) represents a high-level pattern of cross-device usage. Our work explores how device form factor, relative physical proximity between devices, and changing workspace locations all influence the usage of this interaction pattern. The "Controller-Viewer/Analyzer" pattern involves interacting with the digital space through multiple physical devices. Our *clone* pattern, where all devices are able to interact with tasks across the entire workspace, represents users attempting to achieve this pattern given current technology limitations. We also found that device arrangement and orientation is a key aspect of using the "performer-informer" and "performer-informer helper" patterns (where one device is used as a reference or supporting interface, and a second device is considered the primary device for a given task).

Additionally we identified the ways in which multi-device usage patterns are influenced by aspects of both the overall device ecology, but also features of the devices themselves. Grudin [30] describes the way that people partition related tasks across separate monitors. Our work extends these findings across multiple devices of varied form-factor, size, screen orientation, placement, or input capabilities — not just multiple monitors — and also identifies specific types of tasks that result in this type of device usage pattern. People tend to partition personal and work tasks across multiple devices, seeking to separate these different contexts through physical as well as cognitive affordances of distinctly placed devices. Our work also identifies specific challenges that limit the utility of multi-device setups, even when people would prefer to leverage their multiple devices similar to the way Grudin's users did. Grudin's users were primarily working with multiple monitor setups, which connect together with a cable that is relatively permanent. In contrast, we identified the way that cable management and configuration challenges both represent barriers for fully taking advantage of multi-device setups. Images from prior work show similar device ecologies [36], strengthening our findings.

By looking at multi-device experiences via the usage lens, we build upon insights from Jokela et al. [41] regarding the type of tasks people perform with multiple devices, uncovering five patterns that we can compose together to describe people's entire workflows. Our findings demonstrate similar usage patterns as identified by prior work, when people transitioned to work-from-home. We also supplement these insights on usage with detailed descriptions of physical configurations, values, and challenges to provide a rich picture of people's multi-device workflows when working from home. Such end-to-end workflows can serve as frames of reference for researchers and practitioners to compare and assess the value of different technologies for their users.

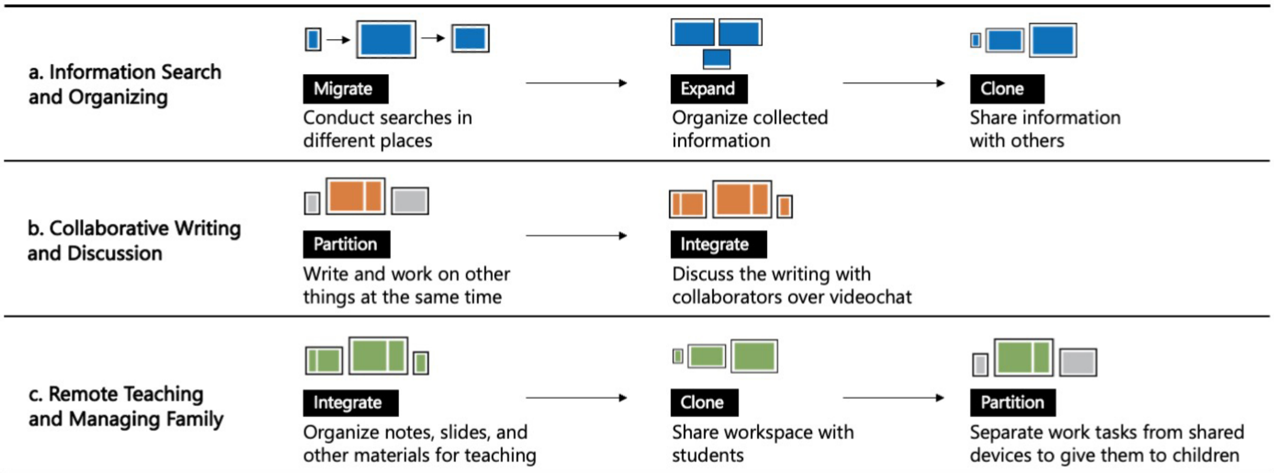

Figure 7: Example workflows built upon our participants' responses. Example a demonstrates a general information search workflow. Example b presents a remote collaborative writing process. Example c shows an example of balancing between work and family needs.

6.2 Bridging the Gap between Empirical Findings and Opportunities for Future Design

6.2.1 People have fragmented workflows. Our insights from the analysis of the physical configurations indicate that people own a substantial number of devices and use them in distinct sets. Transitioning to work-from-home also contributed to these distinct device setups in their workflows, as they often work in multiple locations, on multiple work spaces, and migrate between these places to adapt to different tasks' requirements and their changing priorities (i.e., juggling between child care and work). Their workflow is thus fragmented into multiple sessions which may involve different sets of devices in different physical configurations.

Our insights from the usage of multiple devices together indicates that people vary in their usage patterns, depending on the groups of tasks they seek to accomplish such as coordinating multiple related tasks (e.g., taking notes while participating to a live meeting via video and chat), or juggling independent tasks (e.g., working on a professional document while listening to music and conversing on social media with friends). Their workflow is thus fragmented into multiple tasks that require different levels of attention, and possibly different device capabilities.

In Figure 7, we illustrate three examples of such fragmented workflows, shaped by the survey responses we gathered (e.g., information workers like P36 and P79, or professionals balancing between family and work tasks like P25 and P98):

- (Figure 7a) conduct information searches from different devices (*migrate*), organize all information collected (*expand*), and share with other people, such as colleagues or family members (*clone*);
- (Figure 7b) write reports while working on other tasks at the same time (*partition*), then attend a remote conference call to discuss the reports with collaborators (*clone*);
- (Figure 7c) prepare course materials and teach remotely (*integrate* and *clone*), while managing kids' distant learning needs at the same time (*partition*).

Considering such end-to-end scenarios and understanding the different ways people fragment their workflows (both from the task and physical configuration perspectives) is critical to evaluating the value of existing multi-device technologies and informing novel solutions, whether hardware or software. Ultimately, the technology we want to build should better support what people want to do with the devices available to them. This means 1) better supporting each usage pattern and 2) better supporting transitions between these usage patterns (an entire workflow, which might encompass a compound task across multiple devices or multiple subsets of devices that support meaningful cognitive chunks [14] and thereby help to interweave different portions of the user's workflow).

6.2.2 Better supporting each usage pattern: the interplay between usage and physical configuration. There is a tight relationship between usage patterns and physical configurations: some physical configurations are better suited to certain usage patterns; conversely some usage patterns prompt a reconfiguration of the physical configuration. For example, devices of similar form factors, placed in a continuous manner naturally lead to expanding content. Figure 8 summarizes the insights we gained about the interplay between usage and physical configuration when looking more closely at a subset of participants (26) who provided specific configuration photos to supplement their textual descriptions of tasks performed on multiple devices.

The most salient dimensions of the physical configuration are the homogeneity (or heterogeneity) of the device form-factors and their arrangement in space. Heterogeneous forms of devices allow people to have a diverse of range of device form factors to choose from for their tasks. Diverse form factors provided participants with the opportunities to choose the best device for tasks with their preferred input modality and platform (e.g., *integrate* usage)

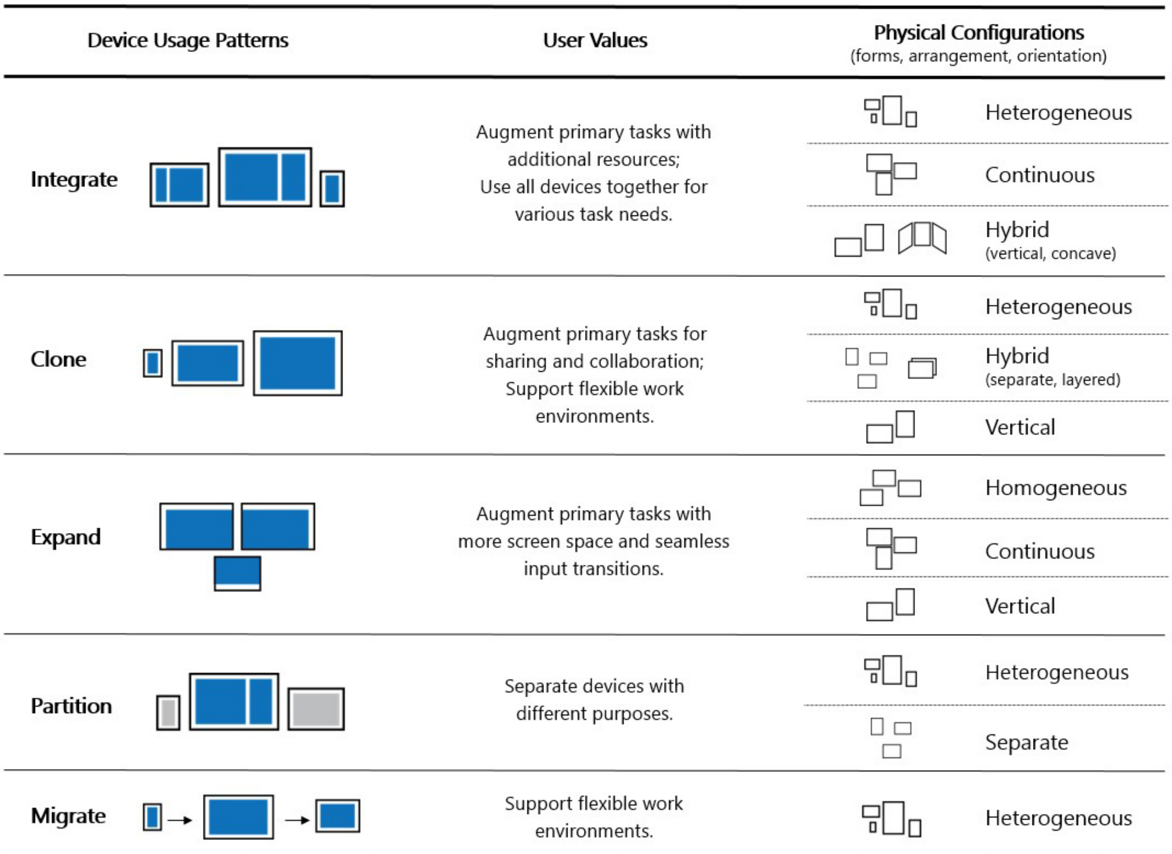

Figure 8: The connection between five usage patterns and device forms, arrangement and orientation from physical device configurations. User values provide potential links in explaining how some device physical configurations might facilitate some device usage patterns.

or the device that was best suited to a certain environment (e.g., *clone* and *migrate* usages). On the contrary, having homogeneous forms of devices allowed our participants to have a more unified experience across devices for extending tasks to multiple devices (e.g., *expand* usage). Looking at the arrangement of these devices in space, when working on complex tasks that requires more space, participants often arranged their devices continuously to form a connected screen space (e.g., *integrate* and *expand* usages). Several participants also arranged their device screens concavely, for easier viewing of information and tasks on multiple screens. On the other hand, participants intentionally keep devices physically apart when they did not want to mix tasks or want to reduce distraction from a certain device (e.g., *partition* usage). In addition, participants associated devices with different locations which helped them pick available devices as they move between different workplaces (e.g., *clone* usage).

These findings directly call for novel hardware solutions to enable people to compose continuous or separate arrangements of heterogeneous or homogeneous sets of devices. Recent research (SurfaceConstellations [47], AirConstellations [48]) started investigating such flexible and (re)composable arrangements of sets of devices in space with novel fixations or articulated arms, yet they did not investigate more heterogeneous sets of devices.

6.2.3 Opportunities for better supporting people's fragmented workflows. Insights we gained from this study make it clear that considering people's ecology of devices as a whole is key to crafting more compelling multi-device experiences. For example, automatically sharing the mobile data connection if another device's WiFi connection fails, and sharing more than content such as peripherals and applications between devices, are recurrent needs expressed by our participants. These findings provide fresh supporting evidence and direct observation of the physical device configurations and real user needs articulated by people working from home across multiple devices — and directly relate to higher-level ideas described previously in (for example) the *society of devices* [25] and reiterated in the more recent *SurfaceFleet* [13] paper.

Prior research examined specific sets of devices and proposed novel compelling experiences for these sets such as Duet [20] for phone and watches, or SurfaceConstellation [47] for sets of tablets.

Yet, insights from our research revealed that people have vastly different sets of devices (both in number and in form-factors). We advocate that a shift from technology-focused to usage-focused research is valuable to move the field forward. We need to understand how people can accomplish a compelling experience to achieve the same types of tasks given vastly different sets of devices.

These different usage patterns uncovered the need for relatively **complex application behaviors**. For example, "maximizing" an application across multiple devices may mean stretching the same view across two devices if users wish to *expand*, whereas *integrate* may result into two different yet complementary views on different devices. Our findings indicate that distributing applications across multiple devices does not have a single deterministic optimal solution. Depending on the user's task, situation, or usage intent, the optimal solution may be vastly different. Thus, there is a need for novel interfaces components and visual feedback to enable people to understand how applications are distributed across a set of devices and gain agency over their behavior to achieve a given pattern — without introducing inordinate complexity or an overwhelming number of options.

Tightly interconnected to the user interface, there is also a need for rethinking **multi-device interaction techniques** to encompass the entire range of usage patterns. For example, existing techniques such as stitching [33] — enabling users to start a gesture on a device and complete it on another — mostly support the *expand* pattern. There is a need to investigate how this and other multi-device interactions may be leveraged for different usage patterns. A much larger research undertaking is to survey the whole landscape of multi-device interactions and extract their strengths and weaknesses in the context of usage patterns, in order to extract higher-level principles and guidelines.

From our data analysis, we believe that people organize their dedicated work area to achieve the usage pattern that they value most or, that appears most prevalent in their workflow. Many participants used semi-fixed setups, enabling them to transition to different setups facilitating different usage patterns. Better supporting these transitions is thus essential. This means supporting transitions between different physical configurations by **designing novel hardware** such as motorized articulated arms, or new cases that enable people to easily (un)snap devices together. Transitioning between usage patterns calls for **novel systems to (re)distribute UIs** in different ways even for a fixed set of devices. Existing research on novel cross-device user interfaces [8, 24, 27, 67] already suggest different models and propose technical solutions. Future research should account for patterns of existing usage and solutions encompassing the large variety of devices ecologies that people own. Given the large variation in device ecologies and the multiple usage patterns, we believe it unlikely that systems can recognize both usage and physical configuration to automatically distribute UIs. Instead, these solutions will likely need to provide interaction mechanisms to support users in (re)distributing applications modules to support their usage. These novel solutions should enable what people expect: the ability to just drag running applications or parts of them across devices. Since people's usage patterns go beyond the application level, the community will also need to provide an overarching guidance for developers of applications to support experiences where multiple components of different applications share state, feel compatible, and behave in ways that are consistent with user expectations across different devices and form-factors.

Supporting fragmented workflows probably means **redefining existing paradigms for multi-device user interfaces**. People's current mental model for multi-device experiences is based on how they use external monitors. In fact, in some cases, comments we received in the survey indicate that some participants do not necessarily understand the difference between "device" and "screen" and are often expecting that working with multiple devices should mirror the experience of connecting multiple external monitors. Yet, when connecting an external monitor, most UIs provide three options — extend, clone, project. Such menu options do not scale when considering connecting *n* separate devices together and when dealing with different physical configurations and multiple usage patterns. The grand challenge the multi-device community faces is to identify a paradigm that falls in line with how people currently understand the behaviour of external monitors, or propose compelling novel principles that will change people's mental model relating to how multiple devices should work together.

6.3 Limitations

Our work intended to develop a detailed description of multi-device configurations and usage patterns contextualized in people's motivation and values during the COVID-19 pandemic, when in-person interactions were strictly limited. This intend drove our decision in investigating our research questions through a qualitative approach, gaining in-depth insights from a limited group of people. Given the challenges with in-person research, we decided to use a qualitative survey methodology. We intentionally designed our questions to collect a large set of rich qualitative data where participants textually describe their practices and contextualize them with photographs, rather than aiming for quantitative ratings and statistics aimed at characterizing practices of the general population. This approach provided us with rich insights into people's multi-device usage when shifting to remote work during the pandemic. However, our findings are affected by the demographics of participants in our study. Although our data included representatives from a diverse range of background (Table 1), the majority of our participants were male, and located in North America. The preponderance of responses from people identifying as male in our group of participants may reflect a response bias, given that women have been disproportionately impacted by work-from-home situations, for example in bearing a greater burden of family, elder care, and childcare work, and hence perhaps were less able or inclined to respond to online surveys of multi-device work practices even if they would have had compelling ideas and perspectives to contribute. Complementary investigations dedicate to gather insights from different groups of people (e.g., different types of household compositions or income) or a large scale quantitative study to validate our findings may provide additional insights on both physical configurations and usage patterns.

We also acknowledge that the unique global pandemic context of working from home — while an interesting and important aspect of this study — will continue to change and may look different as the situation around the pandemic evolves. Perhaps the major limitation of this research is that we observed the usage of the current state of technology. More patterns may emerge as technology advances and people's workflow evolves. Seeking to grow our understanding on what people want to do with multiple devices should certainly be an on-going effort in our community.

7 CONCLUSION AND FUTURE WORK

Our work expands the empirical knowledge on how people use multiple devices together. We surveyed 97 persons, gathering a corpus of over 150 photographs of people's physical devices configurations at home during the COVID-19 pandemic, and close to 900 textual descriptions our participants submitted about the way they organize their devices in space, the type of tasks they conduct, the values they gain from using multiple devices together, and challenges encountered.

Our insights shed light on how people fragment their workflows, following different usage patterns with diverse sets of devices. Unpacking four aspects of device physical configurations, and identifying five recurring usage patterns can inform future research. In particular, the usage-centric lens we offer in this paper outlines specific implications for the design of novel applications supporting tasks that users want to achieve, calling for novel hardware and software solutions for composing physical configuration of devices and distributing user interfaces as well as advocating for novel interfaces and interaction paradigms that support users in their fragmented workflows. Our research aims at bridging the gap between existing empirical findings and cross-device technology research. We characterize people's relatively complex multi-device behavior highlighting the interdependence between physical device configurations and usage patterns. This characterization and the end-to-end example workflows can act as a frame of reference to inform and assess novel hardware and software solutions. In the future, as health restrictions may evolve, we plan to conduct more in-depth ethnographic studies, observing multi-device usage in action and probing further to understand motivations and barriers to the usage of multiple devices. Studying the nature of multi-device configurations and usage for different groups of users — such as different types of household compositions or geographic locations — could reveal interesting nuances and open up novel opportunities for researchers to (re)invent more compelling and delightful multi-device experiences.

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A CODEBOOK FOR ANALYZING COLLECTED PHOTOS

Area	Category	Code	Description
Configuration	Arrangement	Separate	Devices are not at all arranged and separated from each other. Potential values include 0, in none of the devices is arranged in this way, and 1, if some devices are arranged in this way.
		Continuous	Devices are arranged next to each other and form a continuous area of screens. Potential values include 0, in none of the devices is arranged in this way, and 1, if some devices are arranged in this way.
		Overlapping	Devices are arranged that one device occludes other devices, or devices have overlapping areas with other devices. Potential values include 0, in none of the devices is arranged in this way, and 1, if some devices are arranged in this way.
		Layered	Devices are arranged and spread out in various distance from users (i.e., devices are spread out in the z-axis). For example, a laptop is placed in the front and TV placed in the background at distance from the laptop. Potential values include 0, in none of the devices is arranged in this way, and 1, if some devices are arranged in this way.
	Orientation	Horizontal	Devices are placed flat on the surface. Potential values include 0, if none of the devices is placed in this orientation, and 1, if some devices are placed in this orientation.
		Vertical	Devices are placed perpendicular to the workspace surface. Potential values include 0, if none of the devices is placed in this orientation, and 1, if some devices are placed in this orientation.
		Titled	Devices are tilted in a certain angle relative to the workspace surface. Potential values include 0, if none of the devices is placed in this orientation, and 1, if some devices are placed in this orientation.
		Concave	Multiple devices are placed in vertical orientation but arranged in certain angle to other devices and form a concave surface. For example, two vertical monitors are placed perpendicular to each other. Potential values include 0, if none of the devices is placed in this orientation, and 1, if some devices are placed in this orientation.
		Convex	Devices are placed to form a convex surface. Potential values include 0, if none of the devices is placed in this orientation, and 1, if some devices are placed in this orientation.
	Form	Homogeneous to Heterogeneous	Describe how similar each device is from other devices. Potential values include 1, all devices are the same type of devices (e.g., all devices are laptops), 2, most devices are the same type of devices (e.g., the photo includes four devices, where three are monitors and one is mobile phone), 3, mixed types of devices, or cannot tell, 4, most devices are different types of devices (e.g., the photo includes five devices, with two monitors, one laptop and one mobile phone), and 5, all devices are different types of devices (e.g., one phone, one laptop, and one tablet).
Workspace	Workspace	Number of Workspaces	Number of workspaces in the photo. A worskpace can be considered as a group of devices which is clearly separated from other groups of devices, and can be on separated table surfaces. Values include a specific number describing number of workspaces observed.
	Workspace Size	Small to Large	The size of the workspace. A small workspace is a space that just fit the devices (e.g., a laptop stand just fits the laptop), and a large workspace is a space that is much larger than the space devices need. Potential values include 1, a small workspace, 2, a medium workspace, and 3, a large workspace.

Area	Category	Code	Description
	Clutter	Low to High	Describe how cluttered a workspace is. A low value represents a space that is not cluttered at all (i.e., clean and tidy) and a high value represents a space that is really cluttered. Potential values include 1, not cluttered at all, 2, a little bit cluttered, and 3, really cluttered.
Environment	Place	Living Room	The workspace is set up in the living room. Potential values include 0, the space is not this specific environment, and 1, the space is this specific environment.
		Dining Room	The workspace is set up in the dining room. Potential values include 0, the space is not this specific environment, and 1, the space is this specific environment.
		Office Area	The workspace is set up in a certain office area (e.g., desk, dedicated office space at home, home office). Potential values include 0, the space is not this specific environment, and 1, the space is this specific environment.
		Bedroom	The workspace is set up in the bedroom. Potential values include 0, the space is not this specific environment, and 1, the space is this specific environment.
		Outdoor	The workspace is set up outdoor. Potential values include 0, the space is not this specific environment, and 1, the space is this specific environment.
		Other	Other places not included in the previous codes. Potential values include 0, the space is not this specific environment, and 1, the space is this specific environment.
	Lighting	Additional lighting support	Whether there are additional lighting support for the workspace, e.g., a lamp placed over the monitor, a light next to webcam. Potential values include 0, there is no additional lighting support in the workspace, and 1, there is additional lighting support in the workspace.
	Physical Artefacts	Sticky note	There are sticky notes in the photo. Potential values include 0, this specific physical artefact is not in the photo, and 1, this specific physical artefact is in the photo.
		Notetaking paper	There is paper in the photo which is mainly for note-taking (notebook, notepad, etc.). Potential values include 0, this specific physical artefact is not in the photo, and 1, this specific physical artefact is in the photo.
		Reading paper	There is paper in the photo which is mainly for reading (printed documents, newspaper, etc.). Potential values include 0, this specific physical artefact is not in the photo, and 1, this specific physical artefact is in the photo.
		Whiteboard	There is whiteboard in the photo. Potential values include 0, this specific physical artefact is not in the photo, and 1, this specific physical artefact is in the photo.
Device & Modality	Device	Number of Smart Phones	Total number of phones in the photo. Potential values include a specific number of devices belong to this category.
		Number Tablets	Total number of tablets in the photo. Potential values include a specific number of devices belong to this category.
		Number of Laptops	Total number of laptops in the photo. Potential values include a specific number of devices belong to this category.
		Number of Desktops or Monitors	Total number of desktops or monitors in the photo. Potential values include a specific number of devices belong to this category.
		Number of TVs	Total number of TVs in the photo. Potential values include a specific number of devices belong to this category.

Area	Category	Code	Description
	Input	Number of Mouses, Trackpads, or Trackballs	Total number of mouses, trackpads or trackballs in the photo. Potential values include a specific number of input devices belong to this category.
		Number of Keyboards or Laptop Keyboards	Total number of keyboards or laptop keyboards in the photo. Potential values include a specific number of input devices belong to this category.
		Number of Webcams	Total number of webcams in the photo. Potential values include a specific number of input devices belong to this category.
		Number of Digital Pens	Total number of digital pens in the photo. Potential values include a specific number of input devices belong to this category.
		Number of Microphones	Total number of microphones in the photo. Potential values include a specific number of input devices belong to this category.
		Number of Remote Controls or Game Controllers	Total number of remote or game controllers in the photo. Potential values include a specific number of input devices belong to this category.
	Output	Number of Headsets	Total number of headsets in the photo. Potential values include a specific number of output devices belong to this category.
		Number of Speakers	Total number of speakers in the photo. Potential values include a specific number of output devices belong to this category.
	Distance	At Hands' Reach (in front)	Devices are placed in a distance that users don't need to turn their heads to reach and only need the lowest effort to get the devices, e.g., phone and keyboard placed in front of the user. Potential values include 0, there is no device placed in this distance range, 1, there is at least one device placed in this distance range, and 2, most devices are placed in this distance range.
		In Arms' Reach (periphery)	Devices are placed in arms reach that users might need to extend their arms to get the devices. For example, monitors or tablets that are set aside. Potential values include 0, there is no device placed in this distance range, 1, there is at least one device placed in this distance range, and 2, most devices are placed in this distance range.
		Far or Unreachable	Devices that are placed far from the users that users might need to walk to the devices, or devices are not reachable. Potential values include 0, there is no device placed in this distance range, 1, there is at least one device placed in this distance range, and 2, most devices are placed in this distance range.
	Fixation	Fixed	Devices that are fixed on some surfaces. These devices cannot be moved or are rarely moved by users, e.g., TV hanging on the wall, monitors on the desk. Potential values include 0, there is no device in this fixation setup, 1, there is at least one device in this fixation setup, and 2, most devices are in this fixation setup.
		Semi-Fixed	Devices that are attached to some surfaces but can still be easily moved if needed, e.g., laptop placed on a stand, phone attached to a charging cable. Potential values include 0, there is no device in this fixation setup, 1, there is at least one device in this fixation setup, and 2, most devices are in this fixation setup.
		Mobile	Devices that are not attached to any cables, stand, etc. These devices can be grabbed and moved freely. Potential values include 0, there is no device in this fixation setup, 1, there is at least one device in this fixation setup, and 2, most devices are in this fixation setup.