Intelligent Shifting Cues: Increasing the Awareness of Multi-Device Interaction Opportunities

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ABSTRACT

The ever-increasing ubiquity of smart devices is creating new opportunities for people to interact and engage with digital information using multiple devices. In the simplest case this can refer to choosing which device to use for a particular task (e.g., phone, laptop or smartwatch), whereas a more complex example is simultaneously taking advantage of the capabilities of different devices (e.g., laptop and smart TV). Despite these types of opportunities becoming increasing available, currently the full potential of multi-device interactions is not being realized as people struggle to take advantage of them. As our first contribution, we study people's willingness to engage with multi-device interactions and rank the factors that mediate this response through an online survey ($N = 60$). Our results show that users are strongly in favour of using multiple devices, but lack the awareness or information to engage with them, or feel that establishing the interactions is too laborious and would disrupt the fluidity of the interactions. Motivated by this result, as our second contribution we design and evaluate *intelligent shifting cues*, visualizations that offer information about available interaction opportunities and how to establish them, and study how they influence users willingness to engage in multi-device interactions. Results of our study show that the cues can be effective in helping people to engage with multiple devices, but that the suitability of the proposed device and fit with task are important mediating factors. We end the paper by deriving design implications for intelligent systems that can support people in engaging with multi-device interactions.

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CCS CONCEPTS

• **Human-centered computing** → *Ubiquitous and mobile computing design and evaluation methods.*

KEYWORDS

Opportunistic, Collaborative, Shifting cues, Device shift, Multi-device interaction

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1 INTRODUCTION

Increasing ubiquity and prevalence of smart devices offer opportunities to engage with different devices and to personalize device usage to suit our needs. For example, in an online meeting, one user can run a video call application on a laptop and use a tablet to read document relevant to the discussion whereas another user can do the opposite - perform the video call on the tablet and read on the laptop. The motivation for engaging through multiple devices is that no single device has the required functions, the data, or the form factors that meet all of the user's requirement [3, 9, 28, 30].

Despite the increase in opportunities for multi-device interaction, currently users struggle to take advantage of them – especially in tasks where multiple devices could be used *simultaneously.* Indeed, the majority of real world use cases for multi-device interaction refer to sequential interactions where one part of the task is performed on one device and another part is later performed on another device [6, 30]. A simple example is online shopping where users often browse for products on their smartphones, but make the final purchase on a laptop or another device with larger form factor and better interaction capabilities. The existing work on supporting simultaneous interactions, in turn, has focused on designing interaction modalities for scenarios where dedicated tools for supporting such interactions are available, such as combining tablets and interactive surfaces to support collaborative work and design [15, 22] or combining smartwatches with smartphones or wearable headsets [1, 20], without examining user's willingness to engage in such interactions or the factors that mediate this response. Simultaneous interactions on multiple devices can bring users several benefits, e.g., by facilitating user experience by separating input and output tasks to devices that are best suited for them [1, 14, 20], by enhancing decision making in collaborative group contexts [4], or by facilitating privacy and security management in multiple occupant homes or other device-rich environments [31]. Improving our understanding of the factors mediating user's willingness to engage in multi-device interactions and designing better support for motivating people to engage in multi-device interactions are essential for improving the user's interactions and supporting them in carrying out tasks effectively and with minimal cognitive burden.

In this paper, as our first contribution, we conduct a survey on people's willingness to engage with multi-device interactions and the factors that mediate this response through an online survey (N = 60). We build on the theory of planned behavior [2] and the task-technology fit model [11] to study decision factors affecting user response in different multi-device scenarios, measuring the participants' attitudes towards multi-device use, their willingness to engage in multi-device interactions, and rank the motivational and impeding factors that influence their decisions of multi-device interactions. The results of the survey show that users are strongly in favour of using multiple devices, but lack the awareness or information to engage with them, or feel that establishing the interactions is too laborious and would disrupt the fluidity of the interactions.

To improve the support for simultaneous interactions on multiple devices, as our second contribution, we propose *intelligent shifting cues* – intelligent visualizations that inform and offer a possibility to engage in a multi-device interaction with one of the devices within user's proximity – as a mechanisms to increase user awareness of multi-device interaction opportunities and to engage in them. We study the potential effectiveness of the cues and the factors that mediate this response through an online study (N = 25). In the study, users are presented with scenarios where multi-device interactions are generally perceived as useful (as validated in our first study) and with different cue conditions (no cue, a minimal cue showing the opportunity, or a detailed cue showing also information about the opportunity). The results of the study show that the cues can be effective in helping people to engage with multiple devices, particularly when the proposed opportunity offers benefits to the users and the cost of engaging in multi-device interaction is sufficiently small. The main benefits mentioned by the users were fit with the task and improved usability resulting from the availability of suitable interaction modality or better form factor. Our results offer insights into the design space of intelligent shifting cues, and pave the way to helping people to better take advantage of interaction opportunities available to them. We end the paper by deriving design implications for intelligent systems that can support people in engaging with multi-device interactions.

2 READINESS AND INTENT TO ENGAGE IN MULTI-DEVICE INTERACTION

Multi-device interactions can enrich user interactions by offering people opportunities to take advantage of different form-factors and modalities. We first conduct an anonymous online survey to investigate the users' readiness and willingness to take advantage of multi-device interaction opportunities, the factors that mediate this response, and the potential obstacles that prevent them from doing so. Ours is the first study to consider the relative importance of these factors as prior works have exclusively focused on identifying different motivating or impeding factors without examining how they affect the user's willingness to engage in multi-device interactions [9, 16, 28, 30].

2.1 Survey Design

Procedure. We conduct our study as an online survey over a four week period. Responses were elicited by circulating invitations to participate in the survey by emails and text messages in two universities located in Singapore and Finland, as well as in the researchers' social circles. Participation to the survey was completely voluntary. Before proceeding to anonymously respond to the survey, participants were invited to read the participant information sheet which provides sufficient information to participants for making an informed decision about whether to take part in the survey. Completing the survey took on average 20 minutes.

Participants. 60 participants (24 female, 33 male and 1 prefers not to say), aged between 19 and 50 years old (M = 28.5, SD = 9.37) responded to the survey. Majority of participants are students residing in Singapore or Finland, the rest are professionals working in business and/or IT. The participants had access to 2 to 7 devices (M = 4.11, SD = 1.25).

Measurement. Participants responded to questions assessing the participants' attitudes towards multi-device use, their willingness to engage in multi-device interactions, and motivational and impeding factors that influence their decisions of multi-device interactions. Responses were elicited on a five-point Likert scale (anchored at 1=strongly disagree/very unlikely/not important at all and 5=strongly agree/very likely/very important) unless otherwise stated.

Attitude towards multi-device interaction was measured through five items including (i) *readiness*: "I use multiple devices for my tasks whenever possible", (ii) *ease of use*: "It is easy to use multiple devices for my tasks", (iii) *usefulness*: "Using multiple devices is more benefit for some tasks than using single device", (iv) *self-efficacy*: "I am confident that I can use multiple devices for my tasks", and (v) *openness*: "I am open to use multiple devices in ways that I haven't used before if it helps me do the task".

Intent to engage in multi-device interactions was evaluated by presenting the users with twelve pre-defined scenarios. Each scenario comprised of a main task and a relevant sub-task (see Table 1). The tasks were selected by inferring from existing systems, observing how multiple devices are used in real life, and considering users' self-reported practices in multi-device use in [16, 30]. To ensure the users can properly contextualize the scenarios, we only chose scenarios that reflect tasks that people already do in reality, some

Table 1: Scenarios and participants' choices of using single-device vs. multi-device (*p<.05, **p<.01, ***p<.001).

Scenario Name	Description	What would you most likely use?
SC1. Watching+Chat	Watching video, chatting about the content with others	Mostly multi-device***
SC2. Writing+Reading	Writing a report and referring to other materials	Mostly multi-device***
SC3. Reading+Searching	Reading documents, while checking relevant info	Single- or multi-device*
SC4. Watching+Reading	Attending an online meeting, skimming or searching for information raised in the discussion	Mostly multi-device**
SC5. Streaming+Controlling	Streaming video or showing photos from personal storage to a group of people	Single- or multi-devices
SC6. Listening+Controlling	Controlling music player while jogging	Mostly single-device***
SC7. Searching+Watching	Searching for recipe video, viewing it while cooking	Mostly single-device***
SC8. Presenting+Reading	Referring to your notes while giving presentation	Mostly multi-device**
SC9. Searching+Viewing	Checking a map while navigating outdoors	Mostly single-device***
SC10. Browsing+Payment	Browsing products online, and paying for them	Single- or multi-device
SC11. Authenticating+Reading	Authenticate the access to secure content	Single- or multi-device
SC12. Capturing+Using	Taking pictures, inserting some of them into a document	Mostly multi-device***

of which have even become common and usual practices. For each scenario, participants were asked to indicate whether they intend to use single device or multiple devices to carry out the tasks, and in the latter case, which device combination participants would use. Participants were then asked to rate the level of importance of different device-related factors to their choices of use.

Finally, motivational and impeding factors were measured using a list of factors which the users were asked to rate in terms of importance. The factors were chosen based on previous literature [3, 6, 9, 16, 28] and were supplemented with open-ended questions asking the participants to list other possible factors that affected their decisions to use (or not) multi-device interactions.

2.2 Results

Attitude Toward Multi-Device Interaction. The majority of the participants had positive attitude towards multi-device interaction. 58% of participants indicated readiness to use multiple devices for daily tasks, and 97% were open to the opportunity to interact with multiple devices even if they have not previously experienced such interactions. 65% of participants perceived interactions with multiple devices easy. 90% perceived benefits from using multiple devices for their tasks and 77% felt confident in engaging multiple devices at the same time. Cronbach's alpha for the scale used to measure users' attitude towards multi-device interaction indicated a high internal consistency ($\alpha = .78$).

Motivation and Impediment Factors. Users ranked the importance of motivating and impeding factors affecting the user's decision to engage in interaction with multiple devices from the most important/concerned to the least important/concerned; see Figure 1a and 1b for the results. These factors extend those reported in prior literature (cf. [9, 12, 16, 30]) by interpreting the convenience of device usage on the grounds of using them together for the task and being aware of the multi-device interaction providing a good fit for the task – not merely considering the fit of individual devices on the task constituents [11]. The differences in participants' rating on these factors were statistically significant (motivation factors: $\chi^2(7) = 31.8, p < .001$, impediment factors: $\chi^2(7) = 35.07, p < .001$). The main findings are that multi-device interactions were seen as potentially convenient and fast way to complete tasks, whereas the overhead in engaging with multiple devices, whether due to preparation of devices or the physical act of handling them, and lack of awareness of interaction opportunity were seen as main impediments.

Characteristics of Devices. Device portability/mobility and screen estate were rated as the two most important factors to entice into multi-device interactions, followed by capabilities of the devices and the availability of data needed for the task (Figure 1c). Prior research has shown that users' choice of using a set of devices for a task is governed by device capabilities [15] and our findings confirm this result, highlighting the portability and screen-size of devices being other important considerations. We also observe weak support for using devices that are owned by others (36% of participants), suggesting multi-device interaction with public devices or share-used device schemes would be welcomed in some scenarios. The differences in device-related factors rating were found statistically significant ($\chi^2(6) = 83.73, p < .001$).

Intention to Engage with Multiple Devices. Table 1 details the task scenarios and user preferences on single and multi-device interaction. Participants' preferences in multi-device use over single-device use, or vice versa, are statistically significant (p<.05) in all scenarios except SC5, SC10 and SC11. From the responses we can see that scenarios where parts of the task can be split across devices seamlessly are best suited for multi-device interactions. Scenarios where single device is clearly preferred over multi-device interactions are ones where all aspects of the task relate to the same data and hence switching device would require copying the data or having it easily accessible on the other device.

Interaction Awareness. Analysis of qualitative responses indicated that lack of awareness in multi-device interaction is a key barrier for taking advantage of multi-device interaction. To improve the situation, participants wish to be informed about the compatibility between devices, how to interact with multiple devices (e.g., *"I want to know the easiest way to do it (multi-device interaction)"*-P48), recommendations on what devices can be used together (e.g., *"I*

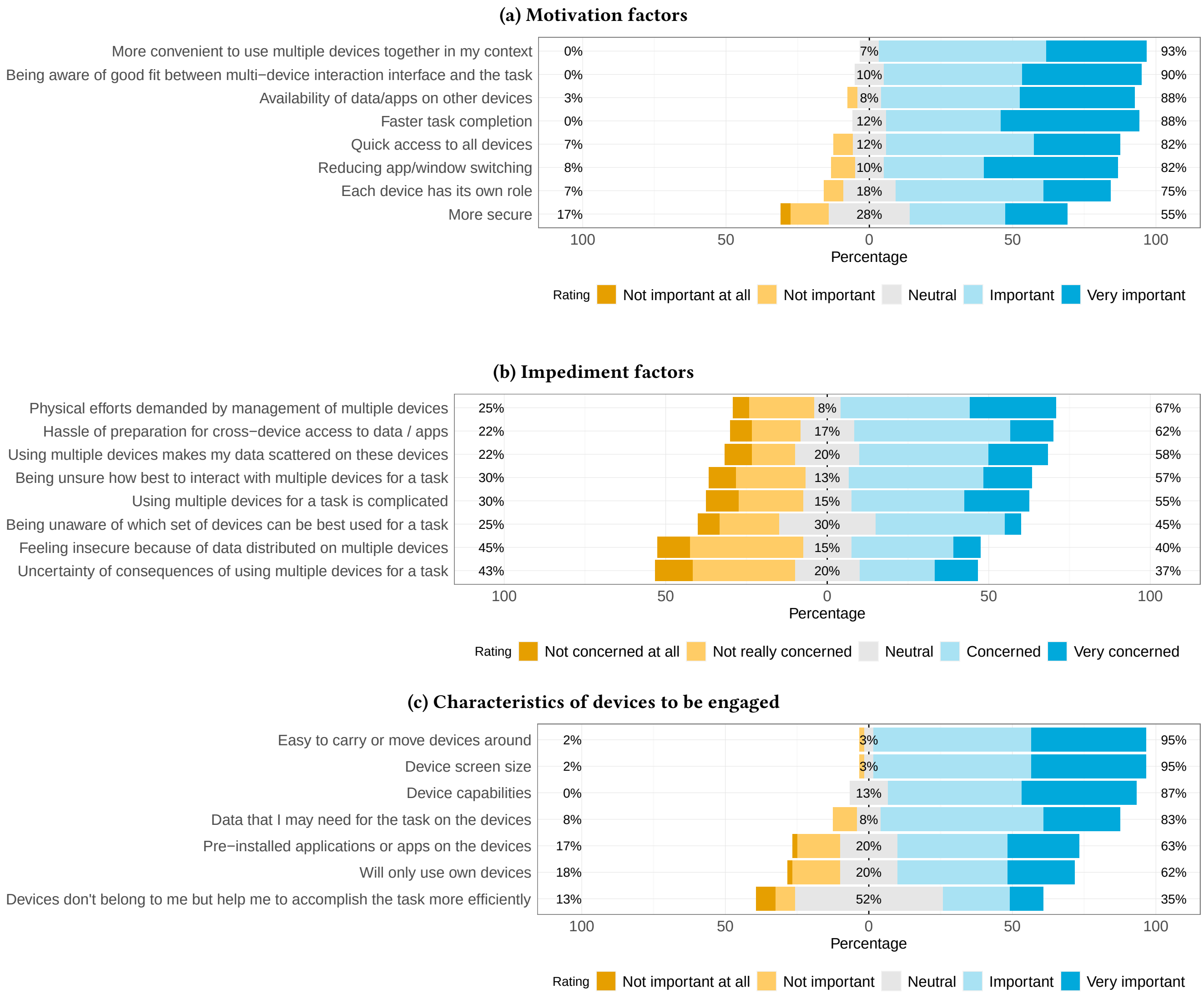


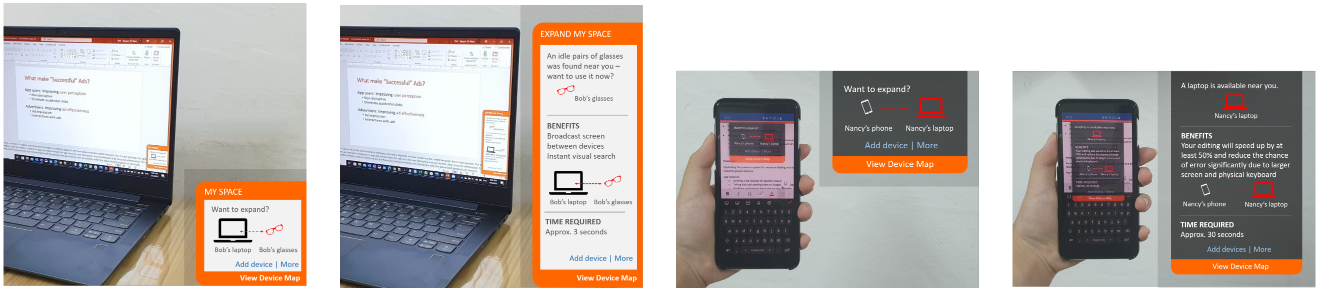
Figure 1: Influence of motivation, impediment, and device factors on user decision of engaging multiple devices.

would like to learn more about the possibilities of being more productive and agile by using multiple devices to carry out a task."-P50), the benefits and consequences of multi-device interaction (e.g., *"How much more efficient can I be if I was to use multiple device instead just one."*-P31). The above responses highlight the need to communicate not only the interaction possibilities but also the benefits and cost for establishing multi-device interaction to users.

Summary: Results of the survey strongly suggest that users are interested in engaging with multi-device interactions, but that different barriers prevent them from doing so – or even attempting that. Device capabilities, including portability, screen size and functionality, were key considerations in device choice, but also ownership of the devices impacts user preferences. Lack of awareness of potential opportunities – or means to establish collaboration – were the leading concerns to hinder multi-device usage. In tasks where the data was already available on one device, benefits of shifting were often seen smaller than the cost of doing so. Taken together, these findings emphasize the needs for raising user awareness about interaction opportunities and assisting users in making informed decisions about how to engage with these opportunities.

3 INTELLIGENT SHIFTING CUES

The results of the survey clearly highlighted that users are interested in multi-device interaction, but that several factors impede them from taking advantage of such interactions. We next introduce *intelligent shifting cues* – interactive visualizations that inform and provide means to engage in multi-device interaction – as a potential mechanism for facilitating multi-device interactions. Intelligent



(a) Minimal cue **(b) Detailed cue** **(c) Minimal cue** **(d) Detailed cue**

Figure 2: Cue types on laptop (a, b) and phone (c, d).

shifting cues are inspired by the concept of *shifting cue* [26] which aim at helping users to be aware of the input and output modalities offered by nearby devices. The main design goals of shifting cues are to be intelligible and actionable: identify and offer guidance on challenges that prevent from progressing with the task while using devices, observing nearby devices that are opened for use before recommending the most suitable devices that help overcoming the obstacles, and guiding the shift in user engagement with the devices.

3.1 Parameters of Intelligent Shifting Cue Model.

The shifting cue model considers a set of parameters to notify users about interaction opportunities while accommodating individuals' differences with respect to their competence in interacting with technology.

Device Proximity and Shareability are to be assessed before the devices are recommended to users. The *degree of shareability* refers to the extent to which a device can share its resources based on the device-to-device social relationship [25]. As examples, any department staff's laptop can connect to a projector in a meeting room, and previously paired smart TVs that are switched on are readily available for displaying content to be cast from the user's phone. The proximity and shareability of surrounding devices are conveyed by the shifting indicator.

Shifting Urgency reflects how important it is to inform users about the interaction opportunities. The level of shifting urgency can be determined by sensing and modeling the challenges the user experiences (i.e., the usability difficulties arising when using a device for certain tasks) and comparing them with the user interaction profile (i.e., constructed using an interaction-driven user modeling process [8]). Unless overridden by the user, shifting urgency decides when a shifting indicator transitions into a shifting cue.

User's Competence in Multi-Device Interactions can be determined by self-assessment or through the records of the frequency of multi-device interactions that involve the current device. Novice/expert users can be classified as having low/high level of competence in using multiple devices for tasks.

3.2 Design of Shifting Cues

Adaptive Shifting Indicator for signaling the level of shifting urgency, the shareability and proximity of nearby devices. The indicator takes the form of a thin strip appearing along the side of the device screen (i.e., a vertical strip positions at the right side of the device screen as seen in Figure 2). The length of the cue strip reflects the level of usability difficulties the user encounters while using the device for a task. For example, a short cue strip appears as a warning of the difficulty for typing on the smartphone, and increases its length in proportion with the observed typing errors. The shifting indicator contains band(s) of color that conveys the shareability degree of surrounding devices. A glowing band further indicates the target device is ready to share its resources. With a glowing orange band, the shifting indicator reminds the user that their own devices are nearby and ready to use; a glowing blue band indicates devices belonging to family members are idle; and a non-glowing grey band informs the user that a nearby public device is currently in use, the user needs to wait for it to be idle. The darker the shade of color the band is, the closer the proximity the device is to the user. Bright, saturated orange colour was chosen as the primary cue for the availability of nearby devices, due to its saliency and ability to be noticeable against the edges of laptop and smartphone screens regardless of the overall colour orientation of the OS (e.g., black, grey or white background on the screen and the bezel on the typical devices today). Using a warm color can also help reduce negative emotional responses to the cue [33].

Adaptive Shifting Cue Content offers a recommendation for the most suitable device usage solution for the problem the user encounters, highlighting the benefits and the cost of adopting the recommended solution, and providing information on how to establish the interaction. Discrepancies in users' competence in interaction with devices call for presenting shifting cues at different level of detail. The *minimal shifting cue* visualizes suggestions of multi-device interaction model (i.e., a phone as an input device to a laptop) and provides information about the ownership of participating devices. This brief information gives the user a glimpse of how nearby devices can augment the interaction with their current device. Minimal shifting cues are intended for expert users who know the benefits gained from coordinating multiple devices for the task. For novice users, the minimal shifting cue extends to a *detailed shifting cue* by additionally providing explanations about the

Table 2: Cue types and content

Cue content	Purpose	Cue types		
		No cue	Minimal cue	Detailed cue
Multi-device interaction model	Recommendation		x	x
Device ownership	Recommendation		x	x
Benefits and cost	Explanation			x

benefits and the cost incurred from the recommended multi-device interaction; see Table 2 for a summary of the cue types.

Transition between Shifting Indicator and Shifting Cue. To mitigate interruption to the user's primary task, a shifting indicator is shown before the display of its respective shifting cue. The transition between the two components follows two of the four interruption policies proposed by McFarlane's [23]: immediately transit to shifting cue (immediate transition), or the user chooses when to attend to shifting indicator (negotiated transition).

4 EFFECTIVENESS OF INTELLIGENT SHIFTING CUES

We now study the influence of intelligent shifting cues on the user's intention of shifting from single-device interaction to multi-device interaction and evaluate the design of the intelligent shifting cues.

4.1 Experiment Design

Task Scenario Selection. We study the effects of intelligent shifting cues in three scenarios, chosen from the first study as ones where multi-device interactions were strongly preferred over single-device interaction. These scenarios are an online meeting, presentation practice, and report writing, corresponding to scenarios SC2, SC4, and SC8 in Table 1. The motivation for considering the same scenarios was to validate the generality of the findings in the first study and to ensure the participants would be intent on using multi-device interactions.

Shifting Urgency. In each scenario, a usability difficulty for single device usage in the task was demonstrated: frequent swapping back and forth among applications (online meeting); increased mental workload (presentation practice); pressure on task completion time (report writing). The occurrence, impact and potential recurrence of usability difficulties associated with a task-device context reflect different levels of shifting urgency. For example, being unable to view the presentation notes on the screen which is being recorded corresponds to a usability difficulty, which leads to the user missing out on what to speak (impact). This, in turn, results in the user repeating the recording of the presentation several times (recurrence of usability difficulty), leading to increased frustration (impact of usability difficulty).

Study Design. The study follows a 3 (scenario type) x 3 (cue type) within subject design where the cue types contain three levels: no cue (NA), minimal cue (L1) and detailed cue (L2). To eliminate any possible order effect, the order of cue types was fully counterbalanced across participants whereas the order of scenarios was counterbalanced using a Latin square design. This resulted in nine counterbalanced experiment setups which were randomly presented to participants.

Participants. Responses were received from 25 participants who were between 19 and 50 years of age ($M = 33.52, SD = 10.75$, 11 females, 13 males, 1 prefers not to say) from different cultures (Singapore: 36% of participants, Malaysia, Finland, Estonia, Switzerland, USA, Vietnam, Thailand, Indonesia, and India) and backgrounds (13 students, 11 full-time employed, and 1 is not in employment).

Procedure. Participants were shown 9 video prototypes that demonstrated the 9 experimental conditions. Each video presents the task context, the challenges of performing the task using a phone or a laptop, and a cue type in action. After viewing each video clip, participants stated what action they would take between: (1) keep using the same device (single-device interaction), or (2) shift to multi-device interaction. We also asked the participants to rate their perception toward the interface (5 items), the cue delivery moment (5 items), evaluate the appropriateness of using the recommended device (4 items), and assess how different levels of device ownership would affect the acceptance of the multi-device interaction (5 items, corresponding to self-own, family, friend, public or stranger). Answers for all items were elicited on a five-point Likert scale (anchored at 1=strongly disagree/very unlikely and 5=strongly agree/very likely). Open-ended questions asking participants to elaborate their choices were included for all items except the ones measuring device ownership. Completing the study took approximately 30 minutes, though some users took longer as they repeated the video clips until they fully understood the interactions taken placed in a given task context – similarly to how people would interact with tangible prototypes. Video prototyping offers an inexpensive tool for collecting valid feedback from early-stage design prototypes [21], and the possibility to pause, repeat, and otherwise interact with the videos further helps engaging the users and offering them ways to fully grasp the presented designs.

Ecological Validity. The ongoing pandemic has naturally introduced significant challenges for conducting field trials or controlled laboratory studies. Our work builds on the rich research tradition of using video-prototypes to evaluate user interface designs [34], which has been shown to produce results that are comparable with controlled user studies. Indeed, studies assessing the ecological validity of video-based study designs have shown the results to closely mirror reality, particularly when assessing user acceptance and usability considerations. The main difference between video and usage-based studies is that users may not always be able to fully assess restrictions posed by the context where the interaction takes place [35]. Video prototypes also offer other benefits as they help in obtaining a higher number of participants and responses from a variety of regions, where users opinion and adoption of multi-device systems can differ significantly, and as they help reproducing and replicating the study at different locations. Alternative designs, such as remote-meeting based evaluations or assessments of static mock up challenges are sensitive to the level of immersion that can be provided and hence their ecological validity can be volatile to technical limitations. For example, software engineering studies have shown video-based prototypes to be better at eliciting realistic responses than scenario or mockup-based alternatives and to improve the speed at which users can understand and conceptualize the presented information [18].

4.2 Effects of Intelligent Shifting Cues

Effects of Cue Type and Scenarios for Own Device. We found a main effect of cue type on intention to shift to multi-device interaction (Friedman-test, $\chi^2(2) = 10.06, p < .01$). Participants' intention to shift to multi-device interaction was higher with the minimal cue type (post-hoc comparison with Bonferroni, $p < .05$), or detailed cue type ($p = .05$) than when no cue was presented. For most of the participants, the main motivation behind intention to shift to multi-device interaction as suggested by the shifting cue is the recommendation of the right thing to do at the right time in a comprehensive manner, for example, *"The cue is extremely timely and provides easy and familiar way of sharing the document so that I can perform my task"* (G5P3), *"I am even more interested [in it] after hearing about the benefits and how easily it is paired"* (G5P3). No effect of scenarios on intention to shift to multi-device interaction was found.

Effects of Cue Type and Scenarios for Borrowed Device. Participants were more willing to borrow a device from a family member or a friend to use with their personal device rather than use a public device or device whose ownership they cannot ascertain. The willingness to borrow devices of others is dependent on the scenario (Friedman-test, $\chi^2(2) = 8.821, p = .012$) and generally is the highest when the device in use does not meet the task demands. For example, it is difficult to edit and format a report shown on the smartphone compared to being able to remember a note in the presentation practice scenario ($p = .017$). Finally, we found a statistically significant decrease in willingness to borrow devices from people that are neither family members nor friends ($\chi^2(2) = 7.955, p = .019$). Task influenced the responses also slightly with users being even more unwilling to borrow devices for the online meeting task than for practicing presentation ($p = .036$).

4.3 Evaluation of Intelligent Shifting Cues.

Perceived Usefulness. Participants had high level of agreement on the perceived usefulness of the intelligent cues. Minimal cues were deemed sufficient in most situations, with the detailed cues being perceived as more useful only when they provided information that was overlooked or new to the user. Otherwise, they were deemed as an annoyance.

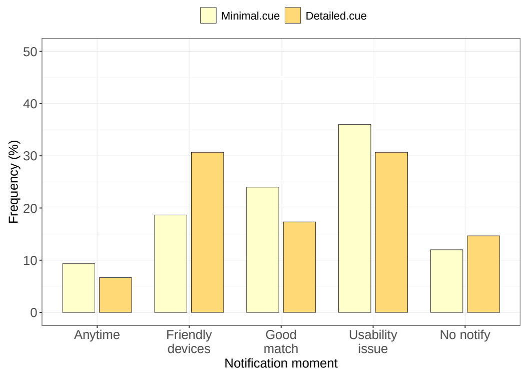
Sufficiency of Cue Content. User perceptions on the sufficiency of cue content depend on how well users know or are aware of the information brought by the cues. Participants agreed that minimal cues are sufficient reminders for their action *"The cue reminds me that I have a device that I can use to assist with my screen recording issues."* (G1P1). G7P1 wanted to know more beyond the device-to-device connectivity as *"Not enough information on the function"*. For the detailed cue, the explanation is useful because *"It tells me why it popped up"* (G4P2), *"It display just enough information about how it works"* (G7P1). On the contrary, few participants commented that certain components of the detailed cues provide information that they *"already know"* (G2P2). Variety differences of opinions on the cue content affirms that adaptive shifting cues in accordance to the user's competence in multi-device interaction are desirable.

Cue Efficiency. Perceived efficiency of the cue reflects how timely the intelligent shifting cue bring useful information to users. Participants agreed that both levels of intelligent shifting cues are efficient to their needs. The cue content and the moment when they are presented appear to influence the user's perceptions. For example, G5P3 commented on the detailed cue presented in the report writing scenario, *"The cue is extremely timely and provides easy and familiar way of sharing the document so that I can perform my task. I do not find the notification annoying or interrupting my device view."*.

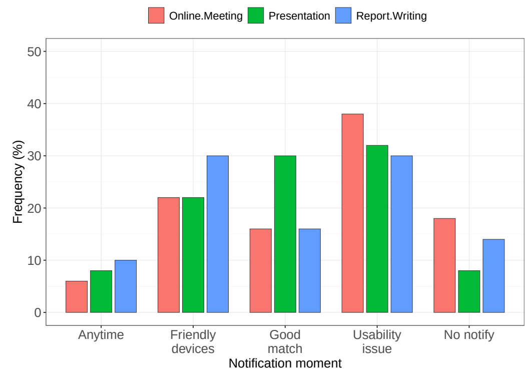
Interruption and Annoyance. Participants felt neutral about the interruption and annoyance caused by the minimal and detailed shifting cues. Indeed, the design and behavior of the 2-step intelligent shifting cues – a shifting indicator and a shifting cue – and its adaptive transition between the indicator and the cue are appreciated by the participants, e.g., *"...the cue is not intrusive. It only expands when clicked on."* (G8P1). When shifting cues are shown on the laptop, minimal cues are perceived *"unobtrusive"* (G8P1) *"It doesn't block anything"* (G2P4). For detailed cues, the value of information the cues bring seems to exceed the cost of interruption or annoyance it may cause, e.g., *"Although the cue is larger than that in Case 2 [detailed cue], it is not too obtrusive as it only obscures a small part of the sidebar and not the centre of the screen. The additional information also allows me to have a better understanding of the sync process and the benefits of linking a device."* (G1P1).

Cue Delivery Moment. Between minimal and detailed cues, participants prefer to receive minimal cues over detailed cues when better matches of device are found or when usability difficulties in using devices for the task emerged (Figure 3). As detailed cues provide information about the benefits and the cost of multi-device interaction, they are preferred in situations where multiple shareable devices are available as the cues can assist in selecting the best device to use.

Task-Device Fit. Participants were asked to rate their anticipated benefits of using the suggested device combination, the perceived ease of using devices together for the task, the match between the suggested devices and their capability (efficiency), and assess whether the suggested device combination is the right choice (effectiveness) for the task and its challenges. There were statistically significant differences in *Scenarios* on efficiency ($\chi^2(2) = 6.792, p = .034$) and effectiveness ($\chi^2(2) = 13.607, p = .001$). The result of post-hoc test with Bonferroni corrections confirms significant difference of effectiveness between the presentation ($Median = 3.5$) and report writing ($Median = 4.5$) scenarios ($p = .007$). That is to say users consider the device combination suggested in the report



(a) by cues



(b) by scenarios

Figure 3: Preferences of notification of device engagement opportunities.

writing scenario a better match with the task and its challenges compared to the combination shown in the presentation scenario.

5 DESIGN IMPLICATIONS

Our results highlighted several effects that influenced the perceived usefulness of the intelligent shifting cues, and the user's willingness to engage in multi-device interactions. Building on our findings, we draw the following seven observations that may be helpful for designing intelligent support for multi-device interactions.

(1) Device Proximity. Responses from our first survey strongly suggested that users would be unlikely to shift parts of the interaction to another device if they secondary device is not in their close proximity. Qualitative responses from the second study show similar trend, with some users only preferring to see the cue if the other device is sufficiently close to them. This supports our design rationale that intelligent cues should provide indications of where the other device is and how proximate the user is to help users engage with the device.

(2) Content. The participants in the second study generally preferred the minimal cue over the detailed cue, unless they were provided with information that was new or highly relevant for evaluating the shift opportunity. Cues should thus be personalized and reflect the expertise level of the individuals and be adapted over time as users become more familiar with different types of opportunities and multi-device interaction mechanisms.

(3) Cue Timing. Shifting cues can be partially understood as notifications that are related to the task that the user is performing. As the cues relate to the task at hand, processing them requires less cognitive effort than the processing of general notifications that can be unrelated to the primary task. While there have been several approaches to modeling user interruptability [19], the wide range of modalities and devices that are available for multi-device interaction mean that it may be difficult to derive accurate and generic models. Instead, a simpler option may be to simply present the cues at the beginning of the task and only present new opportunities dynamically if they are highly likely to be accepted or beneficial to the user. Alternatively, cues of opportunities that emerged can be presented at the end of a task to make the user aware of them for the next time they carry out the task, rather than potentially disrupt them during the task.

(4) Usability. The participants strongly highlighted usability of the secondary device as an important determinant for the usefulness of the shifting cue. Responses from the first survey highlighted that sometimes users prefer to continue using the same device rather than take advantage of opportunities offered by multiple devices. Hence, it is important to model the benefits of the interaction opportunities and only use cues in cases where the multi-device interaction can clearly benefit the overall set of tasks.

(5) Task-Fit. Besides usability, the fit of the second device for supplementing the task was an important determinant for the user's preferences and decisions. Research on *sequential* multi-device interaction has shown that task-technology fit is a key factor in determining which device people are likely to interact with [6]. In the case of *simultaneous* interactions, as explored in our work, the situation is more complex as the secondary device is mostly chosen to supplement the primary device or to support multi-tasking. At the same time, people have different preferences regarding the primary device. Optimal support for multi-device shifting should thus be personalized and model user preferences regarding technology for different tasks and task combinations.

(6) Cost. The cost of engaging in multi-device interactions, e.g., the time and required knowledge to pair devices, was seen as one of the key barriers for adoption. During the task people are unlikely to engage in shifting opportunities that they are not familiar with. Optimally the cue should offer a link to establishing the interaction opportunity directly, but given the current lack of standards or interaction-free methods for pairing and connecting devices across different types of platforms, this is unlikely to happen in the near future. Alternatively, the cue designs could be integrated with the tasks so that when the user finishes a task, information about mechanisms for establishing multi-device interactions for the next time the task repeats are presented.

(7) Device for Cue Presentation. In some situations, it may be beneficial to use the secondary device for presenting the cue –

particularly if the form factor of the primary device is small. For example, if a user is performing a task on a smartwatch and starts to interact with the laptop at the same time, this could be interpreted as a potential sign of the user being interested in an opportunity to combine the two devices. This depends on the modality and type of device and requires careful modeling across different tasks. For example, assuming the user is interacting with a smartwatch while using an AR/VR headset, in this case showing a visual cue on a secondary device is not feasible so the cue needs to be delivered on the primary device – or using a different presentation modality.

6 DISCUSSION AND FUTURE WORK

Room for Improvement. While we demonstrate that the lack of cue mechanisms to make users aware about proximal devices and to interconnect them easily is the key limitation to foster multi-device interactions, our results also show that users are willing to shift the tasks between multiple devices to facilitate their completion. We are interested in investigating further how the nature of the task plays a role when deciding to shift between devices and in exploring interactions between multiple devices beyond personal devices. For instance, by using one's smartphone, it could be possible to trigger the camera of aerial drones to take pictures from a distance.

Multi-Device to Multi-Device Model. Our work considers the shift from single-device interaction to multi-device interaction through which the user continues using the personal device on which the task was started together with a second device available in the user's environment. Although the model only considers a specific shifting direction (i.e., from single to multiple devices), and the two classes of devices of which personal device is used to start the task, the model can be generalized to reversing the shifting direction (i.e., from multiple devices to single device), or shifting between different device combinations (i.e., device configurations and composites [27, 28]).

Emerging Factors for Shifting to Other Devices. Besides the fear of data stealing and privacy loss, there are other emerging factors that can influence the decision to shift between devices identified in our study. These factors are either inherent to emerging device technologies (e.g., new interfaces or interactions that users are not aware of) or they can arise suddenly due to societal interactions. As an example of the latter, device hygiene has become a relevant concern when using a device offered by another person - even if it is a close acquaintance or a family member. Similarly, new devices, e.g., thermal cameras and drones, can induce usage concern in users in early stages of adoption.

Partial Aggregated Contributions from Multiple Devices. While shifting cues can foster the adoption of multi-device interactions, shifting cues also open new opportunities to benefit from multiple devices. One such scenario is aggregating partial contributions from multiple devices for achieving a more robust task completion. For instance, a smartphone whose microphone is damaged or poor quality, can rely on other device's microphone, e.g., smart fridge, to obtain sound measurements, while performing the rest of the task on the smartphone.

Shifting Cues in Multitasking. Our intelligent shifting model can also be adapted for designing intelligent shifting cues for multitasking scenarios. For example, the model can be extended to account for the relationship between the shifting parameters of different tasks before adapting the presentations and behaviors of shifting cues to effectively notify individuals about task interaction opportunities while at the same time minimizing user interruption and annoyance.

Shifting Cue Designs for Devices In General. We rely on a single to multiple devices approach to analyze the usefulness of cues for shifting between devices and the factors that mediate the decision of the user to trigger this shifting. Besides context and device awareness, several other considerations have to be examined for designing cues for the large spectrum of existing devices. These considerations are tied to inherent characteristics of devices. For instance, a public display accepting a fixed number of users to extend their screen, should inform devices around about its queue capacity, such that when the maximum capacity is achieved, the cue is not visible to any other device around until there is available space in the queue again.

Task Performance Optimization. Our results suggest that there are opportunities to use intelligent systems to support and optimize task completion by monitoring the user performance when performing a task on different devices. For instance, a user who is not proficient in editing photos using sophisticated software on a desktop computer can perform the task easily just by relying on image editor apps that run on his/her smartphone whereas another user can perform the task more effectively on a desktop. An intelligent recommendation system can schedule and prepare a shift from a desktop computer to a smartphone, which enables the user to continue the task and improve its efficiency.

7 RELATED WORK

Motivations for Multi-Device Usages. Individuals' choices of using a set of devices for a given task are primarily governed by the capabilities of these devices [15]. Differences in device's form factors, functionalities and portability have been leveraged to support users in multitasking, increasing productivity, separating personal and work activities [9, 28, 30], coping with unexpected changes (e.g., task demands [16], user physical context [28]), meeting the the needs for cross-device data access [9, 17], responding to resource deprivation [28], or simply because of incorrect initial evaluation of the task requirements [16]. At the same time, multi-device usage requires aligning efforts in handling and operating the devices, and getting data ready for the task with the user's work, mobility and social context [28]. Our work is the first to rank the relative importance of different factors that motivate, demotivate, and impede users from engaging in simultaneous multi-device interactions.

Multi-device Usage Patterns. Multi-device interactions are generally split into two categories in the literature [9, 16, 28, 32]: *sequential interaction* and *simultaneous interaction*. The former describes the use of one device after another whereas the latter refers to the use of multiple devices for the tasks. Existing simultaneous interaction scenarios can be characterized by whether data is generated or consumed on the device (e.g., referring to a document displayed on a tablet while writing a report on a desktop characterizes a "performer-informer" pattern [30]), how device resources are coordinated with respect to the tasks (e.g., primary use of a single device which borrows some resources from another device follows the "resource lending" pattern [16]), or information flow (e.g., one device provides input/output to a group of devices follows the "shared input"/"shared output" pattern [27]). These findings suggest that users commonly appropriate differences in device form factors and functionalities for the tasks in different contexts. Our work offers insights into how users make sense of multi-device interaction opportunities, and designs mechanisms for informing them about cross-device interactions and their possible actions.

Multi-Device Interactions Opportunities. Prior research has sought to support the shift of user interaction across devices by devising a variability of opportunistic device-to-device connectivity (e.g., bumping two devices together [13]), novel multi-device interaction techniques (e.g., rotating a tablet belonging to a device group to show the app menu [29]), coordination of information display and navigation between small screen devices and large screen displays [14, 24], or supporting continuity when the user's task is to be shifted from one device to another [32] (for review, see [5]). Furthermore, a same set of devices may come with different interaction techniques (e.g., for zooming in/out the view on a smartphone, one can use a wrist-tilt gesture with the smartwatch-worn left arm while pushing a button on the smartphone [20], or double bump the smartphone on the smartwatch [7]). As a result, the user would need to be aware of such communication possibility when other devices become available, or to remember which cross-device interaction strategies is beneficial based on the context [10]. How to leverage the benefits offered by simultaneous interactions with multiple devices for supporting ongoing tasks is currently understudied. Our work seeks to bridge this gap by communicating the information about interaction opportunities to users through intelligent shifting cues.

8 SUMMARY AND CONCLUSION

We contributed by studying people's willingness to engage with multi-device interactions and the factors that mediate them, and presenting intelligent shifting cues as a potential solution to facilitate multi-device interactions. We showed that users are highly motivated to engage in multi-device interactions, provided they are aware of the benefits and sufficiently knowledgeable of how to establish them. We also showed that cue designs can facilitate multi-device interactions, offering a direct mechanism to connect to other devices rather than having users to search and configure opportunities. We also presented design guidelines for intelligent cues, showing that preferences depend on the accuracy of predicting the appropriate device and user's knowledge of the benefits. Our results pave way toward better utilization of multi-device interaction opportunities and improving the overall user experience in a wide range of scenarios.

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