m+pSpaces: Virtual Workspaces
in the Spatially-Aware Mobile Environment

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ABSTRACT
We introduce spatially-aware virtual workspaces for the mobile environment. The notion of virtual workspaces was initially conceived to alleviate mental workload in desktop environments with limited display real-estate. Using spatial properties of mobile devices, we translate this approach and illustrate that mobile virtual workspaces greatly improve task performance for mobile devices. In a first study, we compare our spatially-aware prototype (*mSpaces*) to existing context switching methods for navigating amongst multiple tasks in the mobile environment. We show that users are faster, make more accurate decisions and require less mental and physical effort when using spatially-aware prototypes. We furthermore prototype *pSpaces* and *m+pSpaces,* two spatially-aware systems equipped with pico-projectors as auxiliary displays to provide dual-display capability to the handheld device. A final study reveals advantages of each of the different configurations and functionalities when comparing all three prototypes. Drawing on these findings, we identify design considerations to create, manipulate and manage spatially-aware virtual workspaces in the mobile environment.

Author Keywords
Mobile virtual workspace; spatially-aware displays; multi-display environments; pico-projectors; m+pSpaces.

ACM Classification Keywords
H.5.2 [Information Interfaces and Presentation]: User Interfaces: Input devices and strategies, Interaction styles.

INTRODUCTION
The use of multiple workspaces is common in desktop computing and integrated into most Operating Systems (OS). Known as *workspaces* on Linux, *spaces* in Mac OS or *virtual desktop* in Windows OS, they allow users to de-clutter their principal workspace and mitigate physical display size limitations by adding virtual display real-estate. For mobile platforms, the concept of virtual display space is

quite different; it is often used to store icons but rarely to switch between tasks or activities that have already been started. Users instead go back to the main menu and select an icon to access the corresponding application. Since the use of multiple virtual workspaces was initially recommended as a technique to alleviate some of the mental workload in limited display real-estate [6], it seems natural to use this concept for mobile phone technologies.

Current desktop environments represent virtual workspaces using thumbnails spatially arranged in a line or grid. In mobile environments, since the devices themselves have intrinsic spatial properties, we propose to use these spatial properties instead of using a graphical representation. This will give users a more tangible and direct interaction with virtual workspaces that does not exist in desktop computing thus expanding the capabilities of current systems.

The concept of virtual workspaces as it exists in desktop computing can be translated to the mobile environment. Yet, this is not a straightforward process and the results obtained would be suboptimal if careful consideration was not given to the design, as the two categories of devices have very different characteristics and capabilities.

In this paper, we explore the use of virtual workspaces in mobile environments. We present *mSpaces*, *pSpaces* and *m+pSpaces*, three phone-based user interface prototypes, which allow simple and fast access to multiple virtual workspaces located around the user, drawing on their spatial memory and awareness. With *mSpaces*, the user accesses different workspaces by moving the phone to different physical locations, while *pSpaces* (Figure 1) gives access to multiple virtual workspaces by pointing a pico-projector attached to the phone at the various locations.

Figure 1: pSpaces: User accesses various virtual workspaces by moving the pico-projector to the associated physical space.

This interface makes full use of the user's spatial awareness. Finally *m+pSpaces* makes use of both the screen and pico-projector. The mobile virtual workspaces are always linked to real physical locations relative to the user. In two experiments we compare *mSpaces* to the current use of multiple concurrent applications on a mobile phone and to *p-* and *m+pSpaces*. While this paper explores interaction techniques to access the various workspaces, it does not investigate new interaction techniques for input.

The contributions of this paper are: 1. Findings suggesting that spatially-aware virtual workspaces provide easier and faster switches between applications in the mobile context. 2. We propose three spatially-aware prototypes of mobile virtual workspaces, two of which include the use of mobile projection spaces that capitalizes on the emerging trend of augmenting mobile phones with pico-projectors. 3. Pico-projection improves the capabilities of spatially aware mobile virtual workspaces. 4. We extend our contribution of using mobile workspaces and complete the design of *m-* and *pSpaces* by proposing a set of design considerations to create, manipulate and manage these techniques.

BACKGROUND

Desktop Virtual Workspaces

Virtual workspaces are first introduced by Card and Henderson [6,8], who initially proposed *Rooms*, a system for managing multiple virtual workspaces as a way to cope with limited display real-estate by expanding it into virtual workspaces. Multiple workspaces lower the cognitive overhead created by trying to switch tasks and move windows across a limited physical display real-estate. One of the authors' arguments for virtual workspaces is that they help overcome the limitations of small screen size, which is a highly relevant issue for today's mobile technologies.

Ringel [17] proposes a "taxonomy of organization strategies" for users of multiple virtual workspaces. Five organization strategies emerged from a field study. Participants would consistently use the different workspaces to either: divide tasks, divide subtasks, change context between personal and professional usage, use multiple OS, and classify applications. They also show that virtual workspaces have different uses to multiple displays. It is therefore likely that adding an auxiliary display to a mobile environment would not replace the need for multiple workspaces. Finally, users with smaller displays used "more virtual desktops, on average," [17]. This proves that multiple workspaces will be well suited to mobile environments that traditionally afford smaller displays.

Mobile Virtual Workspaces

We use *mobile devices* to refer to handheld devices such as mobile phones and tablets. Laptops are not considered to be part of this category as they are traditionally used sat down on a flat surface and not handheld. Fitzmaurice [10] presented the Chameleon system in 1993, offering spatially aware interactions with the environment using a palmtop computer. Despite, the concept of virtual workspaces as we know it in desktop environments is seldom implemented in current mobile devices and many mobile phones only offer the possibility of displaying static menu icons on one or more virtual desktops. Moreover while some mobile phones have the capability to display multiple applications at once, they do not exploit advantages offered by virtual workspaces as they exist in the desktop environment. Adapting multiple virtual workspaces to mobile devices will extend the current range of possibilities offered, such as providing users with a task partitioning tool.

While the concept of multiple virtual workspaces can be translated to the mobile domain, the interaction techniques need to be adapted. This is particularly evident since display sizes and interaction techniques are inherently disparate between desktop and mobile environments.

Representation of Virtual Workspaces

In the desktop environment, multiple workspaces are often displayed as a group of thumbnails, each representative of one workspace. They are traditionally organized as a line of thumbnails – such as when pressing ALT+TAB in Windows OS or CMD+TAB in MacOS – or as a 2x2 grid when 4 workspaces are being shown. In early systems, thumbnails were referenced to by numbers. They are now often presented as a thumbnail of the actual workspace with its applications positioned as in the workspace itself.

In existing mobile environments, the main screen can sometimes be extended to display additional static information such as extra application icons. These application launcher spaces can be represented as a line of dots in the main menu where one dot is highlighted, indicating the workspace in view. Some phones also propose solutions close to the concept of multiple workspaces in desktop computing such as the Nokia N900 where multiple applications can be running in additional virtual space. Yet, there is no point of reference to what the user is currently viewing with respect to the virtual space.

In all instances presented above, there is a spatial relationship between the workspaces: one can be represented next to the other, above or below.

Spatial Awareness

The use of spatial awareness to represent and provide users with an understanding of virtual workspaces is to be expected since using spatial memory has proven to be effective for tasks such as the document management technique Data Mountain [18]. Additionally, Tan et al. [20] show that using kinaesthetic cues increases spatial recall. Li et al. build on this theory and propose Virtual Shelves [14], allowing users to orient a mobile phone to trigger shortcuts. They show that the user can "accurately point to 7 regions on the Θ plane and 4 on the Φ plane". A more recent study by Gustafson et al. [12] show that one can interact with mobile devices by transferring the spatial memory of the interaction technique to the palm of their hand.

Earlier, Yee presented Peephole [21], an interaction

technique for a spatially-aware display that "provides a window on a larger virtual workspace". They mention that this window could be used to display several applications on the same workspace where users could draw connections between applications. In *mSpaces*, we take this concept further by mapping the location of each distinct virtual workspace to a physical location, relative to the user. The user can access each workspace by orienting the mobile device in the direction of the workspace, hereby receiving permanent visual feedback to which workspace they are looking at. This technique utilizes the intrinsic properties of a context-aware mobile device, the user's spatial memory, as well as kinaesthetic cues that will ostensibly alleviate some of the user's mental workload.

Besides, Cao and Balakrishnan [5] explore using a handheld projector to access multiple items on a single virtual space. We take a step further by accessing multiple virtual spaces at different physical locations with constant visual feedback. In *m-* and *pSpaces*, each virtual space is linked to a location relative to the user, who then points at the physical location to display the associated virtual space.

In order to determine how virtual workspaces can be displayed in the mobile environment, we conducted a user study comparing various implementations.

USER STUDY 1: MOBILE VIRTUAL WORKSPACES
This study aims to find out the type of interface is suited to implement virtual workspaces in a fully mobile environment. While there are many ways to implement mobile virtual workspaces, we compared the current use of mobile phones to two probable implementations.
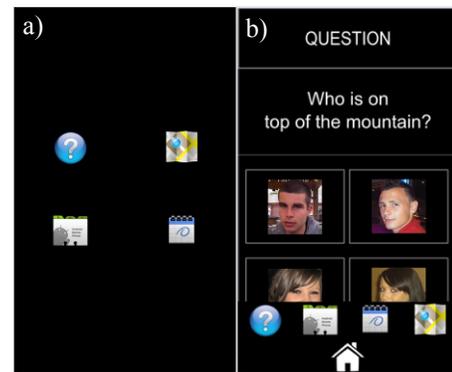
Virtual Workspaces
In order to keep the current display paradigm used in mobile phones, each workspace contains one application only. The mobile phone's screen would quickly become cluttered if more than one application was displayed at a time on such a small display. Ringel [17] indicates that the average number of virtual workspaces used in desktop computing is four; we therefore implemented the prototypes with four virtual workspaces and four running applications.

Apparatus
The three conditions for the experiment are: *no virtual workspace*, which corresponds to the current use of mobile phones; *workspace switcher*, which provides a representation of the workspaces, and *mSpaces*, which distributes the workspaces across space. All conditions have been implemented on the same mobile phone, a Samsung Galaxy S running Android 2.3 OS.

No Virtual Workspace
This condition reflects the current usage of mobile phones. To switch applications, the user returns to the main menu by performing a short click on the home button at the bottom of the screen. There, they click on the icon corresponding to the application they want to open.

**Figure 2: a) No virtual workspace: menu of icons
b) Workspace switcher: a bar of icons representing the workspaces appears at the bottom of the screen.**

This operation must be performed every time the user wants to switch application. This technique is a typical interaction technique for browsing through applications in mobile phones. The menu displayed consists of a 2x2 grid of icons, each one representing an application (Figure 2a).

Workspace Switcher
This condition simulates the current metaphors for switching workspaces in the desktop environment. The *workspace switcher* is a graphical representation of the available workspaces, consisting of a bar of icons that appears at the bottom of the screen superimposing and partially hiding the current visible workspace (Figure 2b). Each icon represents a workspace as in the *no virtual workspace*'s condition menu. The user performs a long click (500 ms.) on the home button to access the *workspace switcher* as they would typically do for switching context on mobile phones when the functionality is available.

mSpaces
The third condition, *mSpaces*, is a prototype that allows the user to choose which virtual workspace they want to display by moving to its physical space. The technique is in the same idiom as the interaction techniques presented in Imaginary Interfaces [11], Virtual Shelves [14] and Peephole [21]. In *mSpaces* however, kinaesthetic cues are attached to the workspace switches. The user accesses the distinct workspaces with permanent visual feedback; without having to press any button; just by moving the device to a new physical location. *mSpaces* is a spatially-aware device, in which 6 degrees of freedom tracking is

Figure 3: mSpaces: spatially-aware mobile device. Different workspaces appear depending on the device's position.
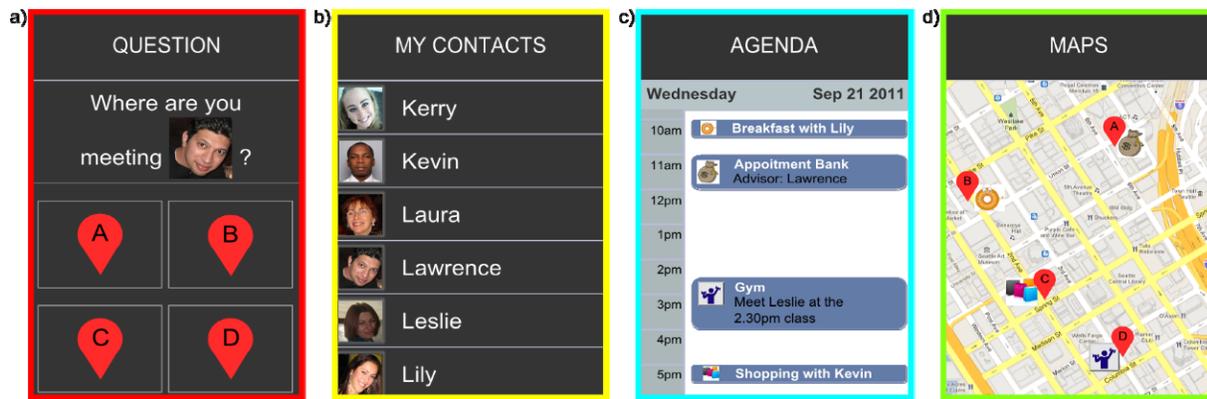
Figure 4: Screenshots of a type4 trial – To answer Question (a), the participant needs to match the picture with the person's name on the Contact list (b) and use the Agenda (c) to identify what activity they will be doing with this person. The next step is to use the Map (d) to locate the activity. Once the participant has navigated through all workspaces, they can answer the Question.

realized using a NaturalPoint OptiTrack motion-capture system through IR-reflecting markers attached to the prototype (Figure 3). Workspace are separated from one another on the horizontal axis by a 30° angle as is advised in the literature [14]. In the experiment, the workspaces are positioned on a single vertical level but the prototype would in addition support having workspaces at multiple heights.

The position of the workspaces was fixed for the experiments and participants had a chance to become familiar with the system prior to the experiment.

Tasks
To evaluate how virtual workspaces need to be designed for mobile devices, we asked participants to answer questions for which they need to look up information using familiar mobile applications. We used spatial search tasks where participants needed to access multiple workspaces to find the right answer. Since the tasks are spatial, the applications do not require any user interaction, aside from navigating between workspaces and using the touch screen to answer the question. The applications visible to the users are pre-designed screenshots of applications that may contain some clues to answer the trial question. The user can retrieve the clues by perusing the screenshots using the workspace switching technique. This task is representative of a task where a user consults their agenda to give a date or location to a person on the phone or next to them. This task is not designed for "on-the-move" scenario but instead a scenario where the user would stop for a short moment to consult some data on their phone as this is current practice.

For the four workspaces available, four applications are proposed: a question (Figure 4a), contact list (Figure 4b), calendar (Figure 4c) and map (Figure 4d). These applications correspond to everyday tasks commonly undertaken on mobile phones. Four types of tasks were presented to generate different sets of workspace switches. type1 respectively involves looking at the contact list and the map; type2 at the map and the calendar; type3 at the contact list and the agenda; while type4 involves all workspaces and is therefore harder than other types.

The aim of each task is to answer the trial question. The participant doesn't know the type of the task; and for each trial, all four workspaces are available even if they do not all provide clues to answering the question. Once the answer is found, the participant gets back to the initial question workspace to validate their choice by touching an answer out of four choices on the touch screen (Figure 4a).

Procedure
12 volunteers (4 female) aged between 23 and 44 ($\mu = 29.5$) were recruited from our research institution. All were right-handed, familiar with smartphones and touch-screen technologies. We used a within-subjects experimental design where each participant had to answer all questions and the type of virtual workspace was counterbalanced across participants. The task was explained individually to each participant who could try out each condition with a randomly chosen task in their own time. When they felt ready, they pressed the "Start" button to start the experiment and again before each trial. At the end of the experiment, users filled out a NASA TLX survey.

The independent variables were: The *type of virtual workspaces*: No virtual workspace (Nv), workspace switcher (Ws), *mSpaces* (mSp). The *type of task*: type 1 to 4 (t1 to t4). There were 6 questions of 4 different types per condition (i.e. type of workspace), which corresponds to 24 questions for each condition and 72 trials overall per participant. The experiment had: 12 participants x 3 virtual workspaces x 4 tasks types x 6 trials for 864 data points.

Measures
The experimental software recorded trial completion time (MT) and error rate (ER) as dependent variables. MT is the total time taken to complete the task and is defined as the time taken for the user to perform a trial. The counter begins when the user presses "Start" and stops when the user clicks on one of the response buttons. If the user did not select the right answer an error was registered and the user was allowed to progress to the next trial. In an exit questionnaire we asked participants to complete the NASA

TLX questionnaire. This allows assessing on a 7-point Likert scale subjective information for mental, physical and temporal demand; performance; effort and frustration. In addition to the NASA TLX we asked participants to rank the techniques and comment on their personal preferences.

Results

We used the univariate ANOVA with Tamhane post-hoc pairwise (unequal variance) comparisons for our analyses.

Error Rate

There were 59 errors out of 864 trials. With 8 incorrect trials, participants made fewest errors with *mSp* followed by 21 incorrect trials for *Nv* and 30 for *Ws*. All 59 trials with incorrect responses were removed from further analysis.

Completion Time (MT)

The average trial completion time over all tasks and techniques was 16.6s with standard deviation of 4.1s. There was a significant effect of technique on trial completion time ($F_{2,22} = 10.85$, $p<0.01$); *mSpaces* was significantly faster than the other two techniques followed by *No virtual workspace* (Nv) and *Workspace switcher* (Ws). We found no significant difference between Nv and Ws. There was a significant effect of task type on MT ($F_{3,33} = 19.6$, $p<0.01$). Figure 5 Left shows the mean MT with standard error-bars for each technique and task type.

Subjective Evaluation

The NASA TLX questions were analysed separately using non-parametric tests (k-related samples with Freidman Test Type) (Table 1). We found a significant difference for the following pairs: Mental Demand: (Ws,mSp), Performance: (mSp,Ws) and Effort: (mSp,Ws) & (mSp,Nv). All other combinations did not reveal significant differences." Low performance value shows that users felt they performed
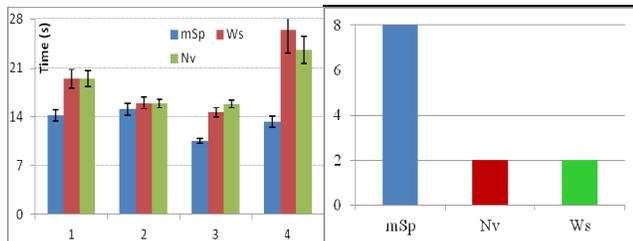

Figure 5: Left: Mean trial completion time for each technique and task. The horizontal axis shows the four task types. Right: Subjective preferences of the different techniques.

Factor	$\chi^2(12)$	P	mSp	Nv	Ws
Physical Demand	4.919	>0.05	1.96	1.62	2.42
Mental Demand	6.645	<0.05	1.54	2.08	2.38
Temporal Demand	0.261	>0.05	1.96	2.08	1.96
Performance	7.0	<0.05	1.67	1.92	2.42
Effort	11.862	<0.05	1.42	2.08	2.50
Frustration	2.606	>0.05	1.75	1.96	2.29

Table 1: Results of NASA TLX questionnaire.

well. Users felt *mSpaces* required the least mental demand and effort. In overall ranking of techniques, 8 out of 12 participants preferred *mSpaces* to the other two conditions (Figure 5 Right).

DISCUSSION

Virtual Workspaces in Mobile Devices

Participants felt that the traditional use of a phone, as in the *no virtual workspace* condition, although it "was already common" and well understood, was "annoying to always start in the menu". Our experiment shows that the use of virtual workspaces to complete tasks requiring serial switching through different applications can be significantly faster and less prone to errors than the traditional use of mobile phones. This is the case when comparing *mSpaces* to the *no virtual workspace* condition.

In the *workspace switcher* condition, the results were very similar to the ones of the *no virtual workspace* condition and slightly better for type3 tasks and worse for type4. This provides evidence that, although virtual workspaces can foster significant improvement over current use of mobile phones, they need to be carefully designed to fully realize their potential.

Spatial Memory to Position Virtual Workspaces

The results show that *mSpaces* improves decision-making accuracy. Additionally, the NASA TLX questionnaire shows that participants felt that they were less frustrated and required less effort to use *mSpaces*. This implies that virtual workspaces can therefore be managed on mobile phones using spatially-aware techniques. With *mSpaces*, people use kinaesthetic cues and spatial memory to intuitively understand the positions of the various workspaces. In addition to being more efficient than the other conditions, *mSpaces* was preferred by 67% of the participants who enjoyed the opportunity to "build a spatial knowledge of the location of apps in space" and were able to "arrange [their] apps around [them]". They found *mSpaces* "faster", "easy to use", "quick and advanced", "very intuitive" and one mentioned that they "could browse everything pretty fast and easily look something up again".

Our implementation of *mSpaces* is built for displaying virtual workspaces, nonetheless the strong results and very positive feedback obtained from the study lead us to believe that the use of spatial awareness and memory to interact with mobile technology is very promising in spite of being under-exploited. It could be used not only to navigate through workspaces (*mSpaces*), menus [11] and shortcuts [14], but also to manage interruptions in mobile technology.

Memory Aids

The results show that using spatial memory only; participants can locate the different workspaces and navigate between them. Participants noted that "after a short learning phase it was easy and comfortable to switch between apps" and "navigational help on the display would

be useful". This suggests that *mSpaces* requires some memory aid. This will also be useful as a reminder when users haven't used *mSpaces* in some time. One way to provide a memory aid would be to display a map with the phone's current position compared to the overall position of all workspaces. We therefore implemented a *workspace viewer* and conducted a user study to investigate if this functionality would improve usability.

Home Button Curse
In this experiment, we noticed that imposing an extra click to request the workspace switch is time consuming and frustrating. Participants commented that the "long press was irritating" and that the *no virtual workspace* condition required a "ridiculous amount of clicking". Users should indeed be able to access a different workspace without having to first return to a main menu. One way would be to use a button dedicated to workspace navigation, which could display all workspaces available and allow navigation between them. This notion of a dedicated workspace button is described in more detail in the design considerations section. *mSpaces* obviously does not suffer from the "Home button curse" as the device is simply moved in order to switch to another workspace, neatly avoiding the issue. The current use of mobile phones with a home button to return to a main menu may then not be optimal, especially for tasks requiring several workspaces or application switches.

One-Handed Interaction Technique
We did not instruct participants on how the phone should be held. They could hold it as they felt comfortable and all held it naturally as they would with their own mobile phone. Nonetheless we noticed that for *mSpaces*, 75% of the participants held the device in their dominant hand only and interacted with the dominant thumb, leaving their second hand completely free. Only two held the phone in their dominant hand while interacting with the other hand. Finally one person used both hands after the first three trials as they "[feared] to drop the phone when moving it too fast". For the two other conditions: *workspace switcher* and *no virtual workspace*, 7 out of 12 participants used two hands to hold the prototype. This is despite both techniques being implemented on the same prototype as *mSpaces*.

Number of Workspaces
For a task with a higher number of switches such as type4 tasks, there was a significant difference in time completion across the techniques. *mSpaces* was more efficient and less error prone than the other two conditions. The number of workspaces may well therefore influence which technique is most appropriate. With the number of applications being concurrently used on mobile phones growing, *mSpaces* seems better suited than other techniques that would clutter the phone's screen with extra icons, switches or scroll bars. Yet, *mSpaces* scalability will need to be determined in future work. According to Ringel [17], some users prefer partitioning information on their screens by using external displays rather than virtual workspaces. We are going

beyond this statement by proposing to improve the use of *mSpaces* by adding an external display (pico-projector) on the mobile phone and fitting it with our *mSpaces* approach.

USER STUDY 2: EXTENDING MSPACES
We propose to test if we can further improve *mSpaces* by including an external display on the mobile phone as well as a workspace viewer. Since pico-projectors are common external displays used for today's mobile phones, we propose to implement *pSpaces*, a projected version of *mSpaces*. *pSpaces* has the added advantage of displaying the workspaces externally from the device via the projection beam, which may improve the speed and accuracy of users when performing a task. In this study, we also compare both solutions to a hybrid version: *m+pSpaces* where the main workspace is displayed on the phone's screen while other workspaces are being projected one at a time depending on the position of the projection as in *pSpaces*. For both *pSpaces* and *m+pSpaces* prototypes, the user points the projector at the physical space to display the virtual workspace corresponding to the location.

Apparatus
All prototypes used a Samsung Galaxy S and Microvision ShowWX+ pico-projector, of size 14mm and weight 122g. To guarantee the comparability of results the *mSpaces* prototype used in this experiment uses the same hardware as *pSpaces* and *m+pSpaces* with the projector turned off.

pSpaces
We implement *mSpaces* on a pico-projector connected to a phone where the user can point at the virtual workspace to display it. The pico-projector is fixed to the phone and the participant moves the projector-phone to different locations to display different content. The motion-capture system used is the same as for the *mSpaces* prototype described in the first user study. The computer determines which workspace to display depending on the prototype's position.

All workspaces are accessible and displayed via the projection. In *pSpaces*, a spatial representation of the virtual workspaces, *workspace viewer* (Figure 6), is displayed on the phone's screen. Workspaces are represented by a thumbnail and not an icon, as in current mobile phones displays; allowing users to benefit from both their visual

Figure 6: Workspace Viewer: Spatial representation of the virtual workspaces on the top part of the phone's screen. The phone's position is represented by a white dot.

and spatial memory [13]. The *workspace viewer* provides constant information on users' location in the environment compared to other workspaces. This answers some of the concerns addressed by participants in user study 1 where some felt that they couldn't remember the exact physical location of workspaces: "you first had to discover and "save" [remember] the positions of the apps". In order for participants to complete the task and to not introduce a new interaction technique, participants used the touch screen to answer the question as for *mSpaces*. Participants needed to return to the question workspace for the answer buttons to appear on the screen below the *workspace viewer*.

m+pSpaces

This condition is a hybrid version of *mSpaces* and *pSpaces* where the main workspace in use is displayed on the phone's screen while the other workspaces are accessible by projecting towards their physical locations (as for *pSpaces*). As the only input needed from the user is on the question workspace, the latter is defined as main workspace, constantly displayed on the phone's screen. Since the screen will be occupied by the main workspace, the *workspace viewer* will not be displayed or made available. We discuss in the design considerations section some interaction techniques that can be used to define what workspace to display on the phone's screen.

Procedures

The tasks used for this experiment are the same as for the previous experiment. We recruited 12 new participants (3 female) for this study aged between 23 and 45 ($\mu = 31.3$), all but one right-handed and all but two smartphone owners. While all participants were familiar with touch screens, only two had used a pico-projector prior to the study.

We used a within-subjects experimental design where all participants had to answer all questions and prototypes were counterbalanced across participants. The tasks were explained individually to each participant who could try out the prototypes with a randomly chosen task in their own time. When they felt ready, they pressed a "Start" button to begin the experiment and again to initiate each trial. After the experiment, users filled out a NASA TLX survey.

The independent variables were: The *virtual workspaces prototype*: mSpaces (m), m+pSpaces (m+p) and pSpaces (p). The *type of task*: type 1 to 4 (t1 to t4).

There were 6 questions of 4 types per prototype corresponding to 24 questions for each prototype and 72 trials overall per participant. In summary the experimental design was: 12 participants x 3 virtual workspace prototypes x 4 types of tasks x 6 trials = 864 data points.

Measures

The experimental software recorded trial completion time (MT) and error rate (ER). In addition, the number of switches between workspaces (SW) was recorded as dependent variable. SW corresponds to the number of times (switches) the user stops on a workspace during a trial. We

measure this data to ensure that visual separation effects [7] in the *m+p* and *pSpaces* conditions do not hinder the results. We count a switch each time the user spends at least 300 consecutive ms on a workspace. There is no maximum number of switches as users can change workspaces as many times as they want until they find the answer to the question. Since *m+pSpaces* has one workspace displayed on the screen, SW is recorded as the actual number of switches per task minus the minimum number of switches required to perform this type of task with a given prototype. We gathered the same qualitative data as for user study 1.

RESULTS

We used the univariate ANOVA with Tamhane post-hoc pairwise (unequal variance) comparisons for our analyses.

Error Rate

There were a total of 43 errors out of 864 trials (Figure 7 Left). With 9 incorrect trials, participants made fewest errors with the *pSpaces* technique followed by 16 incorrect trials for *mSpaces* and 18 for *m+pSpaces*. The 43 trials with incorrect responses were removed from further analysis.

Completion Time (MT)

The average trial completion time overall was 14.4s with standard deviation of 2.6s. There was a significant effect of type of task on trial completion time ($F_{3,33}=17.09$, $p<0.001$). Yet, we found no significant effect of workspace prototype.

Switches Between Workspaces (SW)

The average number of switches overall was 4.2 with standard deviation of 0.2. There was a significant effect of prototype used on number of switches ($F_{2,22}=5.83$, $p<0.05$). *mSpaces* (m) and *m+pSpaces* (m+p) resulted in significantly less switches than *pSpaces* (p) (Figure 8). There was also a significant effect of type of task on trial number of switches ($F_{3,33} = 67.9$, $p<0.001$)
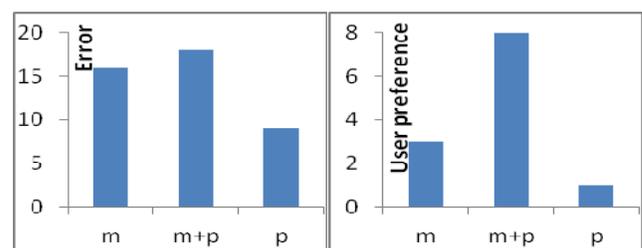

Figure 7: Left: Mean number of errors for each type of workspace prototype – Right: User favorite prototype.
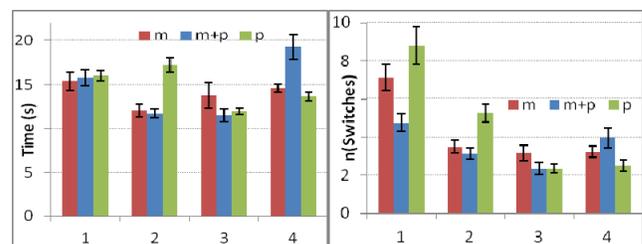

Figure 8: Mean trial completion time (left) and switches between workspaces (right) for each technique and task.

Subjective Evaluation

The NASA TLX questions were analysed separately using non-parametric tests (k-related samples with Freidman Test Type). We found no statistical difference between the different prototypes on any of the NASA TLX factors. In terms of preferences, 8 out of 12 participants preferred *m+pSpaces*, 2 *mSpaces* and 1 *pSpaces*. (Figure 7 Right)

DISCUSSION

Spatially Aware Virtual Workspaces

In this experiment, we did not find any significant difference in the overall task completion time over the three spatially-aware virtual workspaces prototypes. In the first study, for the same tasks, we found that using spatially aware workspaces was significantly faster than current usages of mobile devices. We conclude that while using spatial awareness greatly improves current usages, the way in which the spatially aware system is designed does not seem to influence the system's pace. This further reinforces our first user study finding that virtual workspaces need to be designed with considerations to users' spatial awareness.

Memory Aids

During the first study where *mSpaces* is compared to current usage of mobile phones, users have reported needing time to learn the position of the workspaces and mentioned that "navigational help on the display would be useful". We decided to provide users with a workspace viewer in the *pSpaces* condition since all workspaces were projected and the phone's screen could then be used for displaying the workspace viewer. The idea was to provide users with a constant reference to their position in the environment. This technique also relates well to current existing techniques for switching workspaces in the desktop environment. To our surprise, when we asked users if they found the workspace viewer helpful and if they used it, the 10 out of 12 participants who answered, unanimously replyed that not using it nor finding it useful. The reasons they provided were that "it was quite easy to spot the projections" and "easy to remember the positions". They mentioned they "concentrated on the projection", "knew the arrangement already from the task [they] did before" and "that the other screens were sufficient".

This suggests that with *pSpaces*, users are able to remember the position of the workspaces without needing any workspace viewer. Projection onto the external space has rich spatial cues that, when combined with the kinesthetic cues of moving the device, help users remember the location of the workspace. Additionally, no participant mentioned struggling with finding the position of the workspaces across all conditions, contrary to the first study. Furthermore, in the second study, contrary to the first, all conditions expect users to remember the physical locations of the workspaces so it is possible that the nature of the task condition people to remember the workspaces locations better than in the first study. This leads us to think that when there is no reference to other types of interaction;

people feel comfortable and lose their apprehension towards using such interfaces.

Workspaces Switches

The number of workspace switches is significantly higher for *pSpaces* than for both *mSpaces* and *m+pSpaces* (Figure 8 right) while there is no significant difference in the average time needed to perform the trials; which shows that users switched between workspaces in a faster way using *pSpaces*. At the same time, the NASA TLX shows that participants did not find *pSpaces* more mentally or physically demanding or even more frustrating than the other two prototypes. Since we found that participants had no issue finding the position of the workspaces, we can conclude that participants chose, whether consciously or not, to switch more often betwen workspaces in the *pSpaces* condition. This is also very likely to be the reason why users made considerably less errors in performing the task with *pSpaces*. This higher number of switches seems to indicate that *pSpaces* provide an easy avenue to externalize users' thoughts as in [7]".

One Handed vs. Two-Handed Interaction

In this experiment, only two participants held the prototypes in their dominant hand; while all others always held the prototypes with both hands. We hoped that the projector would be small and light enough to not affect the interaction technique. Unfortunately, the device was bigger and heavier than in the first study and that affected the interaction. Since this *mSpaces* prototype was held in both hands instead of one for the first study prototype, we believe that there is a potential for *pSpaces* and *m+pSpaces* to also be one handed techniques provided a smaller embodiment of pico-projection technology inside phones.

Projected Virtual Workspaces

In terms of performance, *pSpaces* appears to be the best technique as users answered more accurately for the same completion time and swap workspaces more often, probably as a way to externalize their thoughts. Nonetheless, *m+pSpaces* was preferred by 75% of the participants and for performances similar to *mSpaces*. Participants preferred *mSpaces* as "it [is] useful to have the task visible all the time while working on it" and as it was "interesting to have one workspace always in sight". Some participants also liked "having the screens in [a] big size on the wall and at the same time to have the question at hand" and finally one mentioned that "it somehow "divided" the task and space".

In summary, whether due to performances (*pSpaces*) or user preferences (*m+pSpaces*), external projection improves the capabilities of spatially aware virtual workspaces.

DESIGN CONSIDERATIONS

Our experiments show that virtual workspaces have the potential to improve the usability of mobile environments. In this section we would like to propose some design considerations for *m-* and *pSpaces*.

Creating Virtual Workspaces & Managing Applications

There are different aspects to take into consideration when designing virtual workspaces. The workspace needs to be created and an application needs to be allocated to this particular workspace. The virtual workspace also has some attributes such as size and position that need to be defined. We present this set of design considerations below.

Creating & Positioning New Workspaces

There are two strategies for creating workspaces in the space around the user. The first consists of creating an empty workspace and moving applications inside it in separate actions. The second consists in directly positioning an application and creating the workspace at the same time. The latter strategy is the most efficient when there is only one application per workspace. We advise no more than one application per workspace to keep the current mobile device interaction paradigm, and due to the small amount of screen real-estate available for phone handsets.

We propose to introduce a specific button – software or hardware – to trigger and control the workspaces management. This will preserve the one-handedness of the interaction technique while keeping it intuitive for the user. The interaction can be "hold and release" based where the user holds the button, moves the device to a physical location and releases the button to complete the operation. This technique allows a direct allocation of the application in view to the newly created workspace.

Another solution is to implement a drag-and-drop approach similar to Boring et al. [3]. For *pSpaces*, an application launcher could be displayed on the mobile screen for the selected application to open up on the actual external projection at the current pointing direction of the device. The workspace position can then be directly controlled by pointing or moving the device to the physical location corresponding to where the workspace will be residing.

Workspaces Dimension

While in *mSpaces* the workspace size is limited to the size of the mobile phone's screen, as discussed in the previous section, in *pSpaces* the corners and size of the workspaces could directly be defined by manipulating the projection area in the environment through an appropriate gesture via the device itself. We could envisage having a virtual workspace larger than the size of the phone's screen in *mSpaces*, similarly to the concept of Peephole displays [21], but this would require a set-up stage via the touch screen or some movement recognition technique and incur additional interaction controls to scroll through the virtual workspace.

Moving Applications Across Workspaces

When moving applications across workspaces we need to differentiate between *m-* and *pSpaces*. In *mSpaces* we propose to use a similar approach to the way applications are already organized on a smartphone application launcher space. In *pSpaces* we can take advantage of the mobile device screen to "grab" an application and "drop" it on an

arbitrary workspace after having "pointed" at it. We propose a special "grab" gesture (such as quickly tilting towards the user, as in Boring's Tilt interface [4]) to copy the actual projected workspace to the screen in *m+pSpaces* so the user can provide touch input to an application.

Repositioning Workspaces

The thumbnails representing workspaces or applications can be rearranged on the *workspaces viewer* on the mobile device's screen to rearrange the actual physical location of workspaces. The spatial alignment of the thumbnails and their sizes on the screen will directly translate into the spatial alignment and actual sizes of the workspaces surrounding the user in an appropriate manner – such as by inserting at least 30 degree separation angles between workspaces. The rearrangement of thumbnails on the screen will then lead to the corresponding spatial realignment of the workspaces themselves. In the case of *m+pSpaces*, the same technique is used for ad-hoc selection and modification of which workspace is to be displayed on the screen and respectively the projection.

Finding Virtual Workspaces

We show that users get shortly accustomed to their current workspaces' spatial configuration and do not need memory aid. Yet, this will be useful when people move workspaces around or create new ones and disturb the established spatial arrangement. Similarly, it will benefit users who have high numbers of workspaces or haven't used the system in a long time. An overview of the arrangement of the workspaces on the device screen is needed as well as a finding function which allows rapid access to a workspace. We can use a graphical representation of space like Nacenta's [16] work on MDEs of the positions and shapes of all available displays – virtual workspaces in our case –. Finding a particular workspace could be done by displaying arrows on the screen pointing to the direction of the workspace's location. Haptic feedback could be used to indicate the position of a workspace, which would allow users to simply wave the device until they receive the haptic feedback (similar to Sweep-Shake [19]).

Favourite Configuration

Storing favourite configurations would allow for the configuration of different arrangements based on context as Böhmer [2] proposes for icons. In fact, when the phone is used in different contexts – e.g. personal or profesional – or when used by more than one person, different favorite configurations may exist. For multi-users, it is equivalent to starting one's own session on a shared computer.

Applications & Tasks Awareness

To be used for more effective task management, we can provide awareness that a task in another virtual workspace requires a user's attention by adding some visual feedback. We could display a coloured bar on one side of the display (reflective of the position of the other workspace) and for example changing its colour [15] to indicate the status of

the task. Another possibility is to use a halo technique [1] or an off-screen visualization pointing triangle [9]; and haptic feedback could also be used. For example, a light vibration would indicate an alert on a workspace which is currently not visible associated to a stronger vibration when the user hovers over the workspace in question – as we describe in the 'creating virtual workspaces' section above.

Deleting a Virtual Workspace
A gesture, such as drawing a cross while pointing at the workspace could be used to delete it. Alternatively, a specific button could indicate deletion of the workspace. This may require a confirmation click or movement. If the deletion is not linked to the deletion of the application on the workspace, then the confirmation is not compulsary as the effects of a mistake will only be minimal.

CONCLUSION
We investigated virtual workspaces in mobile environments. We started with existing techniques for workspace management in the desktop environment with the view to translate them to mobile settings. We show that extra spatial awareness, that is possible in the mobile context, vastly enhances users' performance. We have presented *mSpaces*, a spatially aware prototype for virtual workspaces, which allows workspace switching by moving the phone to various physical locations, providing users with rich spatio-kinesthetic cues. To determine if using external projection spaces further enhances users' performance, we designed the *m+p* and *pSpaces* prototypes. In a final user study we compare the three techniques to show that projection enhances users' abilities to switch between workspaces, potentially encouraging them to use such methods. We conclude with design considerations to create, manipulate and manage virtual workspaces in the spatially-aware mobile environment.

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