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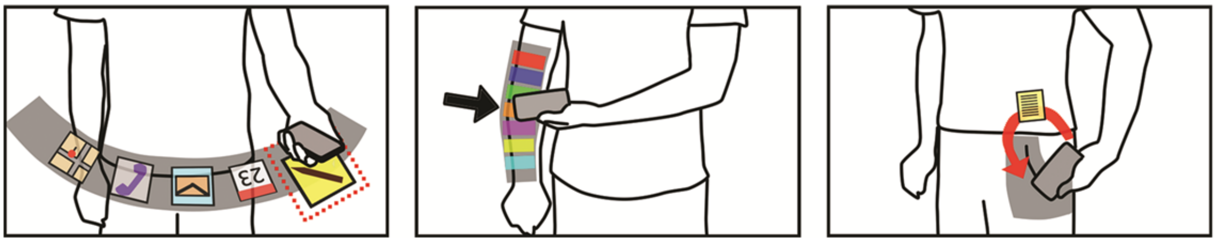

Figure 1. Body-Centric Interaction. Left: the user triggers a 'sketch' app anchored to the body; Center: when sketching, the right arm is a color pallet; Right: sketches can then be stored on body locations for later retrieval, e.g., atop a pocket.

ABSTRACT
Current mobile devices require a person to navigate and interact with applications and their content via on-screen operations. The problem is that mobility trades off with screen size, providing limited space for interactions. To mitigate this problem, we explore how our body can extend the interaction space of a mobile device. We call this *Body-Centric Interaction* (BCI), a design space comprised of three dimensions. First, interactions occur in different *proximal spaces* on/around/far-from the body. Second, different *mapping strategies* can associate digital knowledge or interactions with these spaces. Third, various *input techniques* can help perform such interactions. We make use of this design space to 1) unify existing BCI-related research, and 2) generatively design a set of proof-of-concept prototypes. Overall, we contribute a design space that articulates and envisions how our body can be leveraged to create rich interaction possibilities that extends beyond a mobile device's limited screen space.

Author Keywords
Body-centric interaction, mobile interaction, design space.

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

General Terms
Design, Experimentation, Human Factors

INTRODUCTION
Mobile devices such as smart phones and PDAs rely on the visual display as a primary output and input modality. Many current devices rely almost entirely on direct touch input, dispensing with most physical buttons. To ensure portability, these displays are fairly small (i.e., between 3.5" and 4" diagonal), with only a very limited window into one's information space. Thus screen size largely restricts both users and designers to a limited interaction palette. The problem is that some actions consequently require long sequences of on-screen operations (e.g. accessing off-screen content requires navigating through hierarchies, or swiping and searching through "pages" of content). The problem worsens as the number and functionality of on-device applications increase.

Recent work, mostly implemented as point systems, has sought to augment these screen-centric devices with other interaction modalities. For example, advances in wearable technology make computing readily available from one's body or clothing (e.g., [17,20]). Similarly, some systems allow users to directly place and access digital information onto different body parts [1,9,25]. Others create virtual workspaces around a user's body, where one orients the device to "peek into" and navigate the information space [16,29]. Researchers also envision screen-less devices that allow people to point and gesture in mid-air [10,18], or towards their own bodies [11] to interact with information.

We find this prior work shares an important theme, which we articulate here to help us understand, relate and analyze them together as a whole. In particular, we believe that they extend mobile interaction from *screen space* to *body space*. In doing so, they create *Body-Centric Interactions (BCI)*—a type of interaction that allows people to perform operations outside the device's screen without working only within a small viewport or input area.

To develop this theme, we construct a design space that helps clarify the role and uniqueness of existing work in BCI, and that suggests new opportunities for design. We articulate this design space using three design dimensions:

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1. *Proximal spaces* around the body (immediately-on, close-to, far-from) provide different affordances and interaction possibilities;
2. *Spatial or semantic mapping strategies* establish connections between body's proximal space and the target interaction scenarios; and
3. To perform such interactions, people use different *input techniques* (position or orientation) with the *measurement* of this input either being discrete or continuous.

To illustrate the utility of this framework, we first show how existing solutions fit into this design space, reveal their relationships to one another, and provide insight into its underexplored areas. Focusing on these areas, we then offer a set of proof-of-concept prototypes. In some cases, we also link these designs together into comprehensive scenarios. Taken as a whole, these provide further insight into the different parts of the design space.

This work makes two contributions. First, we articulate the *Body-Centric Interaction* design space to summarize existing work, and to help guide ongoing research into a new trend of mobile interaction. Second, we contribute a set of proof-of-concept prototypes to illustrate less-explored dimensions in this design space.

BODY-CENTRIC INTERACTIONS

To motivate and formulate our design space, we reviewed work from both neuropsychology and cognitive psychology that relates to our innate understanding of the physical space around our bodies. We consider this literature in two ways: first, how we understand proximal spaces around our body; and second, how we relate those spaces to knowledge of our environment. As BCI essentially serves as input mechanism, we also draw from research on input devices and techniques to identify other dimensions of the design space. Figure 3 provides an overview of each dimension as well as how they can be combined.

Proximal Spaces of Interaction

Subjectively, our interactions in everyday life are guided by an innate spatial "reference frame" for the world. This helps us to locate ourselves in relation to other objects and entities within the world, which in turn guides our relative interactions with those entities. Colby, in reviewing a large body of neuropsychology literature, suggests that our cognition is actually guided by several different spatial representations [5]. Holmes and Spence detail three such spatial representations as they relate to our physical bodies, suggesting that each tightly couples perceptual mechanisms and sensorimotor skills relevant for that spatial reference frame [13].

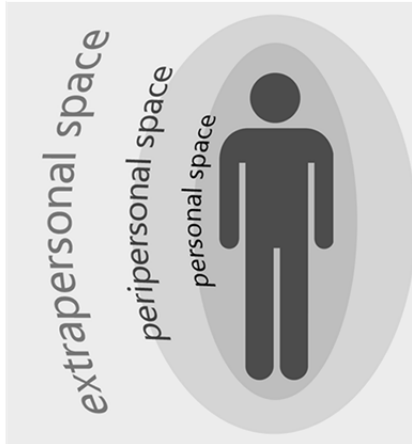

Figure 2. The *Space* design dimension. Among the three body spaces from neuropsychology, we focus on BCI in *personal space* (*body parts* and *wearables*) and *peripersonal space*.

- *Personal space*: space occupied by the body;
- *Peripersonal space*: space immediately surrounding one's body and within easy reach of the hands [24];
- *Extrapersonal space*: space outside of one's reach.

Shoemaker and colleagues [24] argue that although we subjectively operate across these reference frames smoothly, each has distinct perceptual and performance characteristics. For example, we often fail to notice objects around our bodies unless something potentially harmful approaches our body at speed [13]. This shows that our minds differentiate processing of sensory information based on the different proximal spaces around the body.

In our work, we consider these three body-centric spatial regions as being distinct points along the *space* dimension from a design perspective. Our interest is in how these reference frames can be used and exploited to extend mobile device interaction into these three proximal regions around the body. This dimension concerns *where* the BCI is situated relative to the body. For example, within the *personal space*, Guirerro et al. assigned application shortcuts to different body parts [9]. In contrast, *Virtual Shelves* placed digital content in *peripersonal space* (off one's body, but within reach) to be retrieved with a mobile device [16].

Each point in the *space* dimension has different perceptual and ergonomic constraints. For instance, if a mobile device is being interacted within a region of the peripersonal space (e.g., at arm's length), details on the display may be difficult to read. Furthermore, this design dimension allows us to see how seemingly different interaction techniques are thematically related, but vary mainly in how they address concerns germane to a particular proximal space of interaction.

Mappings between Space and Interaction/Knowledge

HCI has traditionally relied on two mechanisms to relate our knowledge with the world [19]: spatial memory, and knowledge-in-the-world. *Spatial memory* helps us remember where things are located in space. This is a common design tact employed in graphical user interface design: screen locations, user pointing and other visual/audio cues are used to help people associate and remember information [22,26,27]. Current consumer desktop systems, for example, locate familiar and common operations on the corners of the screen (e.g. in Windows, the "Start" menu appears on the bottom left; in OS X, the Apple menu appears on the top left, and finally, most menu bars appear at the top of the screen or window). We have

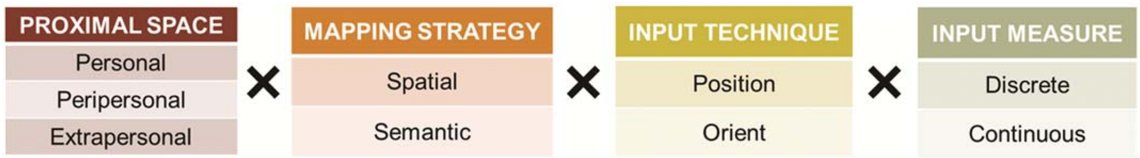

Figure 3. The BCI design dimensions.

also seen this design approach in ubiquitous computing, where spatial memory facilitates people's interactions situated in the environment, such as Cao et al.'s information space 'on any surface' which is viewed and interacted using a hand-held projector [3].

In contrast, the *knowledge-in-the-world* approach guides interaction with cues and constraints from the real world [19]. We employ this approach in everyday life, for example, by placing objects in locations to *remind* us of related information, or to take certain actions [21]. This idea is exploited in design by building affordances and constraints that guide user interaction without having to rely on their memory. Such interfaces are said to have *natural mappings* between spatial knowledge and interaction [19].

To monitor one's body in relation to itself and to nearby objects/entities, our brain maintains an integrated neural representation of the body (*body schema*) and of the space around the body (*peripersonal space*) [13]. This sensory ability allows people to accurately move to and reach locations in space [1,8]. This sense is impaired when we are inebriated, but when fully functional, it allows us to perform some interactions without necessarily being able to see (e.g. we can touch the top of our head without needing to see our hand or the top of our head while performing this action).

These mechanisms for mapping knowledge with the world inform our second design dimension, which addresses the question of *how space (in relation to the body) is mapped to knowledge/interaction*. By definition, BCI techniques are oriented around one's body; consequently, the reference frame for interaction as well as mappings between this interaction and the resulting action are centered around one's body. This builds on prior work that asked people to explicitly associate data and applications with their body [1]. In particular, we find that these various mapping strategies (particularly dealing with the body) range within a continuum defined by the following two directions.

- ***Spatial*** mappings are enabled by spatial memory or the natural constraints of the body's proximal spaces. For example, people can associate a web page with an arbitrary body part (say, the arm) as a short-term bookmark. Similarly, Shoemaker et al. mapped a user's arm to a slider, using its length as a natural constraint [24].
- ***Semantic*** mappings are enabled by knowledge-in-the-world (in this case, in the body's proximal spaces). An *associative experience* maps (for example) raising a calendar application on a device by bringing it closer to the wrist which might associated with a wristwatch [9]. A *functional characteristic* maps (for example) shuffling music on a music player by bringing it close to the ear (the function of hearing) [25].

This design dimension provides several conceptual mechanisms for associating body space with interaction to a given context. As we will see later, it also provides a generative mechanism to use mappings from body space to potential new interaction techniques.

Input Techniques and Measures

Next, we develop and characterize how people interact with their body in BCIs by revisiting taxonomies of input devices, as developed for computer graphics subtasks [8], as a design space for input devices [4], and around smart phone interaction in ubiquitous spaces [2]. In particular, existing BCI work tends to focus on mainly two input techniques: *position* and *orientation* [2][6], where the measure of such input is either *discrete* or *continuous* [4].

First, position and orientation serve as two *subtasks* to accomplish *tasks* in BCI scenarios. We re-define these two subtasks within the context of BCI.

- ***Position***. When performing a *position* action, people specify position(s) in the body's proximal space, e.g., placing the music player near the ear [25], tapping on the forearm [12], or pointing at mid-air locations;
- ***Orient***. When performing an *orient* action, people specify orientation(s) relative to the entire body or particular body parts, e.g., orienting the device towards a mid-air location [16], or tilting the device towards different arm parts.

Our definitions differ from Foley et al. [6] or Ballagas et al [2]. Their work narrowed *position* and *oriention* as specific to *discrete* input 'points' only while creating another subtask *path* to characterize the *continuous* changes of either position or orientation. We restructure this dichotomy onto two dimensions:

Table 1. Examples of different input techniques × measures.

Technique / Measure	Position	Orientation
Discrete	Tap on the forearm	Pointing device outward the body
Continuous	Draw in mid-air	Moving the device around the body

As shown in Table 1, each example interaction technique can specify either discrete or continuous input 'point(s)', which in turn creates different BCI possibilities. While prior work [6] also included *select*, *quantify*, and *text entry* as subtasks, we consider them as *tasks* that are accomplished by performing the two input techniques (discretely or continuously) in BCIs.

SITUATING RELATED WORK IN THE DESIGN SPACE

Several recent works have argued that designers should carefully consider the role of body in both design [15], and reality-based interaction [14]. They advocate designing interfaces that take advantage of humans' innate understanding of their physical bodies, and their skill for "controlling and coordinating their bodies" [14]. The design space we introduced (summarized in Figure 3) builds on these ideas, focusing on their application in the handheld mobile interaction domain.

In this section, we illustrate how our design space unifies a wide range of existing point solutions in designing spatial interactions that operate in the body's proximal spaces. We selectively present them based on their projections on this space. We use the proximal space dimension as our first-order category, but fit each technique within categories suggested by a mix of the other dimensions.

Personal Space

Personal space directly concerns the body. In this space, most prior work focused on associating *body parts* to interacting with digital information.

Semantic Mapping × Discrete Input. In this sub-space, distinct body locations are used to semantically associate or retrieve digital information. In *Body Mnemonics*, users were asked to describe what kind of information and applications would be associated with particular body locations, and use that to suggest an associative map of the body [1]. *BodySpace* applied this idea to a music player which is controlled by placing the device at different parts of the body [25]. Similarly, *Body Shortcuts* enabled quick access to applications by moving the device from one's chest to a number of designated body parts [9]. *Body-based Data Storage* is an interaction technique that uses the user's torso as a virtual container for personal data files [24]. *Snaplet* is a wearable flexible E-Ink display with varied functions decided by how and where people hold it [28].

Spatial Mapping × Discrete Input. In this sub-space, the body is usually used as an input surface with less regard to the semantic meaning of that body part. Shoemaker et al. let people point on their body to operate a 2D color selector projected in their shadow [24]. *Skinput* used people's skin as an input surface by listening to the *acoustic input,* such as tapping the forearm [12]. *Imaginary Phone* appropriated the human palm as a phone interface: by transferring the knowledge of using a regular phone, people instead imagine the interface is on their non-dominant hand and use the dominant one to perform touch gestures [11].

Spatial Mapping × Continuous Input. In this sub-space, the body behaves like an analog UI control or widget. For example, Shoemaker et al. let people 'scroll' on their arm to control a slider [24]. *BodySpace*'s music player mapped movements near body parts as volume and track controls [26].

Summary. The first column of Figure 4 shows how prior work is positioned in the design space. In particular, within personal space, we find most BCIs employ *discrete positioning* as input techniques where both *semantic* and *spatial* mappings are used to associate digital information to body parts. The least amount of work is in continuous input, with none (to our knowledge) using semantic mapping.

First, most interactions tend to use *discrete position* as the main input technique. Some let people 'reach' certain body locations with the hand or device [1,9,24,25,28] while others envision users tapping or touching their body like an input surface [11,12]. However, a few also realized the body's dimensionality and enabled *continuous position* input on it [24,25].

Second, the personal space affords both semantic and

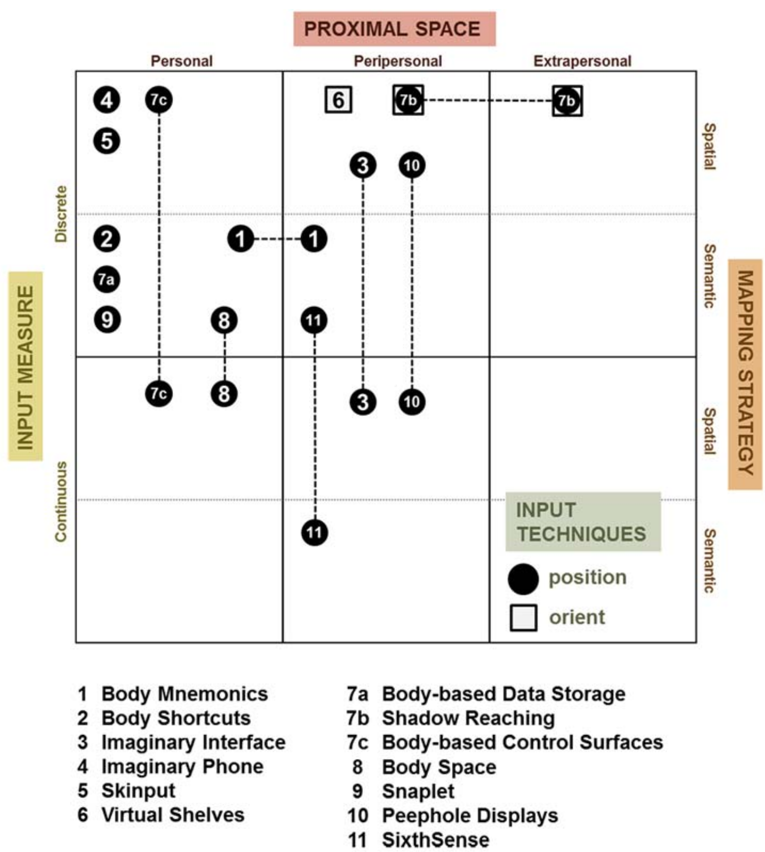

Figure 4. Situating existing work in the design space.

spatial mappings. Semantic mappings usually relate to people's associative experience or the inherent functionalities of body parts [1,9,24,25,28] while spatial mapping was used when considering body parts as interfaces [11,12] or controls [24,25].

Peripersonal Space

Peripersonal space is the space immediately surrounding us and within arm's reach. We find this space embraces a number of interaction possibilities, spanning across various input techniques.

Spatial Mapping × Discrete/Continuous Input. In this sub-space, a virtual information space can be positioned around the body. For example, *Peephole Displays* make use of an invisible information space in front of people, where they use a handheld device as a mobile window to 'peep' into that space [29]. *Virtual Shelves* enables users to trigger programmable shortcuts by spatially orienting their devices within a circular hemisphere in front of them [16]. *Imaginary Interface* lets people create an interface in mid-air, where they use the non-dominant hand to form a reference frame and the dominant one to draw on that interface [10].

Semantic Mapping × Discrete/Continuous Input. In both discrete and continuous sub-spaces, *SixthSense* demonstrates a type of gestural input by positioning/moving hands. The space is semantic only in the sense that the gestures have semantic meaning [18]. For example, as discrete inputs, forming a frame posture triggers a camera. For continuous input, moving the hands apart and together zooms in and out, semantically 'stretching' or 'shrinking' the spatial area.

Summary. As summarized in Figure 4 (second column), spatial mapping plays a more active role in peripersonal space, with which BCIs span across both *position* and *orienitation* input techniques. Yet most prior work made use of its *spatial* characteristics, where the use of the peripersonal space to indicate semantic mappings is somewhat weak. As a result, peripersonal space was used to create free orienting interaction with a device [16], pointing and drawing on an imaginary interface [10], or positioning and navigating as if within a virtual information space [29].

Extrapersonal Space

Few projects have connected the body to interactions in extrapersonal space. A notable exception is by Shoemaker et al [23]. Their design considered the body's three proximal spaces as a continuum for interacting with large wall displays [23]. In particular, they designed a *shadow reaching* technique where people can interact with objects in their extrapersonal space – one's shadow becomes the extension of users' hands which can then span and reach across the three proximal spaces.

Summarizing Design Opportunities/Limits

A critical value of the design space constructed in Figure 3 is to inform us of what has and has not been explored (Figure 4). As such, it unifies our view of how these seemingly disparate systems complement and overlap each other. It also reveals empty or sparsely populated 'cells' that have not been filled by existing work. Below we analyze these 'cells' and discuss whether they represent design opportunities or limits.

1) Orientation is usually absent in input techniques. Most inputs are accomplished by moving a device to or on certain body locations, by tapping body parts, or by pointing/drawing in mid-air (represented by the black circles in Figure 4). Orientation has been largely neglected as an input modality (the single empty rectangle in Figure 4). This omission suggests new interaction opportunities; we illustrate a sampling of these in our proof-of-concept prototypes.

2) Continuous input measure and semantic mapping seldom meet. Most systems apply spatial rather than semantic mapping to continuous position and orientation. This is likely because people normally do not assign semantic meaning to the immediate space they 'carry' around them. Still, semantic mapping presents a design opportunity. For example, in everyday life, we often gesture semantically in space by continuous motion, such as moving hands together and apart to quantify a value. Semantic meaning can also be constructed. For example, while the authors of Virtual Shelves emphasized spatial memory [16], an alternate approach could have a person construct a set of imaginary but spatially fixed shelves, containers, and boxes relative to the body, each with its own semantic meaning of what can be contained by them.

3) Extrapersonal space is almost untouched. Instead, most interactions take place in personal and peripersonal spaces. Shoemaker et al.'s work shows promise for exploring this proximal space, and indeed it would be interesting to consider how people can store and retrieve information in their surrounding environment. We do expect this work to be more challenging, as neither the body nor the mobile device can physically reach that space (by definition).

For the remainder of this paper, we will focus on BCI with mobile devices that take place in personal and peripersonal spaces. We leave extrapersonal space for future work.

DESIGNING PROOF-OF-CONCEPT PROTOTYPES

In this section, we demonstrate the usefulness and expressiveness of the design space through design practice. In particular, we build three sets of proof-of-concept prototypes based on combining different portions of the design space. Overall, our goal is to illustrate how we can use the body to create an off-screen mobile interaction space. To achieve this goal, we consider various usage contexts of mobile interaction, as well as how the body can play different roles in the changing contexts.

During this prototyping process, we developed three different design directions, each of which assigns a specific role to the body in mobile interaction. First, the body can

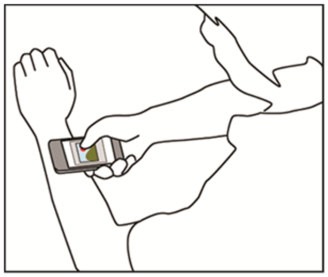

Figure 5. *Body Viewer* is an image viewer that allows people to place/retrieve a digital image to/from their body parts by moving the device towards desired body locations (e.g., forearm).

act as a *canvas* where people place/retrieve digital objects within its proximal spaces. Second, the body can act as *shortcuts* where people trigger programmed digital actions by bringing a device to an area. Third, the body can serve as *controls* in a particular application context.

Below, we explain and illustrate these roles as manifested by our prototypes. We also present scenarios of using selected prototypes, where we discuss how the design space helped expand and explore various solutions towards realizing these roles.

Designing the Body as Canvas

Three prototypes demonstrate how we applied the design space to consider the body as canvas. In particular, we employ various mapping strategies for people to place and retrieve digital objects to and from their personal space (Body Viewer) or peripersonal space (Body Cobweb). We also select and apply input techniques that adapt to both the proximal space and the interaction scenario.

Body Viewer

Body Viewer (Figure 5) is an image viewer that allows people to place and retrieve digital content – in this case images – to or from their body parts. It operates by moving the device towards a desired body location. The device recognizes that location and associates particular images to it (anchored with a tap). Retrieving the image simply recalls an association when the device returns to that location. In other words, body parts are used to index images located on the body 'canvas'. *Body Viewer* also lets one browse a collection of images dropped onto nearby body parts. In particular, it uses a fisheye view [7] to smoothly transition from one image to another as the device continuously moves between contiguous body parts.

Body Cobweb

Body Cobweb, inspired by Virtual Shelves [16], is an imaginary cobweb anchored to people's body (Figure 6). They can bookmark a web page onto it by pushing the device to arm's length to just 'touch' the cobweb. Retrieval is somewhat similar. The software recognizes three operation 'layers' at three distinct distances within people's peripersonal space. Layer A is at normal reading distance (Figure 6,a); Layer C covers the 'end zone' of peripersonal space; Layer B sit in between. Bookmarking the current page occurs at Layer C, while retrieving occurs on Layer B. Moving past layer B to Layer C will overwrite and existing bookmark with a new one.

Similar to Body Viewer, Body Cobweb also supports fluid manipulations with multiple bookmarks. For example, moving forward from Layer A transitions from an overview of all bookmarks, to narrowing the view, and finally to retrieving one web page (at Layer B).

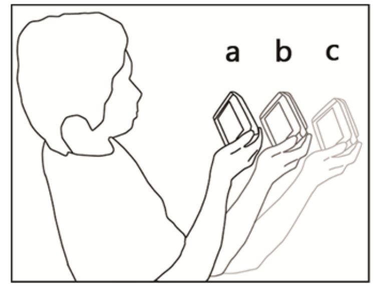

Figure 6. *Body Cobweb* is an imaginary cobweb anchored to people's body. When viewing a web page (a), pushing the device afar bookmarks the current page (c). To retrieve that page, simply move towards the same location where the page will appear (b).

Interaction Scenario: Body Cobweb

Larry's smart phone shows an email notifying him of a job interview. Not to miss this important interview, he 'bookmarks' this email for future reference to the area immediately to his right-front side, where he normally stores critical information. He pushes his phone to arm's length at his right-front (Figure 6, c), which bookmarks that email onto that spatial position relative to his body. The next day, he quickly scans that spot to remind himself of important events by moving his phone rightwards. At first, the screen shows several bookmarked emails. As he moves farther, he sees and finds that job email. Because it is happening that day, Larry retrieves it to get that company's address.

Discussing [Body→Canvas] Design Practice

Most of our digital objects (e.g., files, emails) are stored in a hierarchical structure. Even on a PC, navigating through such directories can sometimes be time- and effort-consuming, not to mention doing it on a small mobile device. To address this problem, BCI proposes using the body as a mobile canvas, an extension to mobile device's file storage/access mechanism. As a result, people are provided with the option of virtually placing/retrieving multiple digital objects in their body spaces. Various mapping strategies can further help them learn and make sense of this new kind of interaction (e.g., associating pockets to storing personal digital belongings).

More generally, the design practice behind the *Body Viewer* and *Body Cobweb* prototypes considers the body as a canvas to 'hold' and 'show' digital objects. First, the design space considers the body's two proximal spaces as canvases. Starting from the personal space, *Body Viewer* applies spatial mapping onto body parts. People place digital images by *discrete positioning* at body locations, but browse them by moving (continuous positioning) across these locations. *Body Cobweb* is similar, but occurs in the peripersonal space. To make use of the natural constraints (*spatial* mapping) of this circular space, we instead use *orient* as the main input technique. Orientation, plus the movement along a given orientation (*continuous position*)

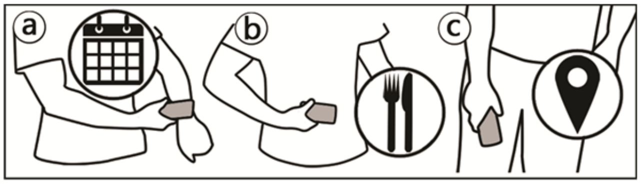

Figure 7. ***Body Shortcuts*** **use body parts to trigger digital actions. (a) The wrist wears a watch hence triggers a calendar (b) stomach digests food hence finds restaurant; (c) knees are used when walking hence searches routes, and so on.**

creates continuous inputs to fluidly view and manipulate a collection of bookmarks in mid-air.

The span of these two designs is shown in Figure 12, from which we can discover even more design possibilities. For example, we can explore the *semantics* of personal space (e.g., using body locations of pockets) to store digital personal belongings. Alternately, the space around one's body can map to her office desk, where she can place digital documents similar to the way she does in real world setting. The prototypes presented are just a subset of design variations suggested by Figure 12.

Designing the Body as Shortcuts

The next two prototypes demonstrate the role of the body as shortcuts, which people use to associate and trigger digital actions. *Body Shortcuts* shows how such designs are realized, whereas *Whereable* envisions a type of mobile device inspired by this design dimension.

Body Shortcuts

Body Shortcuts, inspired by Guerreiro et al [9] performs *programmable digital actions* (e.g., checking today's calendar, finding nearby restaurant, searching routes home) by using various body parts (e.g., wrist, abdomen, knee) to trigger these actions. For example, the wrist wears a watch, hence triggering a calendar (Figure 7a). The stomach digests food hence finds restaurant (Figure 7b), while knees are used for walking hence searches routes (Figure 7c). The underlying interaction mechanism is similar to *Body Viewer*. What has changed is that the digital meanings carried by body parts are *actions* rather than *objects*.

Interaction Scenario: Body Shortcuts

*Larry has finished his job interview and is about to go back to the university. He taps his right knee with the phone which triggers a map search from current location to the university (*Figure 7*c). (Tapping the left knee will instead search for the route to go home)*

Our body can be designed to memorize and execute digital actions which otherwise need to be manually repeated every time, e.g., searching for transit information before going to work every weekday. Further, various mapping strategies allow people to delegate such digital actions to different body spaces in a way that they can most naturally and easily recall the associations.

Whereable

As shown above, *Body Shortcuts* mostly rely on the semantics of body parts (associative experience or body parts' functions). To extend the mapping possibility, we designed the *Whereable* – a device whose functions are triggered by wearing it on different body locations semantically related to that function. An example is a smart phone that is plays music when attached to the arm (e.g., via a band), but that automatically switches to a phone when held by the ear. This is in sharp contrast to the application juggling that now occurs to do something similar on-screen.

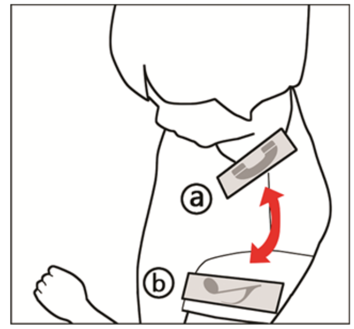

Figure 8. ***Whereable*** **is a device whose functions are triggered by wearing it on different body locations: wearing it near ears → phone (a), on the arm → music player (b).**

The Whereable idea develops Tarun et al.'s vision ([28], where, we stress how *body locations* can decide a device's functions, instead of focusing on flexible form factors.

Discussing [Body→Shortcuts] Design Practice

The goal of this design practice is to use the body to trigger programmable digital actions, which would otherwise need to be manually performed on the device. To achieve this goal, both *Body Shortcuts* and *Whereable* focus on the *personal space* and use *discrete position* as an input technique. Both *Whereable* and *Body Shortcuts* are well suited to semantic mapping strategies – which could also be applied to spatial mapping to enable a wider range of shortcuts.

The design space, as shown in Figure 12, suggests other design possibilities. 1) We can create such shortcuts not only from body parts, but also from the space around the body such as Li et al.'s Virtual Shelves [16]. Here, people would now orient the device in mid-air to trigger application shortcuts. 2) Somewhat similar to Mistry & Maes [18], continuous gestural movement can serve as input technique, where people can gesture in mid-air to perform digital actions.

Designing the Body as Controls

Two prototypes show how the body can assume the role of controls specific to a given application. *Body Toolbar* works in the personal space, while *Rotating Watch* is in the peripersonal space. Both illustrate different input techniques and mapping possibilities.

Body Toolbar

Body Toolbar, inspired by Shoemaker et al [24], creates toolbars on body locations. People select a tool by orienting and positioning the device along the dimension of their body parts, where that location is mapped to an array of

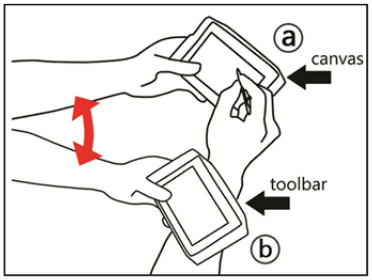

Figure 9. ***Body Toolbar*** **is a toolbar outside the screen, on our body: sketch on the screen (a), toolbar on the right arm (b) – its locations map to an array of tools.**

tools specific to the current application. Two mechanisms support this style of interaction. 1) Identifying discrete body locations simply creates a one-to-one mapping to different tools. 2) Sensing a device's continuous movement further enables more usage possibilities, e.g., in a color pallet, continuous motion adjusts the saturation/brightness of a given hue.

We also explored how this 'toolbar' concept can be extended to a wider set of UI widgets. For example, we could implement a knob-like control mechanism by rotating the device on the wrist, or tune the radio channel by rotating the device near the ear.

Interaction Scenario: Body Toolbar

*On the train, Larry uses his smart phone to take down some notes of today's interview. Because screen space is limited, the program displays no menus or toolbars. Instead, they are 'embedded' in Larry's body. For example, to select a 'highlighter' tool, Larry moves the device across his right arm, where a side bar shows up and different tools appear in a row (*Figure 9*b). Stopping at the 'highlighter' icon selects that tool and then Larry goes back to the default screen to continue writing (*Figure 9*a).*

Mobile devices' screens are too small to contain everything in one view – usually mode switching is required to navigate between the main workspace and other views. As an alternate mechanism, our body can extend applications' view: its dimensions (length, width, angles, etc.) can be spatially mapped to applications' controls, thus enabling readily available access to such controls while keeping the main workspace as the primary view.

Rotating Watch

Rotating Watch is a watch that shows a person's calendar one event at a time. People move the watch around their body to go through their daily schedule (Figure 10). The watch measures its angle relative to people's body and maps it to the change of time. For example, the present time is immediately in front, while future times appear as the arm is rotated to the right. Events appear when the device rotates to particular time positions. While this prototype is deliberately simple and concept-centered, its design can be adopted in a wider set of applications, such as an interface for going through a browser's history list.

Discussing [Body→Control] Design Practice

This practice tries to design the body for controlling a running application, reducing the need for conventional on-screen widgets that compete for the limited screen real estate, as well as reducing navigation to off-screen widgets. *Body Toolbar* uses body parts in the personal space as natural constraints for *spatially* mapping controls. People can use *discrete position* to select tools or *continuous position* to quantify a value. *Rotating Watch* uses the peripersonal space, where people *spatially* map a natural but continuous movement to the change of time.

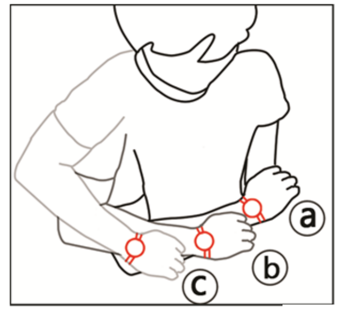

Figure 10. ***RotatingWatch*** **is a watch that shows one of your calendar events at a time. Move it around the body and it goes through your scheduled events one by one.**

To create more design possibilities, we could place the toolbar in people's peripersonal space (similar to Imaginary Interface [10]). In doing so, we can combine input techniques of the *Rotating Watch* where people can now position in the air, rotate the device around itself, or around the body.

Summarizing Proof-of-Concept Prototypes

We applied the design space in sketching and building prototypes that appropriate the body variously in mobile interaction. They collectively illustrate that, given a design goal (canvas, shortcuts, controls), the design space is useful in both extending existing ideas and generating new ones. Further, as shown in Figure 12, we also deliberately addressed the design opportunities somewhat absent in prior work: we adopted *orient* to enrich the interaction styles, and *semantic mappings* to strengthen how continuous inputs are used. We presented three sets of prototypes, each including several variations, as the results of this design process.

Implementation Technologies

While our prototypes can be best considered design sketches, they are fully implemented albeit using technology that is not really suitable for day to day deployment. This is because our focus is on design rather than sensor technology.

Most of our personal space prototypes use RFID tags embedded in clothes, which in turn is associated with the underlying body part. Tags are read by an RFID reader tied to a mobile device. As an alternative recognition technology, we also used the smart phone camera to recognize either fiduciary tags or shapes imprinted on clothes. All setups approximated how devices can distinguish different body parts and body locations. Some were more suited for discrete vs. continuous input.

For the peripersonal space, we tracked the changing spatial relationships (locations, orientations, etc.) between body

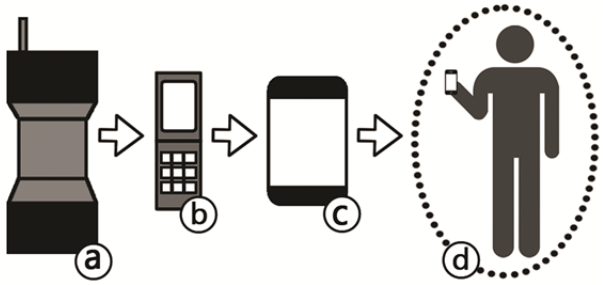

Figure 11. A snapshot of mobile phones' history of development: form factors got smaller for mobility (a→b); screen replaced buttons/styluses and became dominant input/output channel (b→c); our design concept turns the body towards a new form factor, leading to a trend of mobile interaction (d).

parts and devices via tracking systems. To do this, we attached reflexive markers to both the body and the device, where their relative locations were tracked via a set of infrared cameras. Of course, this is an unrealistic sensing environment for it only works within a room-sized space containing these cameras. Still, this setup approximates what we can do when a device knows where it is situated an how it is moved in space relative to the body.

FUTURE WORK

Our work on BCI is inspired by a number of previous projects, where we developed their initial concepts or point solutions towards a class of mobile interaction. Below we envision how this work can be further developed. In particular, we point to two possible directions: designing BCI as 1) more variety of interaction techniques, or 2) a unified new mobile interface.

Designing BCI as Interaction Techniques introduces BCI into existing design frameworks, or adding them as new features. For example, the 'phone call' function can be designed using *body parts* as *shortcuts*: moving the phone to the mouth triggers the phone call; scrolling the phone along the arm goes through the contact list; picking a contact and moving the phone back to the ear finally dials that contact. As another example, consider adding the following features to an eBook reader: the length of the arm maps to the book's pages (*spatial*); to jump to certain parts of the book, just tap the corresponding arm parts. (Harrison et al. demonstrated technical solutions for such interactions [12].)

Designing BCI towards a New Mobile Interface focuses on integrating all design possibilities (as shown in the design space and the subsequent prototypes) in a unified mobile interface. For example, we envision one kind of future smart phone where it has two modes: *free* and *busy*. When *free*, the phone sees the body space as a set of *shortcuts*. The phone is *busy* when a shortcut is triggered, e.g., an app is started. The body then turns into both *controls* and *canvas*, e.g., body parts are toolbars, pockets are related file storage, peripersonal space is a clipboard. Through such mode switching, we can develop BCI

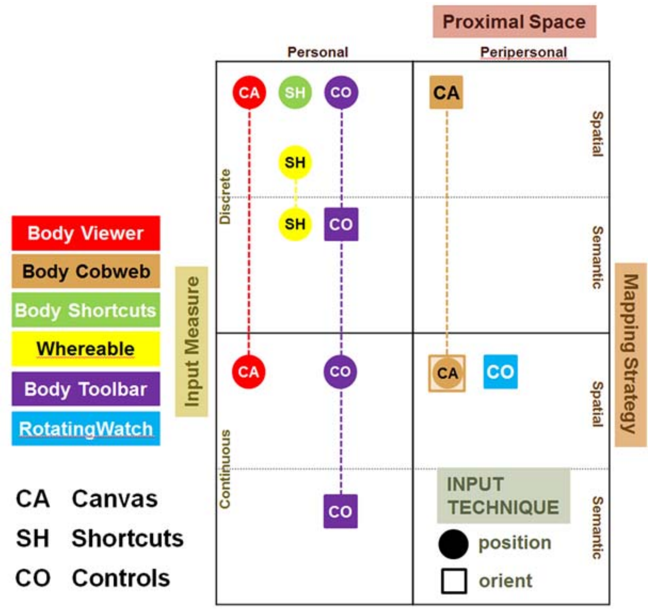

Figure 12. Situating proof-of-concepts prototypes in the design space. Each set of prototypes (Canvas, Shortcuts, Controls) spans across two proximal spaces where most prototypes (listed on the left) span across different mapping strategies, input techniques and measures.

towards a more full-fledged mobile interface that is capable of more than the usual point interaction techniques found in the literature.

CONCLUSIONS

We have merged prior research into a stream that extends mobile interaction from *screen space* to *body space*. We call this *Body-Centric Interaction*, or BCI, and demonstrated how it comprises three dimensions. First, interactions occur in different *proximal spaces* on/around/far-from the body. Second, different *mapping strategies* can associate digital knowledge or interactions with these spaces. Third, various *input techniques* can help perform such interactions. We made use of this design space to unify existing BCI-related research, and (2) generatively design a sampling of proof-of-concept prototypes. Essentially, BCI tries to provide users with alternative off-screen interaction possibilities. We believe this can become a valuable option especially when on-screen operations are less favored.

BCI suggests future development of mobile technologies. Consider the mobile phone as an example. Over time, its for factor was made smaller to improve its mobility (Figure 11[a, b]). Due to less room for GUI-style controls, its interaction mechanism evolved from buttons to stylus to touch. Currently, the screen (and touch) is the dominant input/output channel (Figure 11c). This is not the end-game, as devices have shrunk to the size where the severely limited screen real-estate is becoming one of the biggest constraints in developing mobile interactions, especially as application number and complexity increases. As a result, screen-centric interaction is becoming the liming factor, even as smart phones are increasingly powerful. BCI tries to mitigate this by using the body as an extended interaction space that exists beyond the screen (Figure 11d). BCI and its design space could serve as first steps towards a new trend of mobile interaction, where the device's *limited* size no longer sets the *limit* for the interaction possibilities.

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ACCOMPANYING VIDEO

A video figure accompanies this paper. Alternately, visit http://grouplab.cpsc.ucalgary.ca/papers/ and searching for this paper's title to find both a PDF and the video.

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