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Body-Centric Interaction with a Screen-based Handheld Device

By

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Abstract

Modern mobile devices rely on the screen as a primary input modality. Yet the small screen real-estate limits interaction possibilities, motivating researchers to explore alternate input techniques. Within this arena, this thesis explores *Body-Centric Interaction (BCI)*, specifically in the context of *Using a Screen-based Handheld Device*. In particular, BCI creates a class of interaction techniques that allows a person to position/orient her mobile device to navigate and manipulate digital contents anchored in the space on and around the body. The research methodology consists of an iterative process of bottom-up prototyping, generalizing recurring design themes, reflecting on these themes and on related work, and producing new designs as a consequence. As a result, this thesis contributes a new design direction for interacting with mobile digital contents where the paradigm shifts from the device's screen to the user's body. A class of interaction techniques, delivered as a set of reusable design examples and three recurring design themes, articulate how this new design direction can be realized, what new experience it can offer, and what issues and challenges we need to address.

Publications

Materials, ideas and figures from this thesis have appeared previously in the following publications:

- Chen, X. 'A.', Marquardt, N., Tang, A., Boring, S. and Greenberg, S. (2012) **Extending a Mobile Device's Interaction Space through Body-Centric Interaction**. To appear at the 14th ACM International Conference on Human-Computer Interaction with Mobile Devices and Services - MobileHCI 2012.
- Chen, X. 'A.'. (2012) **Body-Centric Interaction with Mobile Devices**. In Graduate Student Consortium, Proceedings of the ACM 6th International Conference on Tangible, Embedded and Embodied Interaction - TEI'2012. (Kingston, Ontario, Canada), ACM Press.

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An ideal person never has extraordinary talents; he is simply good at drawing help from the others.

-- *Xunzi (Chinese Confucian philosopher)*

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Dedication

For my parents, Meng and Jianing.

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Chapter 1 Introduction: Mobility Trading off Space for Interaction

1.1 Background and Problem

In recent years, mobile technology (e.g., smart phones, PDAs - personal digital assistants) has been adopted at a phenomenal pace in almost all walks of life (Falaki et al., 2010; The Nielsen Company, 2010). While the mobile device's ever increasing computing power has enabled a wide range of digital tasks, its interaction mechanism is still sub-optimal – operating those tasks on a small device is not always enjoyable, often tedious, sometimes difficult, and even impossible to do in particular settings.

This problem stems from the fact that current mobile devices rely on the visual display as a primary output and input modality. Many now rely almost entirely on direct touch input, dispensing with most physical buttons. To ensure mobility, 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 canvas. Consequently, some digital actions require long sequences of on-screen operations. For example, to save screen space, smart phone user interfaces often place control options at the edges of the screen (e.g., as palettes of buttons) which makes it somewhat difficult to locate, identify and touch them to trigger certain operations. As the number of these control options increases, a single screen can no longer host them. A hierarchical approach to manage these options typically 'solves' this problem, but this forces users to explicitly mediate between the main screen and the other control screens. This problem worsens as the number and functionality of on-device applications increase. We can safely predict that future mobile devices will have computing power matching that of today's personal computer; yet it is less certain how the mobile devices' interactive ability will keep pace to let people access that computing power effectively (Baudisch, 2010). As Olsen questioned, "*If I can fit my entire PC in a cubic inch, how will I interact with it?*" (Olsen, 2007). Without breakthroughs in new form factors, we can foresee that the dilemma between a mobile device's mobility and the interaction canvas it can provide will remain a persisting research problem in the Human-Computer Interaction (HCI) community. To summarize, the problem is:

> *Modern mobile devices' mobility has been trading off the space for interaction, limiting how people can interact with their increasingly ubiquitous digital information.*

1.2 Solutions

How can we solve this problem? Since there is a trade-off between 'smaller form factors' and 'more space for interaction', we can try to work on each side. The first approach is to improve existing graphical user interface (GUI) within the limits of the device's small form factors. One example are methods that improve selection accuracy, such as the *Shift* technique developed for selecting small targets on a mobile screen which is otherwise made difficult by the 'fat finger' problem (Vogel and Baudisch, 2007). The second approach is to create more space for interaction, a space that goes beyond the devices' physical boundary. For example, *Peephole Displays* appropriates the space in front of the user's body to enable manipulating a larger virtual information canvas, such as positioning the device as a moving window to browse different parts of a large subway map.

This thesis is interested at this second approach: to create more space for interacting with mobile digital contents. In particular, the literature suggests three ways to do this.

1. *World-centric* interaction allows users to perceive the information as anchored-at/triggered-by/related-to the real world locations/space/objects, where spatial metrics (e.g., position, orientation) are computed in the world coordinate system (Fitzmaurice, 1993; Schilit et al., 1994; Rekimoto and Nagao, 1995; Cao and Balakrishnan, 2006).

2. *Device-centric* interaction considers how the space for interaction can be physically extended from the device itself, resulting in interaction techniques such as device tilting (Hinckley et al., 2000; Hinckley and Song, 2011) or off- or around- device input (Butler et al., 2008; Harrison and Hudson, 2009; Kratz and Rohs, 2009; Ens et al., 2011).
3. *Body-centric* interaction uses people's body, instead of the world containing it, to frame and design interactions (related work is detailed in Chapter 3).

Specifically, this thesis explores the body-centric approach, i.e., focusing on creating space for interaction on and around a user's body. A body-centric approach can be found in a wealth of prior work (e.g., wearable computing, physiological interaction, projector-based interaction). However, this thesis focuses on the specific context of holding, viewing and moving a screen-based handheld device in relation to the body. Even with this narrower context, prior work exists. A number of systems allow users to place digital information from their mobile devices onto different body parts so they can be easily retrieved later (Ängeslevä, J. et al., 2003; Strachan et al., 2007; Guerreiro et al., 2009). Others create virtual workspaces around the user's body (Yee, 2003; Li et al., 2009) or more generally in space (Fitzmaurice, 1993) where one orients the device to 'peep into' and navigate an information space that is significantly larger than the screen. Researchers also envisioned a flexible mobile device whose functions are shaped by the way it is held or worn on the body (Tarun et al., 2011).

All this prior work has extended the spectrum of mobile interaction to include the user's body and its surroundings. We define such interactions as ***Body-Centric Interaction***, specifically, ***with a Screen-based Handheld Device*** (hereafter referred as BCI). In particular, BCI creates:

> *A class of input techniques that allow people to navigate and manipulate mobile digital contents by positioning and orienting the device on and immediately around their bodies*

Figure 1-1 shows three examples of such techniques, all which will be discussed later in this thesis. The user can position/orient the device to navigate multiple virtual objects surrounding his waist (Figure 1-1 top), place/retrieve bookmarks on a virtual canvas anchored to his upper body (Figure 1-1 center), or select an application control option on his right wrist (Figure 1-1 bottom).

1.3 Research Goal and Methods

While a limited amount of prior work in this area does cover the BCI idea, the problem is that they mostly represent point solutions. A broader view of this design theme has not yet been established. Therefore, it is somewhat difficult to generalize ideas from one implementation, or to systematically leverage ideas found across several point systems, or to distill ‘guidelines’ or ‘design strategies’ that stimulate new mobile interaction designs based on the user’s body and the space anchored to it. This thesis builds upon such research opportunities. Its goal is:

Understand the interaction styles, mechanisms, and limitations of current screen-based mobile interaction;

Define Body-Centric Interaction, identify its scope and key components, and situate it in relations to related work;

Develop a class of interaction techniques whose spectrum extends from concrete prototype systems that realize BCI, to recurring themes that summarize the design process; both of which are reusable for future designs.

To achieve the research goal, I took a grounded approach: *theory* supports and elicits a *design* space that is further illustrated with enabling *technology*.

Theory draws on research from neuropsychology and cognitive psychology, where it relates to our innate understanding of the physical space on and around our body. First, Holmes and Spence proposed three cognitive spatial representations organized around the physical body (detailed shortly in Chapter 2): *personal* (immediately-on), *peripersonal* (close-to) and *extrapersonal* (far-from) spaces (Holmes and Spence, 2004). Next, people use *spatial memory* (Baddeley and Hitch, 1994) and sometimes *knowledge-in-the-world* (Norman, 1988) to associate spatial and sensorimotor information with digital information in these spaces. Specifically, this thesis focuses on BCI in *personal* and *peripersonal* spaces where interactions are designed towards utilizing people’s spatial memory and other associative meanings of the body.

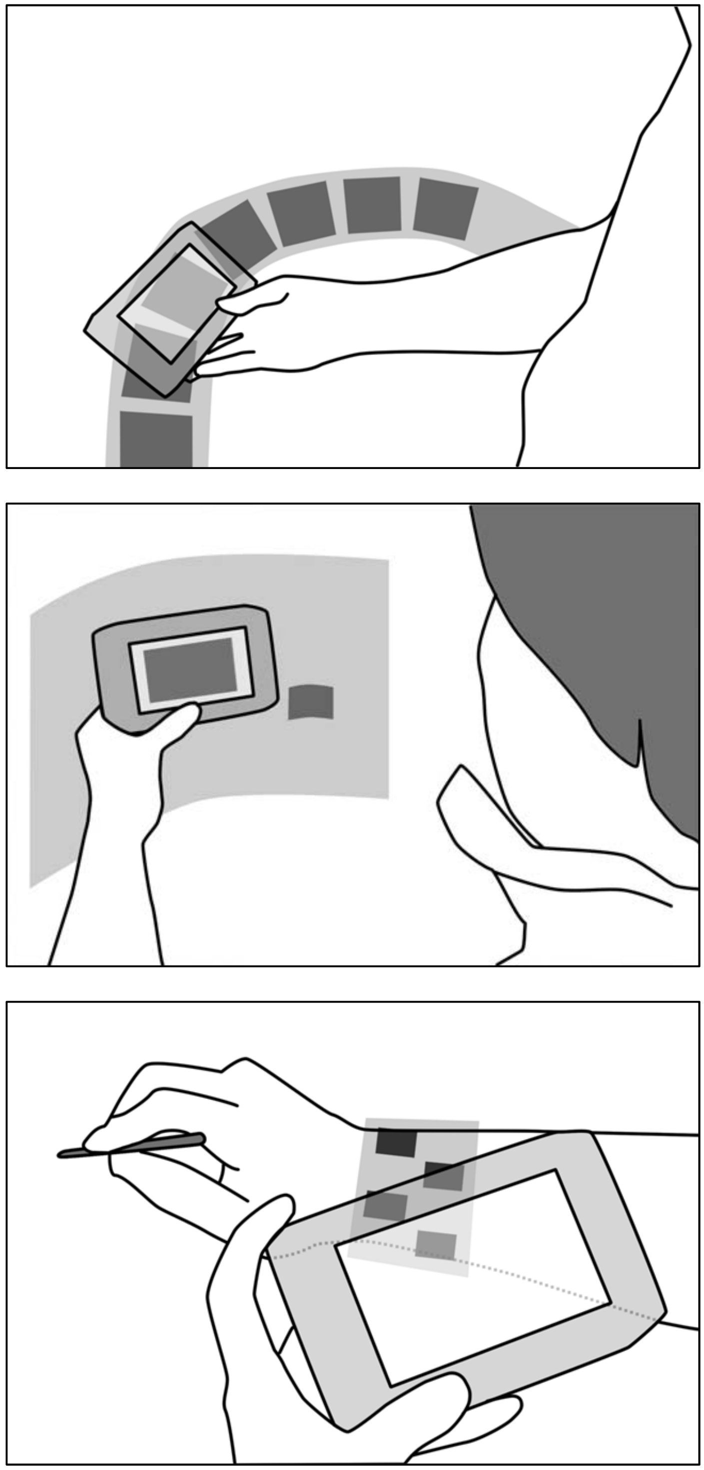


Figure 1-1. Body-Centric Interaction anchors digital contents & actions on & around the body where one can position/orient the device to navigate multiple objects (top), place/retrieve bookmarks on a virtual canvas (center), select an application control option (bottom).

Design is an iterative process between bottom-up prototyping and using these prototypes to compose a design space. The basic strategy is to start with sketching – simply illustrating the interaction scenario, or using storyboards to walk through a sequence of interactions, or plotting other related ideas. The sketches then serve as a roadmap for design and implementation, which is usually achieved through an iterative process. That is, the very first pass usually produces a rough prototype that consists of nothing but the basic interaction. Gradually more details are added and sometimes problems emerge that forces me to return to an earlier stage, and probably to redo the sketching to do the walk-through and 'test' the design. Through this mix of sketches and implementations, I developed fundamental concepts of BCI and identified key design themes that characterize and encapsulate the design process:

1. First, proximal spaces on and around the body are identified and delimited to situate interactions.
2. Second, within these spaces, the spatial relationship between the body and the device serves as 'raw input'.
3. Third, given such 'raw input', various considerations influence the mapping of interactions from the space on and around the user's body. These recurring themes concentrate the essence of BCI, and also uncover several design issues and limitations discussed at the end of thesis.

Technology concerns the implementation of BCIs. In particular, I develop methods to track the spatial relationships between different interaction entities (body parts, mobile devices, etc.). Knowing their locations and directions, I can calculate the distance, orientation, motion and other attributes that lead to modeling and realizing corresponding BCIs.

In brief, the research methodology consists of an iterative process of bottom-up prototyping, generalizing recurring design themes, and reflecting on these themes and on related work as well as new designs.

1.4 Contributions

In general, this thesis contributes a new design direction for interacting with mobile digital contents where the paradigm shifts by extending the device's screen to include the user's body, thus creating more space to situate and compose interaction beyond the limited physical form factor of the device.

In particular, the contribution is situated in a class of *Body-Centric Interaction* techniques with *a Screen-based Handheld Device*. These techniques, delivered as a set of reusable design examples and three recurring design themes, articulate how this new design direction can be realized, what new experience it can offer, and what issues and challenges we need to address.

1.5 Thesis Outline

For the purpose of illustration, the remainder of thesis is organized as follows:

Chapter 2 presents three design themes upfront which typify and articulate the design of BCI.

Chapter 3 reviews related work, with the focus of associating it with the above-mentioned design themes.

Chapter 4 introduces the enabling technology used in prototyping BCI, and the basic implementation approach based on this technology.

Chapter 5 and 6 detail my design exploration. Chapter 5 focuses on designing the body to *switch* between screens of contents and Chapter 6 designs the body to *interact* with contents on the screen. Both chapters present a number of prototype systems, each of which has embodied the design themes (presented in Chapter 2) in creating a specific mobile interaction technique on/around the user's body.

Chapter 7 closes thesis. First I show how the ideas of BCI can be integrally applied to create new experience of using a mobile browser application. Finally I discuss this thesis' contributions, some of the most pressing design issues, and the future work these issues have let.

Chapter 2 Developing Body-Centric Interaction (BCI)

This exploration of BCI followed an iterative process of bottom-up prototyping, generalizing recurring design themes, reflecting on these themes and on related work, and producing new designs as a consequence. This chapter presents upfront the three recurring design themes that are primarily distilled and generalized from the prototyping process. Specifically, these themes encapsulate how BCI can be realized and approached variously. By way of overview:

1. Proximal spaces on and around the body are identified and delimited to situate interactions;
2. Within these spaces, the spatial relationship between the body and the device serves as 'raw input'; and
3. Given such 'raw input', various considerations influence the mapping of interactions from the space on and around the user's body.

These design themes are important lessons learnt from our bottom-up prototyping practice (presented in Chapters 5 & 6). As a whole, they outline an empirical design process; individually, each of them identifies an important design aspect (situating, tracking, and mapping BCI) that unfolds the richness of designing BCI. Below I present a schematic summary of these themes while leaving the details of how I derived and developed them to later chapters.

2.1 Situating Interactions in the Space on/around the Body

While a mobile device typically situates interactions on the screen (and a few physical controls), BCI takes a different stance by situating interactions in the space on and around the person's body. This section tries to establish a fundamental understanding of such *body-centric* space. First, I survey neuropsychology theories in order to deepen our understanding of people's perception of the space on and around their bodies. I then review prior HCI research that addressed the spatial aspect of a person's body. Finally I provide a refined description of the body's proximal spaces wherein BCI is situated.

2.1.1 Understanding Multiple Representations of the Body-Centric Space

As the name indicates, *BCI* requires us to understand people's perception of the space centered on the body before we can appropriate it for interactions. To capture the richness and nuances of this *body-centric* space, I surveyed related literature in Neuropsychology, which has established a number of systematic frameworks to articulate such space.

Colby, in reviewing a large body of neuropsychology literature, suggested that our cognition of our bodies is actually guided by several different spatial representations (Colby, 1998). Holmes and Spence detailed three such spatial representations relating to our physical body, and suggested that each tightly couples perceptual mechanisms and sensorimotor skills relevant for that spatial reference frame. In particular, they describe three distinct regions extended from one's corporeal body (Holmes and Spence, 2004):

- *Personal space*[1]*:* space occupied by the body;
- *Peripersonal space*: space immediately surrounding one's body and within easy reach of the hands (cf. (Shoemaker et al., 2010));
- *Extrapersonal space*: space outside of one's reach.

[1] Note that this term is different from that coined by Hall within Proxemics theory. Hall's 'personal space' refers to the region surrounding a person which they regard as psychologically theirs (Hall, 1968).

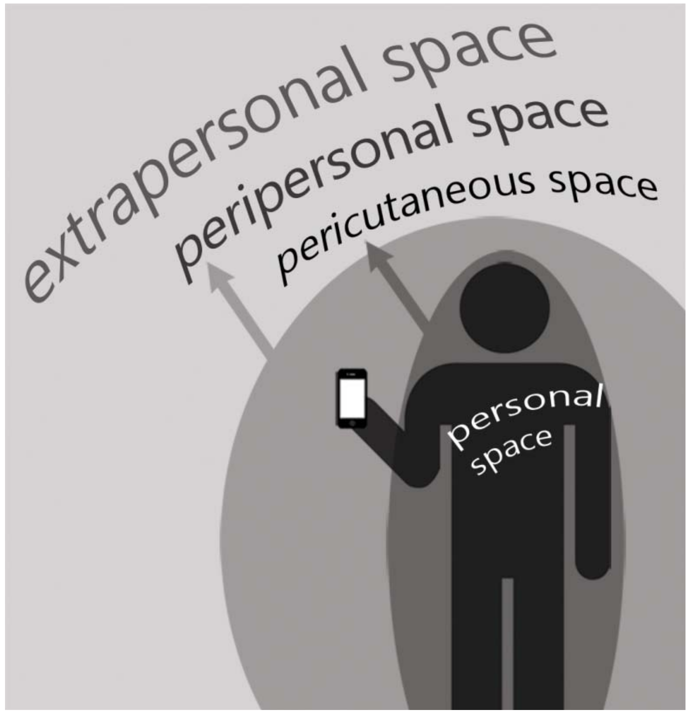


Figure 2-1. Neuropsychologists divide peoples' body and the space around it into four regions: Personal space is space occupied by the corporeal body; Pericutaneous space is the space just near/above body parts; Peripersonal space is the space outside the body but within arm's reach; Extrapersonal space is space beyond arm's reach.

Similarly, some researchers develop a fourth region called *Pericutaneous space* – space just outside the body (Elias and Saucier, 2006). This space can be thought of as layered between *Personal space* and *Peripersonal space*. Combining these theories, Figure 2-1 provides an overview of the body's proximal spaces.

The motivation of discriminating these 'spaces' is that they are considered being processed differently by the brain. Shoemaker et al. argue that although we subjectively operate across these reference frames smoothly, each has distinct perceptual and performance characteristics (Shoemaker et al., 2010). For example, we often fail to notice objects around our bodies unless something potentially harmful approaches our body at speed (Holmes and Spence, 2004). In this thesis, these multiple representations help establish a fundamental understanding of the *body*-

centric space. Below I present examples in HCI research where such spatial understanding of the body was developed and applied in building interactive systems.

2.1.2 The Spatial Aspects of the Body Applied in HCI Research

In HCI research, the development and application of the body's spatial aspects was inspired by related theory in Sociology (e.g., Hall's Proxemics theory about how the distance and orientation between people dictate and reflect their social interaction), the Neuropsychological perspectives introduced earlier, and many other disciplines that try to understand people's body and the space around it.

Benford and Fahlén's spatial model aimed for mediating interaction in a large virtual environment (Benford and Fahlén, 1993). Their spatial model built upon several concepts, each of which was developed from the behaviours of entities (people and objects) inhabiting a virtual space of a Computer-Supported Cooperative Work (CSCW) system:

- *Medium*: through which interactions take place, e.g., image, audio;
- *Aura*: a bounding box of an entity in which interaction with it is possible through certain media;
- *Focus*: a field of view in which an entity is dedicating its attention to;
- *Nimbus*: the periphery of an entity in which it can be kept aware of by the others.
- *Adapter*: artefacts that affect the above measures of an entity.

Spatial metrics were developed from these concepts, e.g., two persons' relative *positions* can tell whether one is in the other's Aura, hence would be empowered with basic communication with the other person. Benford and Fahlén's work was one of the earliest to address the body's spatial aspects in designing interactions. Their model is an important reference for situating BCI in the proximal spaces of the person's body. Their model also suggests how one can apply it to designing interactions. For example, when the entity becomes an object, such as a white board, the Aura concept can be applied to decide the mode/state of that object, e.g., the white board will be turned on when the user enters its Aura.

More recently, Shoemaker explored the three Neuropsychological spaces in designing interactions with large wall displays (Shoemaker, 2010). In his work, these different spaces were leveraged to create interaction techniques tailored for manipulating objects on a large wall display. Essentially, the relation of a person to a large wall display can be thought of as the display standing across one's *Peripersonal* and *Extrapersonal* spaces, where only a small part of it is physically reachable. To address this natural limitation, Shoemaker et al. developed a *Shadow Reaching* technique that allowed a person to 'reach' far-away target (in *Extrapersonal* space) via the shadow of their arms (Shoemaker et al., 2007a). Meanwhile, the person's body (torso, arms, etc.) was appropriated for accessing personal data and tools where these items were projected in the body's shadow, or were manipulated via actions against specific body parts (Shoemaker et al., 2010). Although Shoemaker's work was specifically tailored for large wall displays interactions, most of the ideas are generalizable and, as shown later in Chapter 5 and 6, have inspired various BCI prototypes, particularly how body parts (*Personal* space) can afford data storage and tool using.

Both Benford, Fahlén's and Shoemaker's works typify how the body's spatial aspects can be developed and applied in HCI research, which motivated me to push the spatial boundary of the body, trying to situate BCI in its proximal spaces.

2.1.3 The Body's Proximal Spaces Used in Designing BCI

Based in part on these prior models, I now refine the description of the body's proximal spaces where BCI is situated. (To avoid jargon, I rename some terms using everyday language.)

On-body space, corresponding to both *Personal* and *Pericutaneous* space, hosts interaction where people's actions *specify particular body parts*. For example, a person's arms can become the extension of a device's screen and digital objects tools can be 'placed' on this body surface. Space near the body (say, within 5 to 15 cm) can also be appropriated for interaction (and is also considered part of the on-body space). For example, we can apply this by 'stacking up' digital objects and tools on the arm, similar to how we use a tray or a desktop. Finally, clothes pockets can also be considered part of the on-body space as they are wearables that are 'fixed' to the body (when they are worn), as opposed to the others, e.g., scarf, that are merely 'carried' with the body. Later chapters will show how we can develop associative meanings from pockets for creating interactions on the body.

Around-body space, corresponding to *Peripersonal* space, supports interaction where the user's actions specify a location at an arm-reachable distance from her entire body. Yet in reality, people mostly see in the space in front and to the side of them, and move their arms in that same space. If considered ergonomically, the actual 'reachable' space is specified by people's comfortable arm movement range, and whether that arm movement is in view. Consider holding the device with the right hand. The comfortable movement range will significantly shift to the right; for the left hand, vice versa. In contrast, reaching the area by one's lower back is more awkward and out of one's view. Further, as this space requires larger-scale movement, some other factors also affect how it will/should be delimited to meet the actual scenarios. Consider different social contexts (sitting in a meeting vs. walking in a park), the readability of screen contents (less readable if positioned afar from the eye), etc. – all which will influence how space is used for interaction around the body.

To conclude, BCI is situated on or around the user's body. On-body space is space 'locally' anchored to, and sometimes slightly extended from, certain body parts, including the wearables covering that location. Around-body space is space 'globally' anchored to the entire body (where the body can be referred to as a point in the 3D space). In actual interaction design, both spaces are reduced to a smaller region in which people can comfortably and appropriately hold and move their mobile devices.

Next, I discuss, within these spaces, how we can track the spatial relationship between the body and the device that serves as input for interactions.

2.2 Tracking Devices' Spatial Relationship with the Body

BCI assumes a particular interaction style. One holds a mobile device, where they position and orient it in the space on and around the body (Figure 2-2). While performing BCI, the spatial relationship between the device and the body drives the interactions which are situated on or around the person's body. The vocabulary of describing such spatial relationships can be expressed by two spatial metrics –

position and *orientation* – measured either *discretely* or *continuously*. I consider these two metrics as the most fundamental ones in representing the interaction style of BCI; other metrics can be derived from combining or calculating on these two ‘primitives’, such as learning the *identities* of body parts, or telling the *motion* of the device relative to the body. Next, I revisit one of the earliest works that applied these two metrics in composing input messages to a computer graphic interface. I then discuss, within each proximal space of the body, how these metrics are defined and measured in order to reflect and extract the device-body spatial relationship.

2.2.1 Revisiting the Computer Graphics Subtasks

Foley, Wallace and Chan developed taxonomy of input devices around the computer graphics subtasks they could perform (Foley et al., 1984). Their six subtasks, summarized below, can be thought of as a set of primitive input actions that gradually build up complex task operations.

- *Position*: specifying a position in application coordinates;
- *Orient*: specifying an orientation in a given coordinate system;
- *Select*: selecting from a set of alternatives, such as a set of commands;
- *Path*: specifying a series of positions and orientations over time;
- *Quantify*: specifying a value or number within a range of numbers;
- *Text*: composing textual input.

Although this taxonomy was based on graphical user interface, it was later studied and applied to designing input techniques for mobile and ubiquitous computing. In particular, Ballagas et al. discussed how then emerging cell phones, equipped with physical keys, sensors and cameras, could be turned into a ubiquitous input device, allowing people to interact with digital contents in other ubiquitous computing devices (Ballagas et al., 2006).

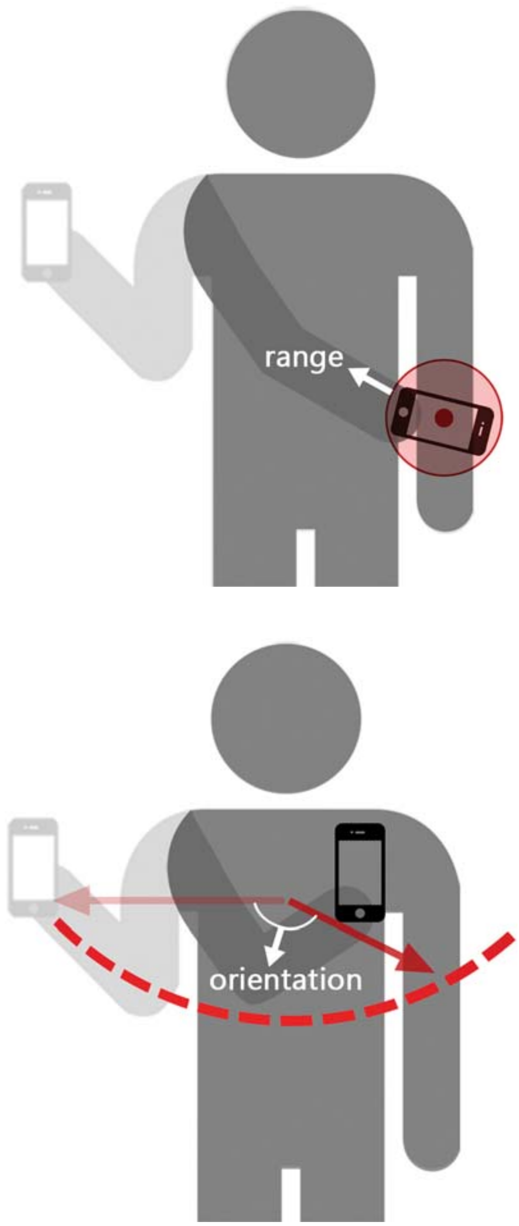


Figure 2-2. Basic approaches of tracking the device's spatial relationship with the body: in the *on-body* proximal space, detecting whether the mobile device is spatially located within certain range of a body part (top); in the *around-body* proximal space, measuring the *position* and *orientation* relative to the *entire body of a person* (bottom).

All this work is similar to this thesis in that both *position* and *orientation* are considered important extra components in composing inputs understandable by a computer (be it GUI-based or Ubicomp-based). Yet BCI is also critically different from the past work: past work considered position and orientation as the primitive *tasks* (i.e., subtasks) that can be combined to build up more complex operations; this thesis considers position and orientation as the primitive metrics (1) that model and represent how one holds and moves a mobile device, and (2) that can be mapped to various interactions (detailed in next section). Below I discuss the first issue, i.e., how to develop the spatial metrics and their measurements so that a device-body spatial relationship can be calculated. I leave it to a later chapter how such spatial relationship can be mapped to interactions.

2.2.2 Developing the Spatial Metrics and Their Measurement

The two metrics – *position* and *orientation* – should be defined and measured differently depending on the proximal space wherein BCI is situated.

In the *on-body* proximal space, our basic approach is to detect whether the mobile device is spatially located within certain range of a body part. For example, a device specifies the wrist if the distance between them is smaller than a threshold. To further explore the richness of interacting with body parts, we can apply and develop the spatial metrics, i.e., *discrete vs. continuous position*, and *orientation*[2]. Thus we create more dimensions which we can alternate for exploring possible interactions. For example, in addition to sensing a binary range (in or out), we can incorporate the continuous changes of position between the device and a body part. As another example, once the device is positioned at a body part (e.g., the mid-forearm), a person can *rotate* the mobile device around it, which further adds an orientation value as input for interaction.

In the *around-body* proximal space, I consider the *position* and *orientation* relative to the *entire body of a person*. For example, one can hold and orient the device around her body, specifying a changing *orientation* value relative to the body as a fixed point (e.g., we can take the geometric center and a vector indicating the forward-facing

[2] Captured as the angle of the device relative to the normal of a particular body location.

direction, all together to represent the entire body). There are various approaches to define and measure such *position* and *orientation* around one's body. Consider using different coordinate systems. A Cartesian system returns the 3D coordinates of the device (with the body as the origin) with which we can specify a point in mid-air that is anchored to the body. A Spherical system returns vectors from the body to the device which can be thought of as directions pointing outward the body. A Cylindrical system returns 1) the height of the device, and 2) its 2D orientation on a horizontal plane (e.g., 11, 12, or 1 o'clock). Chapter 5 will detail the use of these coordinate systems in modelling and designing BCIs.

In short, the device-body spatial relationship can be represented as the device's *position* and *orientation* – measured *discretely* or *continuously* – in relationship either to particular body parts, or to the entire body in the environment.

2.3 Considerations for Mapping Interactions from the Body

So far we have established a fundamental understanding of the body's proximal spaces, and explored, within these spaces, how to track the spatial relationship between the device and the body to provide for 'raw inputs'. In this section, I will discuss how we can *map* these 'raw inputs' to the actual interaction with mobile digital contents. Essentially, mapping explores how the general GUI tasks (or further mobile-specific tasks) can be encoded in people's actions of positioning/orienting the device on/around their body. This discussion of mapping dates back to Ängeslevä et al.'s *Body Mnemonics* project where they explicitly asked people to associate mobile data and applications with their body (Ängeslevä, J. et al., 2003). Both Ängeslevä's and this thesis' goal is to find out what can empower people to think of the space on and around their body as equivalent to some interfaces, and likewise to learn how their actions of positioning/orienting the mobile device will correspond to some interface actions. In referencing Ängeslevä's findings and experimenting with various design ideas (as discussed later in this document), I have identified a number of factors to be considered in deciding on these mappings. For instance, while designers may be limited by the body's physical constraints, they can take advantage of people's spatial memory, associative experience, kinesthetic sense, and visual cues to create mappings that will be easy to identify (visual cues), execute (kinesthetic sense), or remember (spatial memory and associative experience).

2.3.1 Physical Constraints

Based on his classic *The Psychology of Everyday Things* (Norman, 1988), Norman re-introduced the concept of *constraint* in designing user interface (Norman, 1999). Essentially, constraints are properties of the interface that induce users' behavior. In particular, there are three kinds of constraints.

- *Physical constraints* – 'closely related to real affordances' – limit a person's actions on the interface, e.g., a person cannot move the cursor out of the screen;
- *Logical constraints* allow a person to reason and determine the alternatives, e.g., if the page remains the same after editing its information, a person will realize some 'refresh' actions might be needed.
- *Cultural constraints* are conventions shared by a cultural group, e.g., the slider for scrolling a web page is very likely to be placed on the right or bottom of the screen.

In BCI, the body is considered a part of the mobile interface, which encourages us to consider its constraints when mapping interactions from it. Re-interpreting Norman's concepts, I consider the body's (physical) *constraints* as the physical properties of people's bodies that restrict the possible design options. Consider a simple example of associating digital objects to the body. While it is reasonable to associate a digital object to the arm, the interaction becomes cumbersome when placing it, say, in the small of the back, where reaching it becomes more difficult (and where the device would be out of view). Similarly, when mapping the arm to a digital tool, say a slider, it is more reasonable to place it along the arm's length rather than its width as the latter provides very limited sliding range.

The other two constraints (logical and cultural), while under the same category by Norman, are considered differently in this thesis. In particular, they are more germane to exploiting people's associative experience and knowledge, which will be discussed shortly.

2.3.2 Spatial Memory

Spatial memory is our ability to memorably associate space with information (Baddeley and Hitch, 1994). For example, at times we can remember where we have placed a frequently-used book (say, a dictionary) on the book shelf without having to explicitly memorize its location. Meanwhile in HCI, spatial memory 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 (Robertson et al., 1998; Tan et al., 2001, 2002). 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 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 (Cao and Balakrishnan, 2006).

In this thesis, the space on and around the body can be thought of as an interface, and likewise, spatial memory can help people remember, for example, on which body part they have placed a web page bookmark, or which pocket corresponds to a 'payment' function, or how to shortcut an app by orienting the device in the around-body space.

2.3.3 Associative Experience

Spatial memory is a basic skill of human beings to help themselves process the physical world in their heads. But in reality, spatial memory rarely works as an independent factor. As Ängeslevä et al. found out, people can actively develop strategies that assign meanings to their body parts, and therefore create strong associations between their body and the mobile device's digital contents (Ängeslevä, J. et al., 2003). In particular, they found four mapping strategies:

- *Emotional mapping* is related to "culturally shared symbolic perception of the body", e.g., "husband and children in the heart area" and "my dad by my head cause he always knows best";

- *Associative mapping* is “connected to specific past experiences”, and “made sense only to the individual”, e.g., “my sister and my close friend [I would store on my neck], because they gave me necklace and pendant separately but I always wear them together”;
- *Functional mapping* is “connected to specific tools or to ergonomic or behavioural characteristics of the body”, e.g., “MP3 archive to my left ear”:
- *Logical mapping* “treated the space as having some associational starting point, and then built complex information in relation to it”, e.g., right side is generally more logical to the left.

These findings indicate the richness of associating one’s body to the data and application of a mobile device – much richer than simply employing spatial memory. Essentially, how one can relate her body to the device’s digital contents is a function of her innate spatial memory, and her personal knowledge and experience associative to the very context. In particular, one approach is to establish such associations based on various *conventions* (Norman, 1999) developed from the GUI paradigm, where people would use the interface on and around their body in a manner that is similar to using a GUI. For example, consider placing the one-week history of visited web pages around one’s body. Spatial memory can inform the user the earliest pages are on the left end and the latest on the right, and the user can thus extrapolate how to retrieve a particular one. This design can be improved by incorporating people’s knowledge of using a calendar (both paper and digital). The space around the body can be divided into seven regions, each of which corresponds to one day of the week. With this design the user can directly go to or approximate a specific day of her browsing history of the past week.

2.3.4 Kinesthetic Sense and Visual Cues

With interactions situated on the body, the *visual cues* (Tan et al., 2001) of body parts can further strengthen the existing associations – established by either spatial memory or associative experience – between its space and information. To reach these parts and execute the interaction, people also rely on *kinesthetic sense* – our awareness of body parts’ relative positions (Tan et al., 2002; Proske and Gandevia, 2009). Consider associating digital shortcuts to different body parts. The visual cues of one’s wrists, abdomen, and knees will inform them of the digital shortcuts that are readily available from their bodies, while kinesthetic sense allows them to accurately locate these body parts in order to trigger the digital actions from those shortcuts. Further, clothes and items worn on the body also serve as visual cues where one can, for example, easily associate a digital payment card to a pocket that usually holds the wallet. And kinesthetic sense enables them to ‘reach’ the digital payment card with reduced visual attention.

2.4 Summary

BCI lets people position and orient their mobile device towards their body or the space around it as a way to navigate or interact with its on-screen digital contents. This chapter unpacks this definition to explore, in general, the richness of designing such interactions. First, the space *on* and *around* the body are identified and delimited to situate interactions. Second, within these spaces, the spatial relationship between the body and the device serves as ‘raw input’. Third, given such ‘raw input’, various considerations influence the mapping of interactions from the space on and around the user’s body.

These three design themes are important as they as a whole encapsulate an empirical process of realizing the design of BCI, starting from considering the space available on and around the body, to taking the device-body spatial relationship as input, and finally mapping such input to interactions with mobile digital contents. Further, each of them explore the richness of designing BCI, from pushing the spatial boundaries of the *body*, to introducing different spatial metrics/measurements, and to including various considerations that influence the mapping of interactions from the body’s proximal spaces.

This chapter presented a schematic summary of these design themes. Table 2-1 summarizes these themes (and the keywords that describe their contents). The following chapters continue to reflect on these themes by situating them in related work (Chapter 3) and by embodying them in the design of a set of BCI techniques and prototypes (Chapter 4 – 6).

<u>Design Themes of BCI</u>

Theme 1. *Proximal spaces on and around the body are identified and delimited to situate interactions;*

- On-body space
- Around-body space

Theme 2. *Within these spaces, the spatial relationship between the body and the device serves as 'raw input'*

Metrics	*Measurements*
- Position	- Discrete
- Orientation	- Continuous

Theme 3. *Given such 'raw input', various considerations influence the mapping of interactions from the space on and around the user's body.*

- Physical constraints
- Spatial memory
- Associative experience
- Visual cues
- Kinesthetic sense

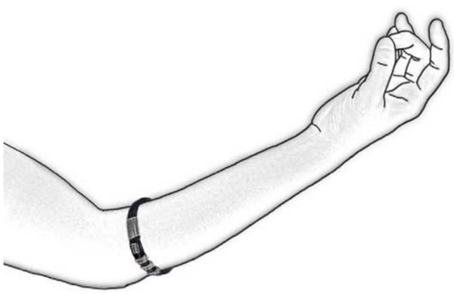
Table 2-1. Summary of the three design themes of BCI.

Chapter 3 Reflecting on Design Themes and Related Work

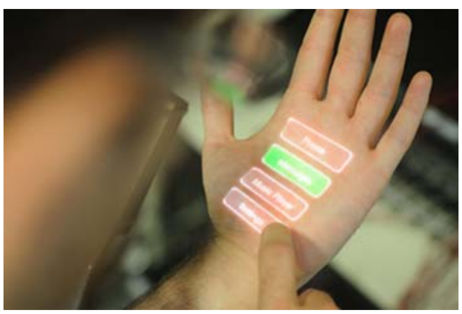
Chapter 2 has provided a schematic summary of BCI's three design themes that characterize how interactions can be situated, tracked and mapped from the space on/around a person's body. Now I discuss these themes in relationship to previous work – how others have applied a *body-centric* approach (see Chapter 1) in designing interactions. For the purpose of illustration, I organize this discussion by the three proximal spaces centered on the body (pericutaneous, peripersonal, and extrapersonal (Holmes and Spence, 2004; Elias and Saucier, 2006)). In each category, I begin with a broader overview of related interactions in this body's proximal space. I then narrow to a specific focus *where BCI takes place using a screen-based handheld device*. The goal here is to reflect on how others have (perhaps tacitly) considered these design themes, as well as to further understand the interplays between interactions and the body.

3.1 On-Body Interactions: Pericutaneous Spaces

Ishii & Ullmer envisioned that the locus of computation would shift into two directions, one of which was to people's skins and bodies (Ishii and Ullmer, 1997). This vision has fostered interactions (1) directly with the body, (2) 'worn' on the body, or (3) via a mobile device close to the body. Recall how neuropsychologists define pericutaneous space (space immediately outside the body). These interactions are all situated in this space while they also differ in whether the interaction is directly with the body, or via wearable items or a close-to-the-body device.



a. Muscle-computer interface



b. Skinput

c. Your noise is my command

Figure 3-1. On-body interactions directly with the body

3.1.1 Interactions Directly with the Body

Using the body's physiological properties to design interactions. A number of projects leveraged the physiological properties of a person's body to develop gestural input from the body such as gripping, pinching, tapping (on the skin) (Saponas et al., 2009; Harrison et al., 2010), or simply orienting one's body in the environment (Cohn et al., 2011).

Saponas et al. designed a set of gripping gestures that trigger the muscles' activities as sensed by a computer (Saponas et al., 2009) (Figure 3-1a). Harrison et al. illustrated how one's entire body surface could become an input device by listening to acoustic input (e.g. tapping) along the skin (Figure 3-1b *Skinput*) (Harrison et al., 2010). Cohn et al. turned the body into an antenna capable of sensing ambient electromagnetic noise from the environment, thus enabling knowing the person's location in the house and his touching points relative to different appliances (Figure 3-1c) (Cohn et al., 2011).

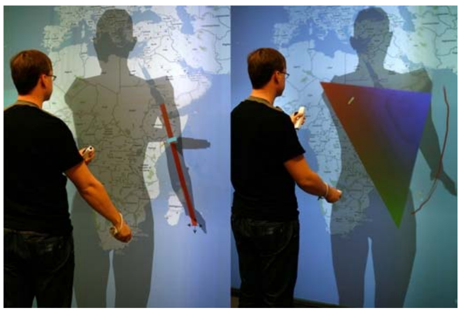
Using external sensing infrastructure to enable interactions. External sensing (e.g., overhead depth-sensing cameras) could also enable similar interactions directly on the body.

With a large wall display, Shoemaker appropriated the user's body as data storage (Figure 3-2a) and control surface (Figure 3-2b) (Shoemaker et al., 2010)

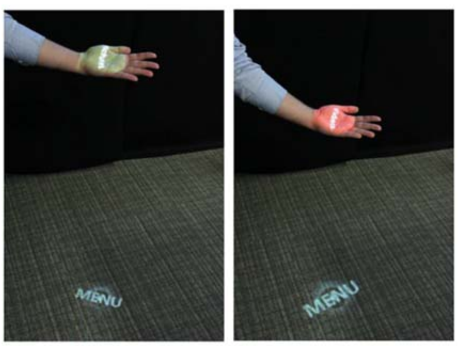
Wilson and Benko's *LightSpace* turned body parts into a mobile display such as menu navigation by lifting/lowering the palm (Figure 3-2c), or using the palm to hold a digital object (Wilson and Benko, 2010).

OmniTouch is a wearable depth-sensing and projection system that enables interactive multi-touch applications on everyday surfaces (Harrison et al., 2011). A person can use her palm as a palette and her finger to pick up different colors and draw on a wall (Figure 3-2d).

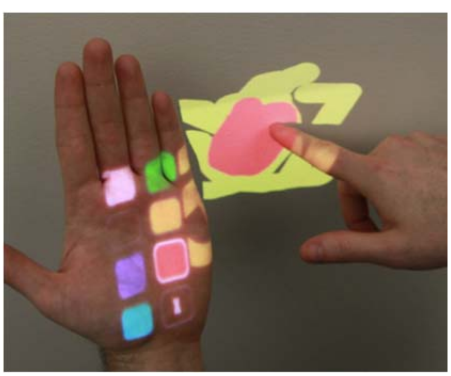
a. Body-based data storage



b. Body-based control surface

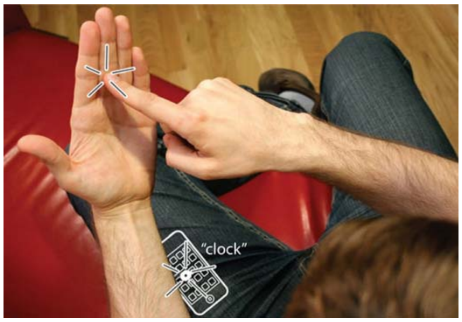


c. LightSpace

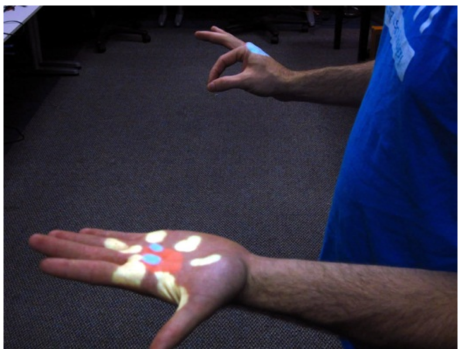


d. OmniTouch

Figure 3-2. On-body interactions directly with the body



a. Imaginary Phone



b. Armura

Figure 3-3. On-body interactions directly with the body

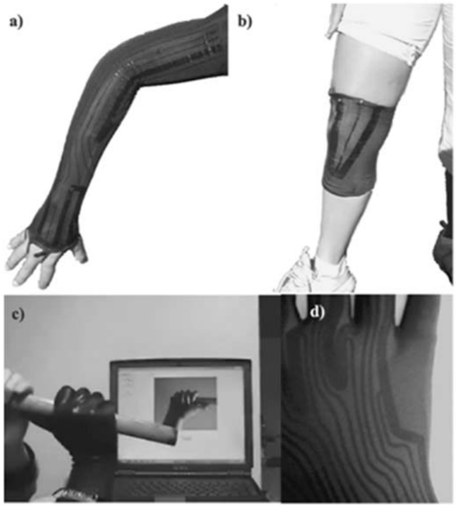
Imaginary Phone appropriated the human palm as a phone interface whereon one can touch and gesture, similar to how a person would use a normal touch screen phone (Gustafson et al., 2011) (Figure 3-3a).

Armura is an interactive on-body system that turns a person's arms as both input and (graphical) output platforms. In particular, a person lays out her arms horizontally as gestural input; the system responds by projecting digital content that spatially matches the locations of the arms (Figure 3-3b).

Despite their difference in implementation technologies, this work as a whole has suggested an important design idea for BCI – we can create GUI-based interactive surface directly on the body. In particular, the input area becomes one's skin or muscle, responsive to both finger touch and hand/arm gestures; meanwhile, the output can be calibrated and projected directly on the body, all together turning the body into an integral input/output modality. Below I discuss a somewhat different approach which considers not the body itself, but what the body wears.

3.1.2 Interactions ‘Worn’ on the Body

Others developed interactions that were not directly based on one’s skin or muscle, but through the use of wearable computational material (clothing or jewelry) or devices.



a. Wearable sensing garments

b. Animated textiles

Figure 3-4. Interactions ‘worn’ on the body: computational clothing.

Computational clothing. The work in wearable computing (Starner et al., 1997), such as Post and Orth’s ‘wearable clothing’, provided examples where conductive textiles, data and power distribution, and sensing circuitry could be incorporated into wash-and-wear clothing, thus making computing power readily available with one’s body (Post and Orth, 1997).

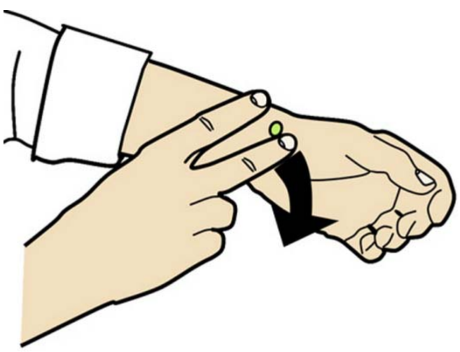
Other examples include Lorussi et al.’s ‘wearable sensing garments’ that record the body’s proprioceptive map (i.e., the spatial relationships between different body parts) (Figure 3-4a) (Lorussi et al., 2004), and the animated textiles developed by Studio subTela at the Hexagram Institute (Figure 3-4b) (Harper, 2008). The former example focuses on collecting input data from the body while the latter aims at enabling artistic expression directly on one’s body (i.e., using the body as output).

Interactive jewelry. Jewelry is closely associated to the space on the body. Hence turning them interactive also allows for interaction with the on-body space. Miner et al. suggested wearable computers can take the forms of jewelry where their placement on the body promotes intuitive interface such as a speaker by the ear in an earring or earpiece, microphone by the mouth in a necklace or pin, display in glasses, watch or bracelet (Miner et al., 2001). *BubbleBadge* is an unusual kind of wearable computer display. Specifically, it is a broach that displays dynamic information, not to the wearer, but to the other people nearby (Falk and Björk, 1999). For example, a Star Trek lover can customize the BubbleBadge to display one-lined quotes from the TV series.

Wearable Devices. Besides clothing and jewelry, others also focused on devices wearable on the body. Mistry and Maes integrated a projector and camera into a pendant cell phone which can be carried by a person, read her gestures and display the results on nearby surfaces (Figure 3-5a) (Mistry and Maes, 2009). Ni and Baudisch's disappearing mobile devices featured an embedded miniaturized device used by swiping one's fingers on the body surface (Figure 3-5b) (Ni and Baudisch, 2009). Tarun et al's *Snaplet* was equipped with bending sensors: when bending it and forming a convex shape (e.g., by wearing it on the forearm), the display becomes a watch and media player (Figure 3-5c) (Tarun et al., 2011).

This work informs BCI that interactions can also be 'worn' on the body without having to directly involve one's skin or muscle. This is achieved by augmenting and mapping clothing to the body locations, by developing interactivity from everyday jewelry, and by designing devices that are wearable and can be anchored to certain body parts.

a. SixthSense



b. Disappearing device

c. Snaplet

Figure 3-5. Interactions 'worn' on the body: computational clothing.

3.1.3 Interactions via a Mobile Device Close to the Body

Perhaps most related to BCI, some research also considered interacting with the body via a mobile device close to it. The device will react to the body parts it is approaching, thus enabling mappings between a person's body locations and the digital contents carried by the device. For the purpose of illustration, I consider three different roles played by the body when interacting with a mobile device close to it: *canvas*, *shortcut*, and *control*:

Designing the body as a canvas. Ängeslevä et al. proposed Body Mnemonics as a *design concept* that '*uses the body space of the user as an interface*' (Ängeslevä, J. et al., 2003). The body acts as a canvas where information can be stored and accessed by moving a device to different locations around one's body (Figure 3-6a). To understand how information can be associated to different body parts, they conducted interviews and studied people's strategies of establishing such connections such as placing MP3 archive to the ear whose function is similar to the music information.

Designing the body as shortcuts. Guerreiro et al. developed a *system* that used a set of mnemonic body shortcuts for mobile phone users to quickly access and retrieve applications by moving the device from their chests to a number of designated body parts (Figure 3-6b) (Guerreiro et al., 2009). In their preliminary user studies, they found a number of common associations between body parts and application, which served as the basis of body shortcuts design.

Designing the body as controls. Strachan et al.'s *BodySpace system* allowed gestural control of a music player by placing and moving the device at different parts of the body (Strachan et al., 2007). For example, moving the device to the ear triggers the playlist shuffling control, then tilting the device forward or backward at the ear switches one sound track forward or backward, respectively (Figure 3-6c).

a. Body Mnemonics

b. Body Shortcuts

c. BodySpace

Figure 3-6. Interactions via a mobile device close to the body

Finally, the above-mentioned *Snaplet* (Figure 3-5c) can also be thought of as a device that reacts to how it is worn on the body (although the way it is implemented – i.e., using bend sensors – does not require doing so).

This work demonstrates an interaction style most similar to BCI. Within the space on the body, the mobile device acts as an interaction entity whose spatial relationship with the body drives the interaction with the mobile digital contents. Chapter 2 has summarized three design themes which tie these point systems together. Using these themes, we see that they are all situated in the *on-body* space (Theme 1). Further, the interactions are primarily driven by the device's *discrete* on-body *positions* (Theme 2) where people's *associative experience* of their body plays an important role in enabling the mapping between pointing to a body part and retrieving a piece of associated digital content (Theme 3).

Further, we can find new design opportunities that could extend these existing systems by considering other possibilities suggested by the design themes. Some of these are explored through Chapter 5 to 7. For example, while most projects considered 'binary' body-device relationships, one can add more expressive actions by considering continuous measurements of *distance* (e.g., how far away is the device from a given body part). *Orientation* was almost always overlooked in previous work but can serve as another input dimension between the device and body parts. In Chapter 7 I will showcase a prototype design where a location on the arm carries an 'armband' of buttons, reachable by rotating the device and the arm relative to each other.

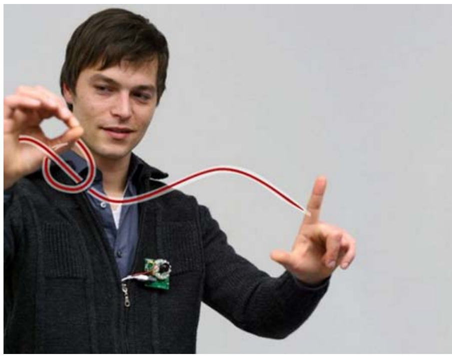
3.2 Off-Body Interactions: Peri- & Extra- personal Spaces

Neuropsychology suggests that the boundaries of the body should be pushed outward from the sheer space occupied by it. Interactions, therefore, can be designed and situated around or even far from the body. In particular, interactions in the peripersonal space (within the arm's reach) fall down into two categories: one that allows people to perform mid-air gesturing, and one that relies on a device as a moving window. However, when it comes to extrapersonal space (outside the arm's reach), most solutions are centered around allowing people to point at and manipulate far-away digital contents.

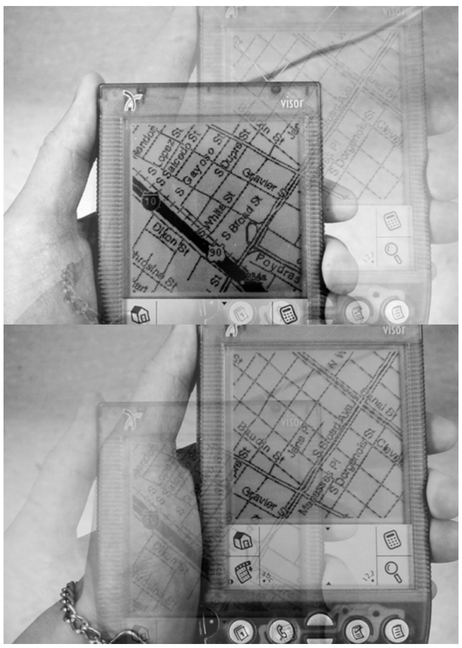
3.2.1 Interactions in Peripersonal Space

Performing mid-air gesturing. The much larger space around the body affords more freedom of making gesture-based input directly by hands. For example, *SixthSense* demonstrated a type of gestural input by positioning and moving hands in front of the body (Figure 3-5a) (Mistry and Maes, 2009). *Imaginary Interface* let people create a virtual interface by using one hand to make a reference frame and the other to point and draw on that interface in mid-air (Figure 3-7a) (Gustafson et al., 2010).

Using the device as a moving window. The other idea of interacting with the around-body space is to hold and place a mobile device within this space where the device serves as a dynamic, moving window. Yee's *Peephole Displays* imagined an invisible information space in front of the user where they used a handheld device to 'peep' into this space (Yee, 2003). For example, one can move the device on a horizontal plane in front of her where the screen consistently reveals parts of a map (Figure 3-7b).



a. Imaginary Interface



b. Peephole Displays

Figure 3-7. Interactions around the body through gestural input or via a mobile device.

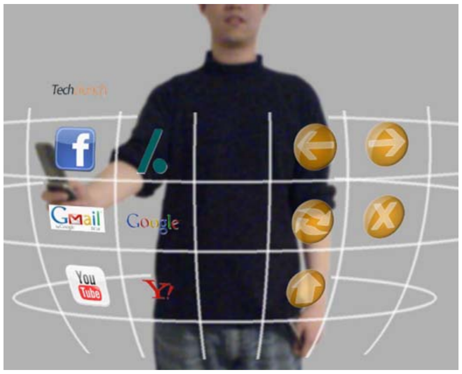
Li et al's *Virtual Shelves* developed a similar idea where they enabled users to trigger programmable shortcuts by spatially orienting their devices within a circular hemisphere in front of them (Figure 3-8a) (Li et al., 2009). The interaction carried the metaphor of a 'shelf' wherein one can organize and retrieve the many mobile apps with reduced visual attention.

3.2.2 Interactions in Extrapersonal Space

Few prior works exist that considered interactions outside the arm's reach (i.e., in the extrapersonal space). Shoemaker proposed a novel solution where they realized peoples' ability to point at and manipulate far-away UI objects using a shadow metaphor (Figure 3-8b) (Shoemaker et al., 2007b). Specifically, a person projects her shadow on a large wall displays and moves her body to control the shadow so that the shadow can point at and manipulate objects that it touches/covers.

3.2.3 Summary and Discussion

Among this related work, the Peephole Displays and the Virtual Shelf share the most in common with the above-mentioned design themes. First, both situated interactions with a mobile device *around* the user's body (Theme 1). *Peephole Displays* tracked the device's *continuous positions* (Theme 2) and mapped it to the movement of a shifting window over the underlying information space. *Virtual Shelves* tracked the device's *orientation* (Theme 2) based on a Spherical coordinate system and mapped it to a number of spatially distributed (*discrete*) shortcuts. Both systems mainly rely on people's associative experience (*how* information is placed around the body) and



a. Virtual Shelf

b. Shadow Reaching

Figure 3-8. Interactions around and afar from the body.

spatial memory (*where* information is placed around the body) to maintain a model of a virtual interaction space in their mind (Theme 3).

By referring to the above-mentioned design themes, we can identify two inter-related approaches in these two projects. First, *discrete orientation* around the body (*Virtual Shelves*) is useful for sorting many digital objects and retrieving them with reduced visual attention. Second, once an object is retrieved, tracking the device's *continuous position* on a virtual canvas (*Peephole Displays*) enables more sophisticated manipulation against that object.

3.3 Summary of Related Work

The two broad categories above – using space on *vs.* around the body, are not mutually exclusive. Neither are the use of both position and orientation for spatial tracking, and the various mapping considerations. Yet each prior work only demonstrates a few 'parameters' of these design themes. By connecting and articulating these parameters, we can now contemplate how interaction design could choose or compare between them to create and experiment different experience of using a mobile application. This will be illustrated in the coming three chapters. In particular, Chapter 4 focuses on the technical aspect – what enabling technologies can be used to realize BCI; Chapter 5 and 6 divide the labor by designing for the two major interaction types on a mobile device – *switching screens of contents* and *manipulating contents on a screen*.

Chapter 4 Enabling Technologies for Prototyping BCI

This chapter introduces two enabling technologies used in prototyping Body-Centric Interaction with a *screen-based handheld device*. These enabling technologies were deliberately chosen to allow for rapid development of design ideas into prototypes that illustrate how BCI can be realized. First, Radio-Frequency Identification (RFID) uses *tags* to augment on-body locations, while the *readers* recognize these locations and map them to specific digital information. Second, Motion Capture Systems (mocap) apply a somewhat similar mechanism but instead use a group of *reflective markers* placed on the body or object to model that person or object. These markers are then tracked in an array of *infrared cameras* and subsequent calculations performed via the Proximity Toolkit (Marquardt et al., 2011) to produce that person or object's 3D spatial information.

These two technologies were heavily used in building my BCI prototypes. In particular, I used them to track the spatial relationships between different interaction entities (the body, the device, the space around the body, etc.), which serve as important input to guide subsequent interactions. Admittedly, these technologies are quite limited, with either limited sensing capability (e.g., RFID) or heavy environmental setup and expense (e.g., mocap). To address these limits, I developed several other technical solutions. In particular, I used computer vision techniques, with images captured via a mounted web cam or a device's built-in front/back cameras, to detect on-body locations and to calculate the spatial relationship between the device and the user. However, it is not this thesis' focus to exhaust such explorations to achieve 'perfect' solutions; they are rather the starting points of future work.

4.1 Radio Frequency Identification

Radio Frequency Identification (RFID) uses radio waves to detect or transfer data strings stored inside electronic *tags* to the *readers* when the two entities are within certain proximity. The detected data strings can be used as identifiers which serve as indices to a set of underlying data entries stored elsewhere. RFID is commonly used in inventory systems, person identifications, access control, etc.

4.1.1 Apparatus

In this thesis, I used PhidgetRFID[3] readers (Figure 4-1b) for building prototypes. This type of readers uses the EM4102 protocol and works only in close proximity (typical read distance ranges from 6 to 11 cm) to the RFID tags. In most of my designed prototypes, a reader was connected and/or attached to an Ultra Mobile Personal Computer (UMPC, Figure 4-1a) via USB cables. While the interface supports multiple programming frameworks, I chose C#/WPF as the programming interface for the hardware.

The RFID tags used are passive sticker tags (Figure 4-2). This allows for attaching these tags to the body (usually to the clothes instead) in a lightweight manner. For example, Figure 4-2 shows a sleeve with RFID tags attached inside, physically

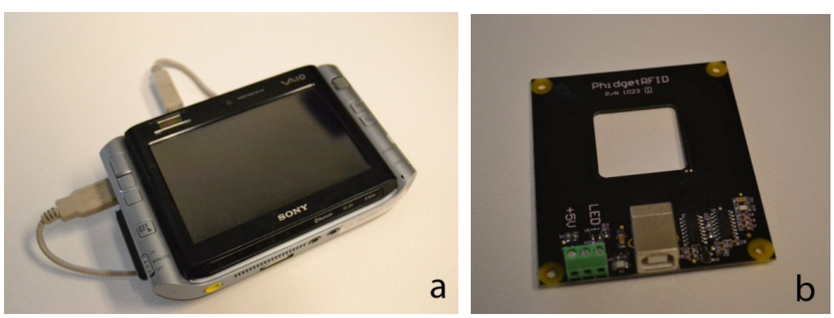


Figure 4-1. RFID sensing setup: (b) the Phidget RFID Reader, and (a) an Ultra Mobile Personal Computer (UMPC) with that PhidgetRFID reader mounted underneath it and connected to it via USB The sensing software is run on the UMPC.

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[3] PhidgetRFID http://www.phidgets.com/products.php?category=14&product_id=1023_1

mapping the tags to one's arm locations.

4.1.2 The BCI Tracking Model

With RFID technology, the tracking model is quite straightforward. Consider tracking body locations on the arms. To start, select a number of tags and align them along the length of the arm as a 1D array. These tags are then configured in an XML file to associate their ID with a name or number that reflects their layout. For example, the tag '**`1000257fc1`**' is named '**`wrist`**' or '**`arm-0`**' to indicate that it marks the wrist location. I use a simple .xml file to associate and store the tags' data strings with these names and numbers. With this setup the reader can 'scan' the arm and infer the discrete change of location simply by matching the tag ID with its name (and possibly with other data associated with it).

The steps above are just a simple example, as the RFID setup can be altered to provide more flexibility. For example, we can have tag arrays on different sides of an arm location (i.e., a 2D array of tags) where one can rotate her arm while holding the reader still. This slightly altered setup can yield interesting interaction design, as shown later in Chapter 7.

4.1.3 Limitations

RFID technology, while sufficient for rapid prototyping, is limited as a sensing system. First, because the readers we use can only read a single tag at a time, the tags must be

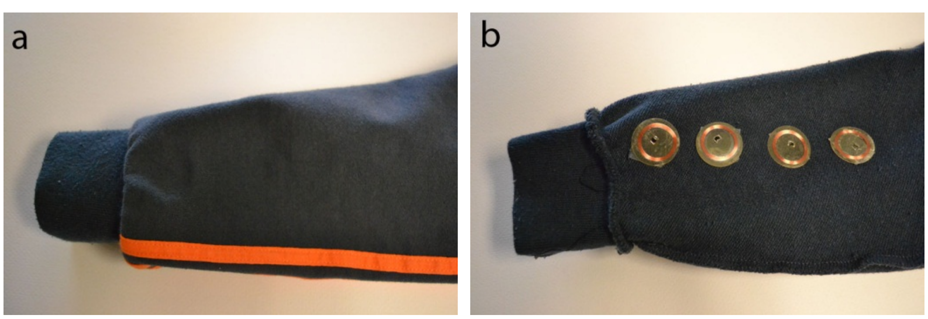


Figure 4-2. RFID tags attached inside the sleeve of a normal jacket.

placed a certain distance apart to avoid interference. This limits the location resolution. Second, tags are attached to the body's surface or clothes, which means that a person can only exploit locations directly on their body (personal space) but not around it (peripersonal space). Third, tags only provide a binary measure – they are either in range and readable, or out of range. No distance measure is provided, nor are there other built-in measures available that may help tune the interaction (e.g., the orientation of device). I will return to these limitations in another enabling technology in the next section.

4.2 Motion Capture Systems

Motion Capture Systems (mocap) use photogrammetic tracking. These systems were originally developed for animation in cinematography. They were used to record and analyze object movements, which can be further translated into digital models. This technology has evolved in its uses, where it has been applied as a biomechanical analysis tool, to athletic training applications, and to a wide adoption in HCI community for designing novel user interfaces.

4.2.1 Apparatus

I used the commercial Vicon Motion Capture System[4], as set up in a room-sized space (Figure 4-3a). A set of passive retro-reflective markers in a particular spatial arrangement are attached to a person's clothing (e.g., the hat worn by a person as illustrated in Figure 4-3c). Similarly, a different set of markers are attached to the handheld device. These markers are illuminated with infrared light generated near the cameras' lens (Figure 4-3b), thus reflecting back the markers' positions in the cameras' field of view. As the cameras capture the markers from different angles, their synthesized image of the markers and their known spatial arrangements can be used to calculate the entity being tracked, and their 3D spatial information such as location, orientation and motion. In this way, the person or the device's spatial information can be derived (though usually with some adjustments, as markers cannot perfectly

[4] http://www.vicon.com/index.html

Figure 4-3. The Vicon Motion Capture System setup: a) the system tracks objects within a room-sized space; b) the infrared cameras targets at that space from different angles; c) reflexive markers are illuminated by the cameras, thus added to objects to represent their geometric structure and track their spatial presence..

represent their geometric structures, e.g., there is always certain offset between the calculated geometric center and the actual one).

4.2.2 The Proximity Toolkit

The Proximity Toolkit (Marquardt et al., 2011) is built atop the Vicon mocap infrastructure. Its purpose is to gather and further process the low-level raw data obtained directly from the Vicon system, where it supplies programmers with high-level fine-grained proxemic information between interaction entities. This toolkit has greatly simplified the building of the BCI tracking model, as introduced below.

4.2.3 The BCI Tracking Model

Following one of the design themes discussed in Chapter 2, I build up two models with mocap to track the spatial relationship between the device and the body: device on the body, and device around the body.

First, mocap can track how the device is spatially associated to particular ***on-body*** locations. To enable this, it requires adding markers to the device and body parts that represent their geometric structures. This can be achieved variously, such as adding a number of markers along one's forearm, or just two or three at the joints (wrist, elbow, etc.). The next step is to adjust the geometric models inferred from the markers, e.g., identifying their geometric centers for tracking the *locations*, adding vectors representing certain pointing *directions*. The resultant tracking mechanism is similar to, but well beyond, the capability of RFID technology. For example, consider the marker-augmented arm and device. We can obtain or calculate the followings (Figure 4-4):

- ***I***dentity of a the arm location;
- ***D****istance* between a device and an arm location;
- ***O****rientation* of a device relative to a given arm location;
- *Motion* of the device relative to an arm location – represented as the device' **V**elocities (which can be also be obtained from the Proximity Toolkit).

Further, mocap can also track how the device is oriented ***around the body*** (as opposed to local body parts), similar to the Virtual Shelves model where the user triggers shortcuts by orienting a spatially-aware mobile device within the circular hemisphere in front of her (Li et al., 2009). To enable this, it only requires adding markers to represent the entire body and the device. There are also various ways to 'mark' the body, such as wearing a marker-augmented cap (Figure 4-3c), or wearing a vest attached with markers, both of which represent a person's entire body in the environment. Then following similar steps, we can calculate the location and direction information of the body and the device, as well as the device's spatial relationship with the body. In other words, we create a body-centric coordinate system whereby we calculate the device's spatial information in this system (Figure 4-5):

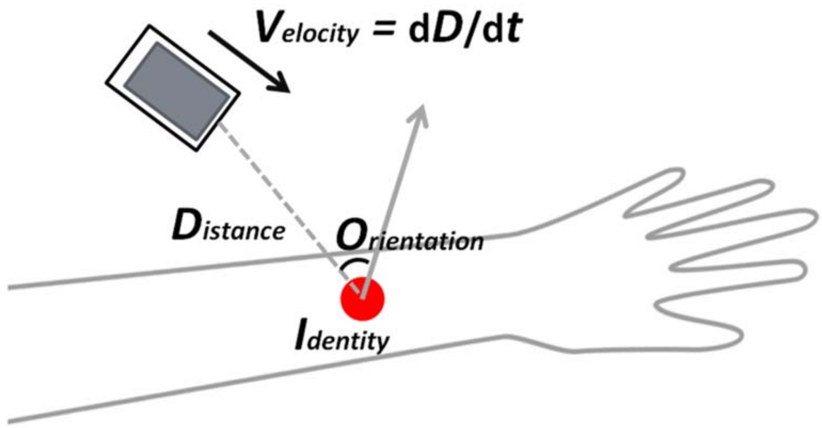


Figure 4-4. Using mocap to track the spatial relationship of the device on the body: the *Identity* of a body location, the *Distance* between the device and that body location, the *Orientation* of the device relative to that body location, and the device's *Velocity*.

- *The body-centric coordinate system* is decided by 1) a *location* representing the entire body in space (e.g., the body's geometric center), and 2) a 'forward' pointing *direction* (i.e., the direction we are facing) telling the front, the back, the left and the right of the person.
- *The device's spatial information*, as discussed earlier in Chapter 2 §2, consists of 1) its *position* P2 (in relations to a person's body P1, Figure 4-5); 2) its *orientation*, calculated from the body-device vector (V = P2 – P1, in relations to the body's 'forward' direction V1, Figure 4-5).

4.2.4 Limitations

While mocap serves as a powerful and efficient tool for rapid prototyping and exploring proofs-of-concept, we should be aware of its limitations when choosing it as an enabling technology. Foremost, the heavy environmental setup and expense prevents it from becoming a real practical solution. Another limitation is the need to coordinate with cameras' line of sight. Since it is possible that the markers are sometimes (partially) occluded by a person's body or the device, the system, at such

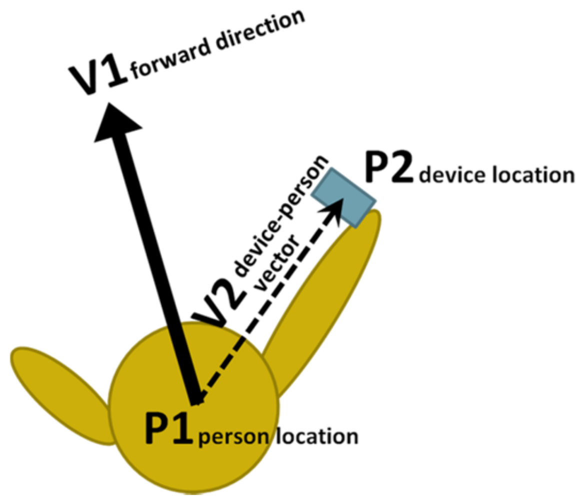


Figure 4-5. Using mocap to track the spatial relationship of the device around the body: the system returns P1 – the person's location, P2 – the device' location, and V1 – the forward direction of the person.

moments, will temporarily lose track of these entities. Further, the use of markers is also limited. For example, in order to identify different entities, any given two sets of markers must be sufficiently different in geometric structure (even though they both represent, say, arms). Finally, entities must maintain certain distance in between to avoid 'merging' their markers and interfering with each other.

4.3 Computer Vision

Computer Vision (CV) is a promising way of sensing and thus of implementing interactions (Freeman et al., 1998). The 'omnipresence' of cameras (e.g., those integrated into smart phones) further makes CV more and more ubiquitously available. We can envision that, as BCI matures, a devices' camera will eventually come into play in routine interactions. Through analyzing camera image sequences, we can perhaps both recognize objects and obtain the spatial relationships between various interaction entities. This would dispense with all the environmental setup in existing prototypes. At the end of this chapter, I briefly present two technical solutions along this direction. While still at a very preliminary stage in this thesis, they are among the most promising future work items.

4.3.1 Augmented Reality Tags

Augmented Reality tags (or ARTags) have been heavily used, as its name tells, in Augmented Reality systems. Here, I appropriate this technology in an unusual way. Specifically, my goal is to track tagged body parts as they appear on the screen, which can be used to approximate the spatial relationships between these parts. The dotted area in Figure 4-6 is trimmed from a screenshot of a program that implements this idea. Three ARTags are captured by the camera (a web cam). The one near the top of the screen represents the upper right arm of the user and the one near the bottom marks the lower end of that arm. The screen locations of these two markers create an arm model in this video frame. Further, the user's left hand is attached with a third marker, all together informing the spatial relationship between the left hand and the right arm. Similarly, though not shown in the figure, a device can also use a marker to identify itself relative to the body parts. The limitation of this method is that the tags must be placed visible to the camera, ideally perpendicularly facing it at a distance. Currently, the device-body spatial relationship is estimated, not accurate, and sometimes erroneous. Also the use context in the above situation is restricted as the camera must be anchored. To address this problem, I explored alternate design of camera-readable tags that are read by a device's built-in camera.

4.3.2 Designing Tags to Continuously Identify the Body

Similar to ARTags, I developed my own vision 'tags' that are easily readable by a camera. As shown in Figure 4-7 Top, when the camera sees a piece of the pattern (in the red frame), it translates the pixels into a numeric value representing the relative location of that area. To use these tags, users can wear them on their body (or clothes) (Figure 4-6 Bottom). Unlike the discrete nature of ARTags, the tag enables fine-grained continuous tracking on the body parts covered by the patterned tag. Other similar but distinct patterns can be used when multiple body parts are involved. This experimentation tries to push the limitations of ARTags – which only provide discrete identifications. However, I did not pursue it further to produce a robust enabling technology, as it is beyond the scope of this thesis.

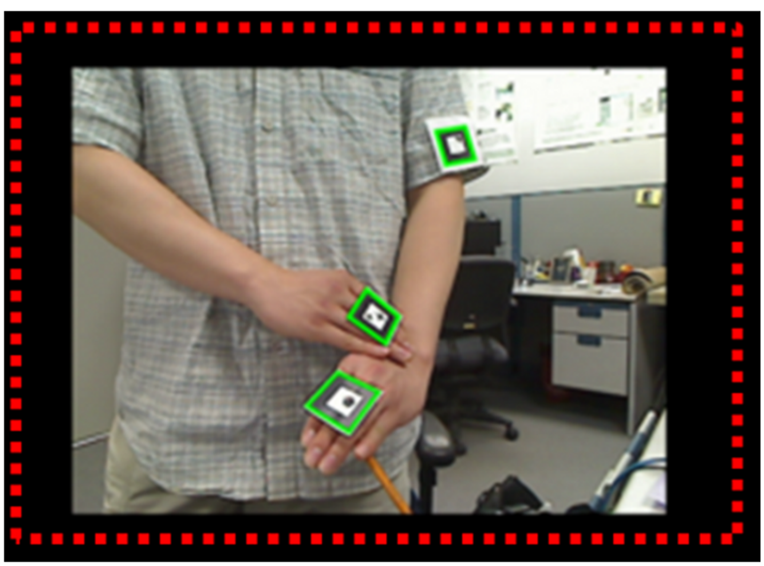


Figure 4-6. Using Augmented Reality tags (ARTags) to approximate the spatial relationship between the user's right arm and his left hand.

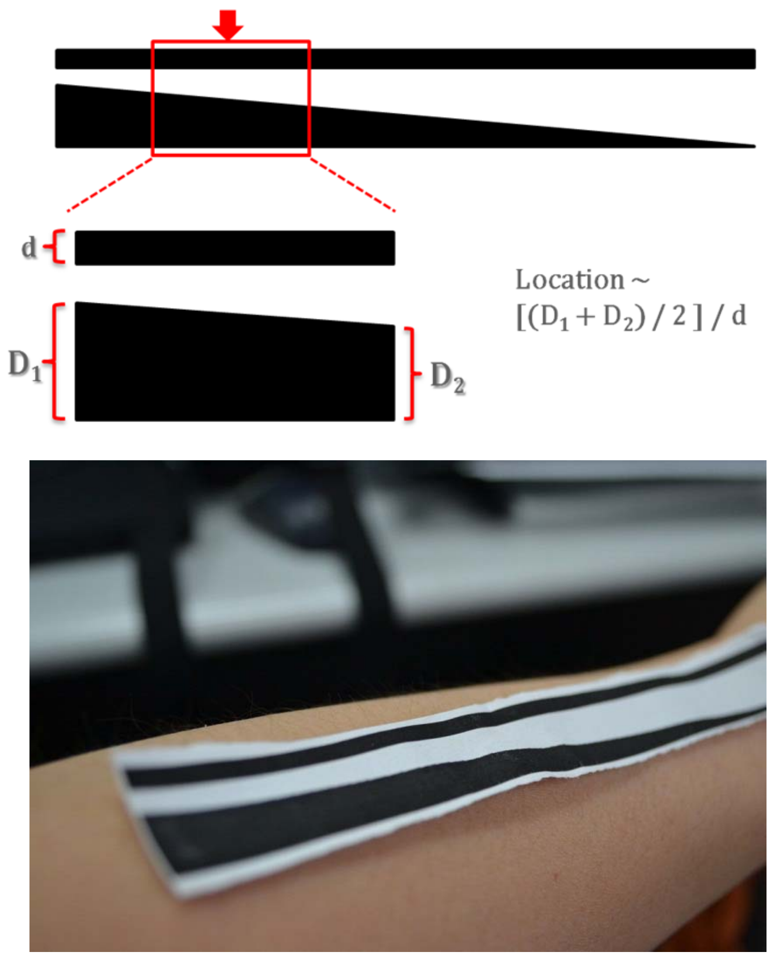


Figure 4-7. An example of the wearable tags that are easily readable by cameras. Top: when the camera sees a piece of the tag, it translates the pixels into a numeric value representing the relative location of that area. Bottom: to use the tags, the user simply wears it on the body (or clothes).

4.4 Summary

Radio Frequency Identification (RFID), motion capture system (mocap), and computer vision (CV) based technologies are used to enable rapid prototyping of BCI. These technologies are not the 'best'; they suffice to implement basic BCI design ideas as proof of concept, i.e., tracking the spatial relationship between the device and the person's body, and further using this as input to drive the interactions. For example, RFID is easy to set up, and provides a quick way to identify the space on the body; yet the information it can offer is limited to discrete locations or identities. Mocap, on the other hand, provides a richer set of spatial information, however, at the cost of heavy setup fixated in the environment. CV-based technologies remain an early exploration in this thesis. Its importance is pointing to future technical development for BCI using the increasingly powerful and ubiquitous cameras. Chapters 5 and 6 will present BCI in a range of prototypes built atop RFID, mocap, and the combination of the two.

Chapter 5 Designing the Body to *Switch* between Screens of Contents

On the train to work, Larry reads a Twitter update on his smart phone about a 7-day all-inclusive budget trip in Thailand. Because he is thinking of travelling to Southeast Asia, Larry decides to archive the link for future reference. He also wants to tell his colleague Sally about this, as she had recently chatted to him about travelling in the holiday season. Larry moves the phone towards his left forearm and, upon reaching a certain proximity to his arm location, its screen shows a canvas on the background – a canvas virtually 'anchored' to that arm location. Larry taps the current tweet, which bookmarks that tweet by stamping a link to it onto the canvas and anchored to the arm. Leaving the left forearm dismisses the canvas and switches back to the Twitter app where Larry can keep browsing his followings' updates.

Later, Larry arrives at work and happens to meet Sally in the elevator. He quickly brings out his phone, moves it to the earlier-visited arm location: the background canvas re-appears and shows the earlier-bookmarked tweet. Larry taps the link and shows Sally that travelling post. Sally reads it, and wants her own copy. She asks Larry for his phone, and she moves it over her pocket. Similar to what Larry did, she taps the tweet to anchor it there. The phone senses her body location, and establishes a connection between Larry's and Sally's 'on-body storage space'. When Larry gets back his phone, it prompts him to confirm sending the link information to Sally. A simple tap by Larry finishes the transfer.

Later that day, when Sally returns home, she simply 'takes out' that information from her pocket by hovering her phone over it, and starts her travel planning.

5.1 Overview of Chapter 5 and 6

Two basic phases occur whenever people use a mobile device: a *switching* phase and an *interacting* phase. In phase 1, a person first *switches* to a particular screen of interest, usually by navigating across a series of screens. In phase 2, the person *interacts* with that screen's contents as they pursue their task. This two-phase paradigm applies both in the large (as in swapping between applications while multi-tasking) and in the small (as in mediating between different parts of a given application, particularly between its controls and menus).

People normally move between these two phases smoothly. Similarly, the systems I developed and describe in the remainder of this thesis work smoothly across these two phases. However, for literary convenience, I divide Chapter 5 and 6 based on this two-phase process.

- Chapter 5 designs for the *switching* phase. It follows a bottom-up path, starting from a fundamental idea of placing and retrieving a digital object to and from a body location. It then extends this initial design approach to handling multiple objects, to considering the space around the body, to developing associative meanings from the body, and to incorporating digital actions into the interaction.
- Chapter 6 designs for the *interacting* phase. In particular, it focuses on two major *interacting* tasks: *direct manipulation* of digital objects, and *mode switching* that frames such manipulation. Two design strategies are employed: *extending the screen's boundaries* to the body, and *appropriating physical actions on/around the body*. These tasks and the strategies explore the richness of the *interacting* phase, yielding a range of interaction possibilities.

These two different design goals drive the underlying exploration of BCI. In particular, while exploring *how* to achieve these two goals, the three design themes gradually emerge. As shown below, not only can they be found commonly across different prototypes, they also in turns affect the results of the prototyping process: one can follow these themes to stimulate a design idea, or branch out from one particular idea to various other alternatives.

5.2 Switching Between Screens of Content

With a mobile device, switching between screens of contents is an essential and frequent task. First, most handhelds do not have multiple windows (which multiplex over space), and instead multiplex over time via switching; Second, digital content is often larger than the single small screen, and thus has to be split across multiple screens; Third, digital content often occupies the entire space, leaving almost no room for other contextual information or for more incidental interactive controls. Consequently, people usually have to navigate between different screens both within and between applications.

As an example, consider the many photos people take using smart phones. The typical method such devices use to organize photos is as either a single collection or as albums; even so, both typically contain many (possibly hundreds) of photos. The devices usually portray these as either a tiled list of thumbnails (e.g., 4×4 per screen) or as a full view (where a single photo is sized to fit the display). In either situation, the person has to 'swipe' through successive screens of images before finding the desired one. Thus to find a particular photo taken (say) last week on a trip, a person would have to sequentially go through a long list of small tiled photos and, if those thumbnails are not detailed enough to find that particular image, switch from the thumbnail to the full view to examine each photo one by one. Either case requires considerable screen-switching.

This extra interaction burden motivated me to develop alternate ways of organizing and navigating the contents of a mobile digital device. As will be seen in the remainder of this chapter, I took a BCI approach where I designed the body as an extended canvas to store and portray contents 'off screen' and to facilitate the process of switching between different screens. As described earlier, BCI primarily consists of positioning and orienting a screen-based handheld device on and around the body (in tandem with simple on-screen interaction, e.g., a simple tap). The design goal here is to enable people to easily associate *screens of contents* to the space on and around their body, and to help them later recall and retrieve them. Further, the design should address associated issues, such as handling the growing number of screens, creating meaningful associations to ease interactions, exploring the variety of digital contents and the interaction with them, and so on.

The remainder of this chapter presents a bottom-up path of prototypes and implementations towards these design goals. The three themes summarized earlier in Chapter 2 arose in part from this process, where they emerged as higher-level ideas while reflecting on this iterative design practice. For a mobile device, most screens of contents involve certain digital objects: a web page, a list of contacts, a screen of image thumbnails, a queue of emails in the inbox, etc. *Switching between screens of contents*, therefore, often means *switching between different digital objects*. This motivated me to start the exploration by asking: can we *design the body so that we can place and retrieve a digital object on it*? A roadmap of this question and its solutions as interaction possibilities are presented in Figure 5-1. In particular, I will provide a series of design solutions in various usage scenarios. For each of them, I will present the underlying concept, the design, its implementation details, and discuss its implications. The evolution follows several directions, as shown below, and illustrated in Figure 5-1:

- *One→Many*: how can we interact with *multiple* objects placed/retrieved to/from the body?
- *On→Around* the Body: how can we extend the space for placing and retrieving digital objects from *on* the body to *around* the body?
- *Body→Wearables*: by relating to our experience of wearing clothing and jewelry, and keeping personal belongings with our body, can we develop associative meanings from these on-body artefacts that map to various digital objects in a mobile device?
- Digital *Objects→Actions*: in addition to placing and retrieving digital objects (nouns), how can we enrich the vocabulary of digital contents by incorporating digital actions (verbs)?

The next section is devoted to the starting design question (i.e., placing/retrieving a digital object on the body). The other sections that follow demonstrate the four extensions above. Taking a BCI approach, an initial design goal has grown into a spectrum of interaction possibilities and thus creating new experiences of using a mobile device can be created. The evolution of this design question reveals several recurring design themes earlier-reported in Chapter 2. These themes are also revisited and reflected on in the presentation of the prototypes below.

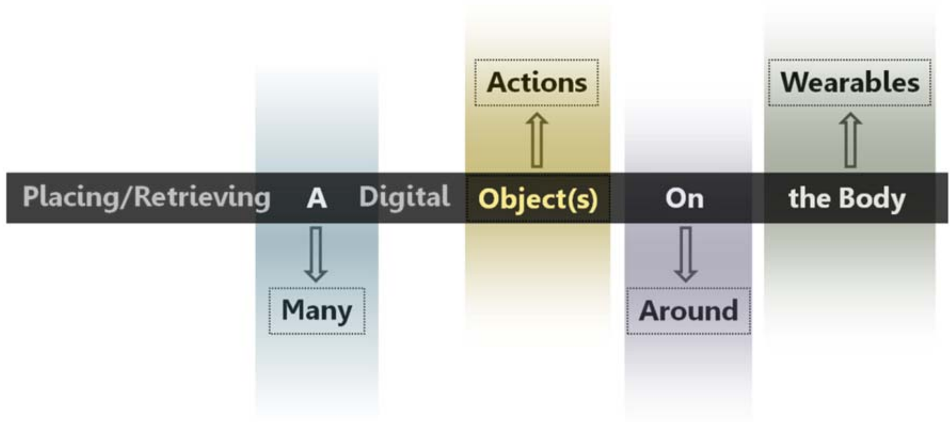


Figure 5-1. Outline of this chapter. Starting with designing for 'placing/retrieving a digital object on the body', I extend the question along various design directions (colored fonts) to consider its alternatives as well as the subsequent design issues.

5.3 Placing/Retrieving a Digital Object on the Body

Recall the scenario at the beginning of this chapter. The digital objects – Twitter feeds – by default are displayed in the timeline of Larry's Twitter app. Larry can archive a tweet in an app-maintained 'favourite' list. However, since he wants to return to that tweet later that day, he wants it to be even more accessible. He chooses to place it on his left forearm, which serves as a storage area that is easily reachable from his device-holding right hand. When meeting Sally in the elevator, he can then rapidly retrieve the stored bookmarked link by a chunk of motion (Buxton, 1986) – moving the device to reach an arm location, followed by a tap on screen to confirm the selection of the retrieved information.

5.3.1 Concept, Prototype and Implementation

The underlying concept is that the body serves as a virtual canvas. People can attach a digital object on the canvas, and retrieve it later by picking it up. In particular, the digital object is virtually 'transferred' from the handheld device to a body location. If a digital object is already placed at a body location, it can be 'transferred' back to the handheld device by performing similar actions.

To illustrate the concept, I built *Body Viewer* – a simple Image Viewer prototype that allows people to 'bookmark' an image (e.g., an image found on Flickr - http://www.flickr.com/) by attaching it onto their body, and retrieving it later from the same body location to show and share with others. Note that this particular implementation, for the sake of simplicity, has narrowed down the idea from a wide range of digital objects to a specific type – digital image. However, the technique could be easily extended to any displayable digital object.

Figure 5-2 illustrates *Body Viewer* as a storyboard. To use *Body Viewer*, a person first uses a handheld screen-based device (in this case, an Ultra Mobile PC) as normal, i.e., to browse images by flipping through screens of them (Figure 5-2a). Upon finding an image he wishes to bookmark, he simply moves the device to a body location, e.g., the other forearm (Figure 5-2b). The sensor-enhanced device 'sees' and recognizes that arm location (e.g., the mid-forearm), and draws a dotted frame around the image indicating that people can 'stamp' that image to that location (Figure 5-2c). Tapping on the image (Figure 5-2d) associates that image to the arm location (by a record kept in the underlying data structure) with feedback provided by enlarging the image to fit the dotted frame. Leaving the arm restores the queue of images the person was browsing. To retrieve the bookmarked image, he repeats the above actions, but in this case he sees the image when it is moved over the forearm, and he taps the image to retrieve it (Figure 5-2e, f, and g).

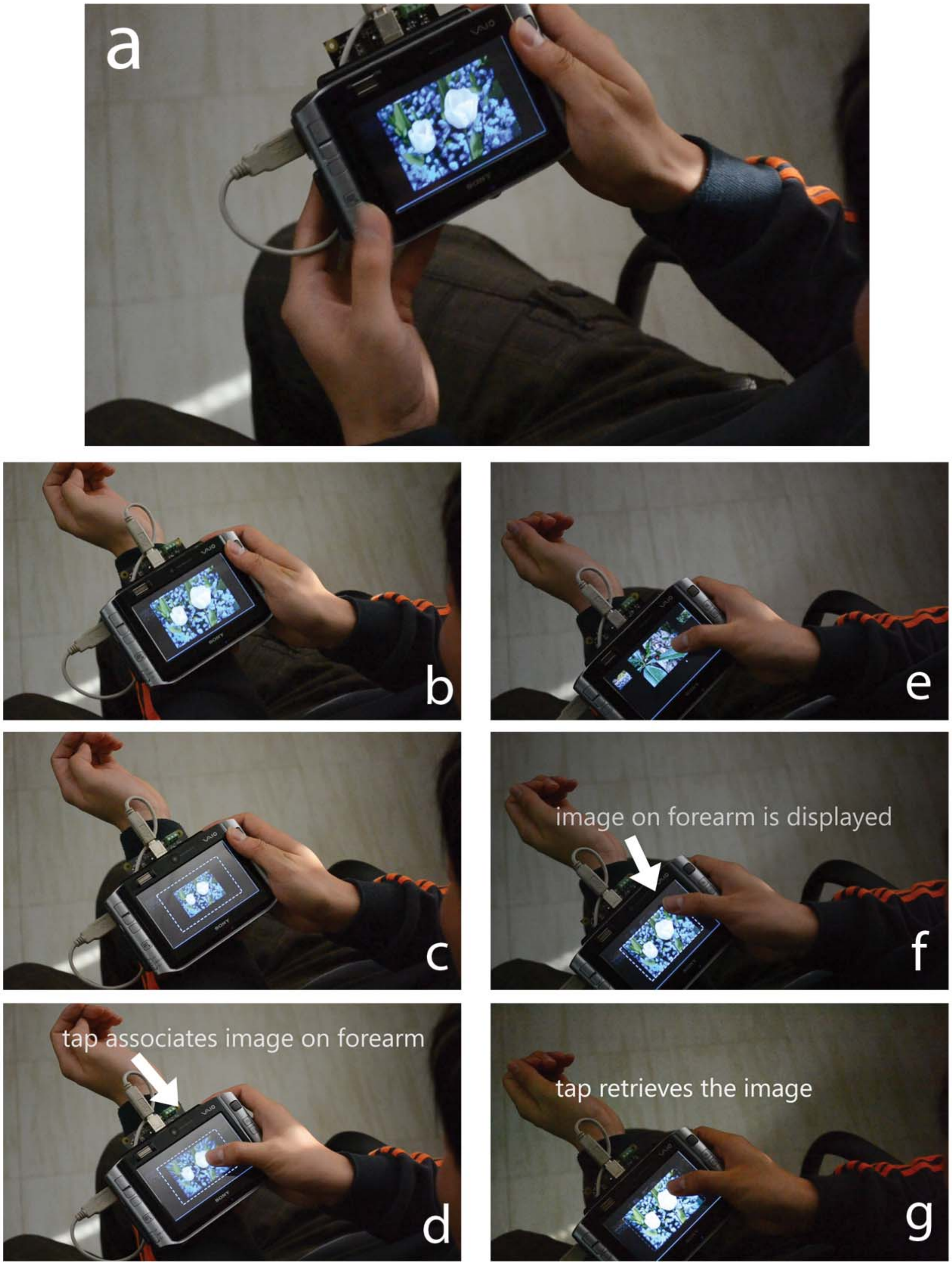


Figure 5-2. *Body Viewer* concentrates the design of 'placing/retrieving digital objects to/from the body' into a image viewing prototype that lets people 'favorite' an image (e.g., those from Flickr - http://www.flickr.com/) by attaching it on their body and later retrieving it from the same body locations. Also see video body-viewer.wmv.

The implementation of *Body Viewer* incorporates two aspects:

At the hardware level, as introduced in Chapter 4, I employed RFID-related technology to enable the sensing and tracking of body locations which are then associated to the images, as detailed below.

At the software level, a hash table maintains a one-to-one relationship between RFIDs and image indices (Figure 5-3). Although it is also possible to have one-to-many/many-to-one/many-to-many mappings, I leave them for later implementations to avoid complicating this very first design. Upon detecting an RFID tag, the software first changes the visual by showing a canvas (the dotted frame shown in Figure 5-2c) as the background. Then the software handles three situations:

- *Placing the current image*. Upon detecting a tap on the image, it writes/updates a hash table entry **`(sensed_ID, image_index)`** (Figure 5-3) and shows the feedback of that image being 'stamped' into the frame (Figure 5-4 top);
- *Retrieving an image*. Tapping the previously stamped image retrieves the

Figure 5-3. Implementing *Body Viewer* in the software level: for example, the left forearm is pre-segmented into several identified regions, each marked with an integer in the software, and then used to index a number of images.

stored hash table entry and opens that image to full view (Figure 5-4 center);

- *A 'hybrid' case.* When an incoming image meets a stamped image (shown as a solid block in Figure 5-4 bottom), one can either replace the previous image with the current one, or leave that image and look for other 'empty spots' on the body. (Future development could, of course, provide more options.)

5.3.2 Discussion

This first design, though deliberately simple, raises a number of issues. As discussed below, some points serve as implications for future development (shown in the remainders of this chapter) while others are noted for future reference.

Spatial memory vs. natural mapping (Theme 3). How can people remember associations such as 'a URL is placed on my left arm'? As there are no obvious cues, people primarily rely on their spatial memory – described in Chapter 2 (Baddeley and Hitch, 1994). Through informal communications, we find most people showed no concern about recalling such associations when introduced to the above interaction scenario. However, one person did ask whether there could be a natural way for people to place digital information on their body. To explore this possibility, I designed and built two prototypes (shown shortly), where I introduce a 'workspace' metaphor to place and retrieve digital objects on the body. In so doing I appropriate people's associative experience of using a real desktop and suggest that in BCI the surface of the body can also be thought of as a mobile 'desktop'.

A growing number of objects pose challenges to interaction design and usability (Theme 2 & 3). One of the main issues with this very first design is scalability. While we can easily envisage *Body Viewer* working for a handful of objects, it clearly won't work well for tens of objects, let alone hundreds of them. How can the body handle this greater number of items? (Another question to ask is: *should* the body be scaled up to meet this number of digital objects?) Current interaction mechanism seems insufficient. People might find it difficult to track these objects and their associated body locations. I respond to these problems in the coming section. In particular, I propose several models for scaling up the current interaction design.

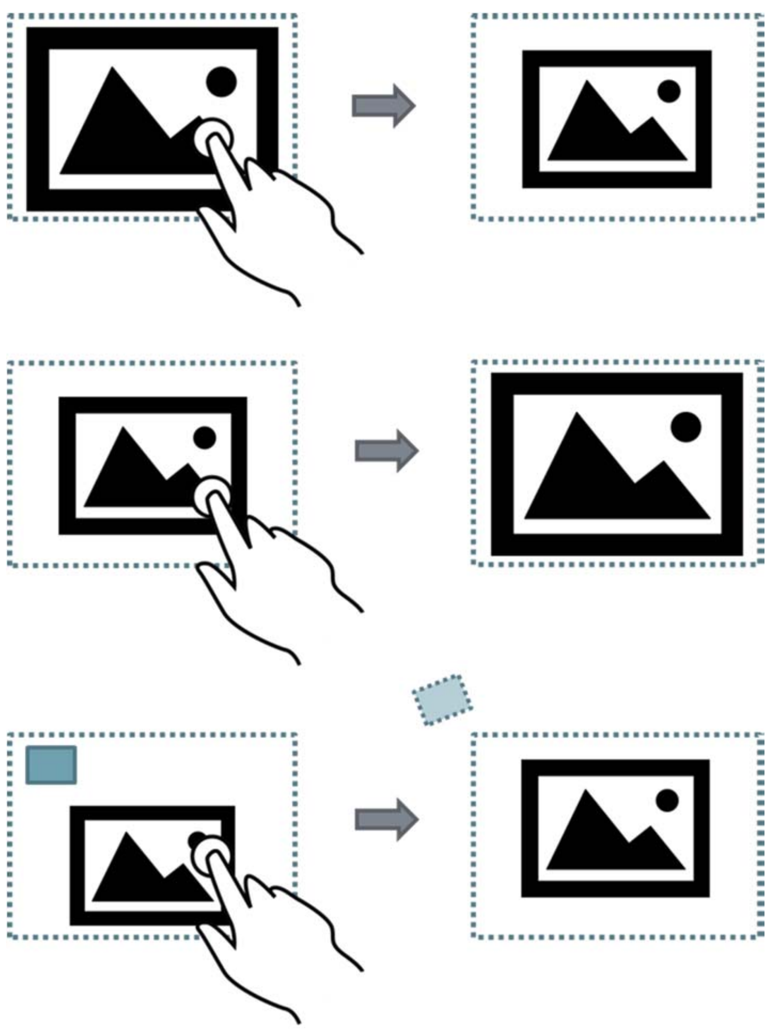


Figure 5-4. Upon sensing certain body locations, tapping finishes the interaction (also see Figure 5-3). Top: tapping at the current image stamps it in that location; Center: when revisiting that location, tapping on a stamped image retrieves it; Bottom: when meeting another stamped image, one can either add the current one (shown in figure) or retrieve the other (not shown but similar to that at the center).

Appropriating the body space should be culturally and socially appropriate. From a cultural and social perspective, body spaces are not equal. While it is fine to orient a device towards the arm, it is probably not when it comes to chest, or forehead, or the back of the body, etc. Some body parts, depending on cultures, could be highly private; some cause unnatural, sometimes socially inappropriate postures when reaching it (e.g., the back of the body). When designing and implementing interactions, one should be aware of these issues; however, it is beyond the scope of this thesis to pursue these issues further.

In summary, this section focuses on a simple design idea that allows a person to place and retrieve a digital object to and from the body. Building upon this idea, the following sections suggest a number of extensions and alternatives, and develop a range of interaction possibilities for switching screens of contents on a mobile device.

5.4 Placing/Retrieving One→Many Digital Objects on the Body

In this section, I extend the starting design question by considering placing and retrieving ***multiple*** digital objects on the body. To address this new issue, I first consider several interaction models, one of which is then illustrated in a prototype system. Finally, I discuss the scalability problem – how many objects can (and should) the body handle in the interactions?

5.4.1 Interaction Models

I propose two basic interaction models to handle multiple digital objects: one-to-one mapping, and one-to-many mapping. Essentially, these two mapping models are two ways of *allocating* on-body space for placing and retrieving digital objects. With a given sensing resolution (e.g. the number of RFID tags (N) added to the body), the two models work as follows:

- **One-to-one (O2O)** allows *one* digital object to be associated to each of these locations. When reaching a body location, an object can be directly placed and retrieved to and from that location;
- **One-to-many (O2M)** allows *multiple* digital objects to be associated to each location. When reaching a body location, these objects are shown upfront where a person will then specify a sub-set of them for further interaction.

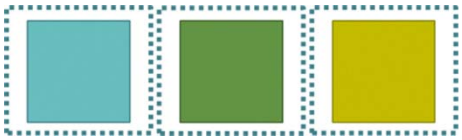
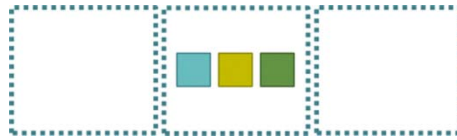
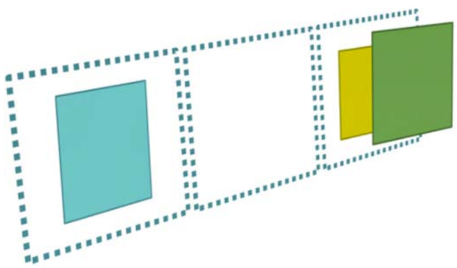
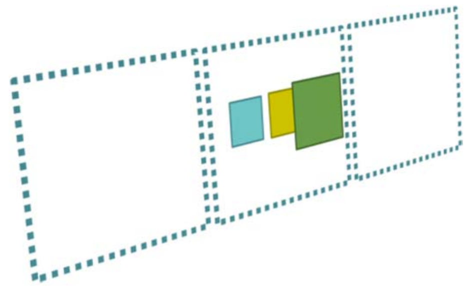
Dimension / Mapping	One-to-one (O2O)	One-to-many (O2M)
2D		
3D		
4D		

Table 5-1. Basic interaction models for handling many digital objects: 1) one sensed body location can be associated to one or many digital objects; 2) the body location can also include the space over it (3D) or present different associated digital objects as a function of time (4D).

Table 5-1 shows the overview of these proposed interaction models. For the purpose of illustration, body locations are simplified as dotted frames and digital objects are represented as different colored blocks. The table also shows how the two models can lead to more design variations when incorporating spatial/temporal dimensions. In particular, when reaching a given body location, the interaction with multiple digital objects varies as the followings (also shown in Table 5-1):

- O2O × 2D. One digital object can be associated to a given location (possibly replacing the existing one if there is any), or the existing digital object will appear and can be retrieved to the screen. (This is what was implemented in the *Body Viewer*).

- O2O × 3D. Building upon the previous case, the interaction can also be extended to the space above a given body location. For instance, one can ‘stack up’ digital objects by hovering the device at different heights.
- O2O × 4D. Further, the interaction can also consider the time variable. For example, as the device approaches, a body location will put on a ‘slideshow’ of digital objects that are previously associated with it. Touching the screen stops the slideshow and the person can ‘insert’ a new object or ‘withdraw’ an existing one.
- O2M × 2D. The user is prompted with tiles of objects among to which she can add a new digital object, or from which she can specify to retrieve a subset of them.
- O2M × 3D. A similar extension (as in the case of O2O) allows for stacking up tiles of digital objects while the device is held at different heights relative to a given body location.
- O2M × 4D. Similarly, Similar to O2O × 4D, the device will slideshow screens of multiple digital objects. Each screen can, for example, represent a time period during which the objects were placed on that body location.

Essentially, the two spatial mappings from the body to multiple digital objects are multiplexed by considering different dimensions. 2D presents a basic approach. 3D is a natural extension from 2D where the boundary of a body part is extended, enabling a continuous mapping between the larger space and the multiple associated digital objects. Incorporating time (4D) introduces new interaction possibilities. The downside is that a person might have to wait for desired slide in the ‘slideshow’ to appear (if not provided with a control option to accelerate it). The generation of these ideas follows a fairly structural way; it remains a question how well they can actually handle multiple digital objects associated to one’s body. To explore this question, I built a prototype to illustrate and explore the O2O × 3D solution.

5.4.2 Example: Body Stack

Interaction Scenario. Recall Larry, a heavy mobile and Twitter user. Every day Larry reads hundreds of tweets in which there are a number of links shared or recommended by his 'Followings'. Larry would like to archive interesting links to read later. He uses *Body Stack* to do this, where he creates a virtual stack of links situated on his forearm. To place a new link in the stack, Larry positions the device at an arm location (Figure 5-5a). Tapping it creates a bookmark placed at the bottom of the stack (meanwhile 'pushing' the other in-stack links one level up). In this way, the links are sorted by time with the earlier ones near the top of the stack and the latest at the bottom. To retrieve them, Larry simply hovers the device up and down over that arm location. The device's relative height to that arm location maps to different 'levels' of the stack (Figure 5-5b).

Implementation. This design idea follows the O2O × 3D model, and is implemented using the Vicon motion capture system and Proximity Toolkit (see Chapter 4). The user's arm is divided into several stacks (Figure 5-6b), each at a different location. In a

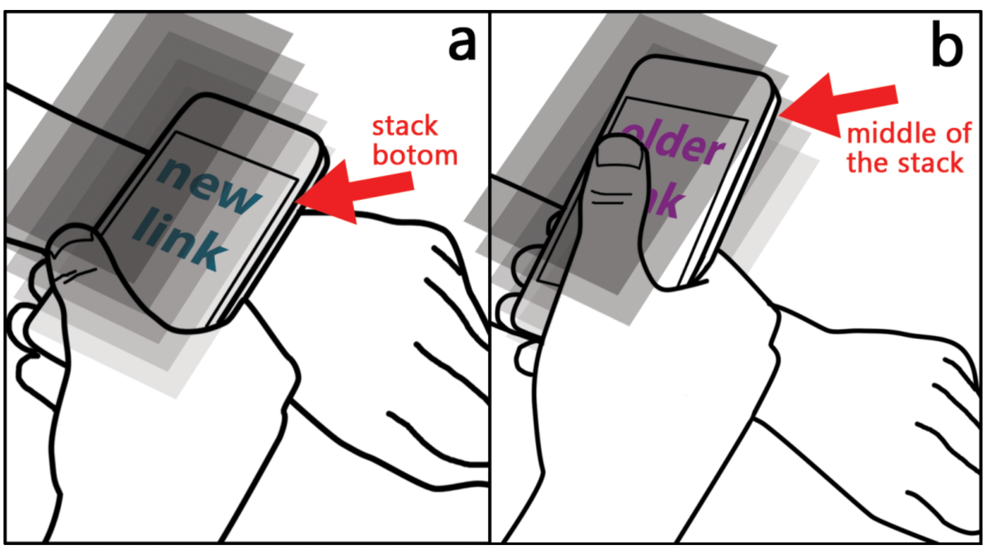


Figure 5-5. *Body Stack* consists of two basic interactions: a) to place a bookmark in the stack, orient the device to approximate the on-body location where the bookmark is automatically pushed to the top of the stack; b) to retrieve a bookmark, hover the device over that location and lift/lower it to go through the stack.

stack, each level maps to one digital object. In the mathematic model, the arm is represented by a vector (v) and the device by a point (p_0) (Figure 5-6). Two variables are calculated: p_0's projection on v (denoted as p_1), and the distance between p_0 and p_1 (denoted as d). The projection p_1 decides which stack to interact with, and the distance d decides the level of that stack. With this implementation, the user hovers the device over her arm, which cast p_1 on v. Moving the device up/down perpendicular to the arm changes d, thus going through different levels of the stack.

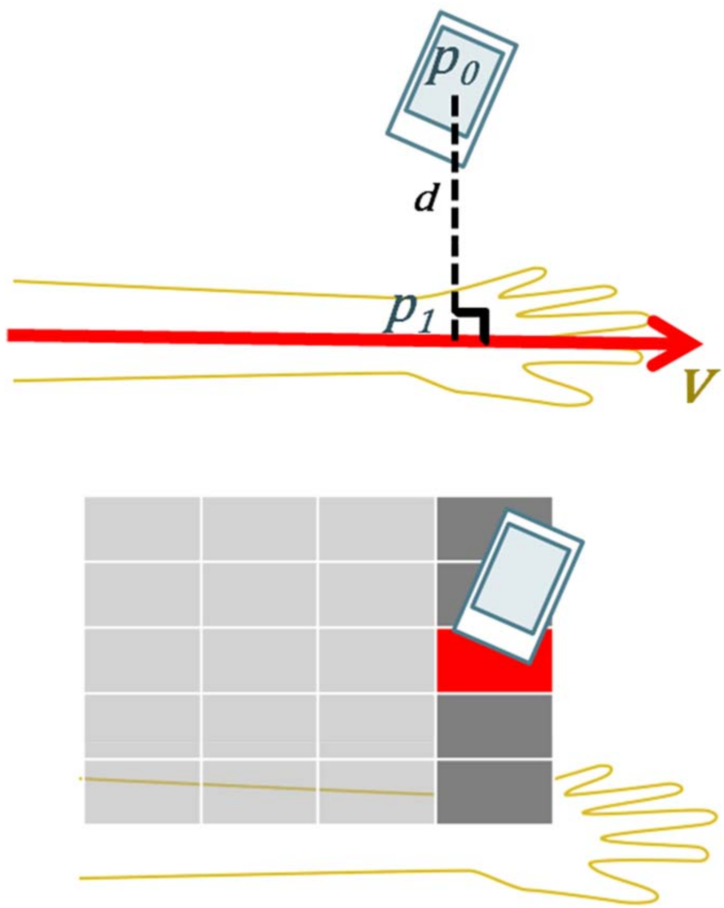


Figure 5-6. *Body Stack* implementation: a) the device's coordinate (p_0) is projected on a vector (v) representing the arm; b) the projection (p_1) and the distance (d) decides which stack and which 'level' the device is referring to.

5.4.3 Discussion: How Many Digital Objects Should We Put on the Body?

Overall, the ‘stack’ metaphor was fully implemented on the arm. This allowed a person to navigate multiple digital objects by lifting/lowering the device hovering the arm, followed by a simple tap to withdraw an object *from* the stack or to insert an object *to* the stack. However, one can feel that the interaction gets increasingly difficult when the number of digital objects in the stack exceeds certain threshold (~10). Foremost, the more objects, the less above-arm space can be assigned and associated to each individual objects. Therefore, it becomes increasingly difficult to hold the device, hovering over the arm and pinpointing a particular ‘stack level’.

The underlying problem is: BCI uses the invariant space on the body to associate a variant number of digital objects in a mobile device. In practice, this means that the number of digital objects that can be placed on the body are not only finite, but modest in number. Therefore, I assert that it is more reasonable to think of the body as a mobile work space that is best used with a modest number of digital objects. *Body Stack* demonstrates one such example, where one can create piles of a small number of items on several arm locations. Of course, the design can be extended to include other body areas. For example, one can turn his lap into a mobile desktop. Once sitting down, a person can pick up work-in-progress documents piled up near (say) the left knee, check the queue of incoming emails on the right knee, or browse a slide show of photos sent by a friend located on the thigh (Figure 5-7). This can create a true ‘laptop’ work space, where the device acts like a spotlight allowing one to navigate through different kinds of multiple digital objects.

5.4.4 Summary

This section explored how we can place and retrieve ***multiple*** digital objects to and from the space on body. This is achieved by considering different spatial mapping (one-to-one and one-to-many) multiplexed by spatial/temporal dimensions (2D, 3D and 4D). The *Body Stack* prototype implements one possible solution. Comparing *Body Viewer* to *Body Stack*, I extended the measurement of device’s on-body *position* from *discrete* to *continuous*, thus enabling a more fine-grained model of interaction. This prototype also raised concerns about practical scalability. BCI is not intended to turn the body into a massive file system. Rather, our body – as seen in the design of

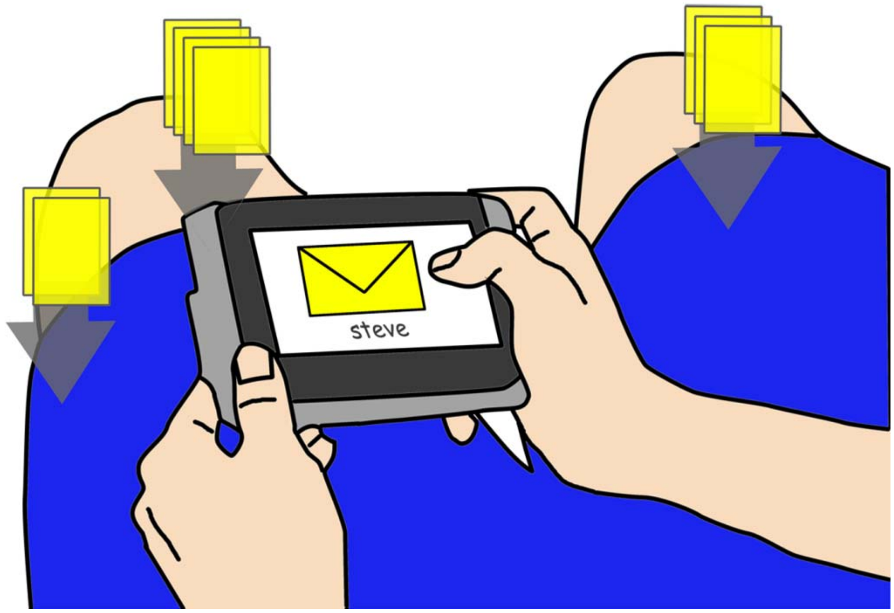


Figure 5-7. BCI is best at use with a moderate number of digital objects where the body acts similarly to a mobile work space, such as a desktop with piles of documents, emails, photos, etc.

BCI – acts more like a mobile work space where it is best at use with a modest number of digital objects.

5.5 Placing/Retrieving Digital Objects on→around the Body

This section turns to another design direction in BCI, where it goes outward from on-the-body to incorporate the space around the body. First, based on different coordinate systems, I discuss various ways of constructing around-body space for interaction. I illustrate this via a concrete implemented prototype, where a person is surrounded and followed by a virtual, interactive ‘cobweb’ on which he can attach and detach web pages as a way to manage bookmarks.

5.5.1 Interaction Models

In on-body space, the interaction always refers to different parts or locations of the actual body surface. Around-body space differs, as it considers the body as a whole. Essentially, the body can be represented as a coordinate system which can in turn situate the device's spatial information as it is positioned or oriented around the body. As briefly mentioned in Chapter 4 §2, by adopting different coordinate systems, we can vary the way we track the body-device relationship. From the interaction's perspective, this suggests various ways of perceiving the space around the body, and how one can place/retrieve digital objects in that space. I discuss three examples below. While it is intuitive to leverage the entire 3D space, the models I propose start from describing a 2D 'slice' around the body where the third dimension can be further added by 'stacking up' these 'slices'.

- **Planar** (based on the Cartesian system). Conceptually, digital objects are located on a vertical/horizontal plane standing/lying in front of the user (Figure 5-8 Left), similar to pasting sticky notes on a whiteboard;
- **Spherical** (based on the Spherical system). Conceptually, digital objects are located on circular hemispheres around the user (Figure 5-8 Middle). An early design example was Virtual Shelves where this hemisphere is mapped to a grid of mobile shortcuts (Li et al., 2009).
- **Cylindrical** (based on the Cylindrical system). Conceptually, digital objects are located on a cylindrical surface (Figure 5-8 Right).

Below I present a prototype that uses the Spherical model to enable interacting with a virtual cobweb anchored to one's body.

5.5.2 Example: Body Cobweb

In our previous prototypes, we discussed how digital objects can be bookmarked on the body. We now reconsider how we can do this by using the space around the body as a way to place and retrieve WWW URLs.

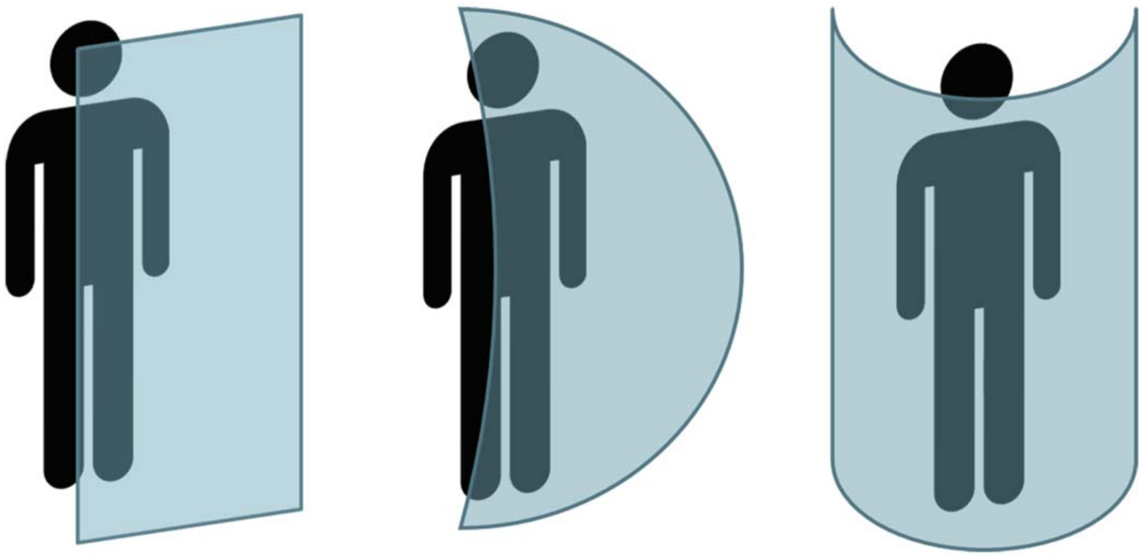


Figure 5-8. Different interaction models for perceiving the space around the body (from left to right: planar, spherical, and cylindrical), and how one can place/retrieve digital objects in that space.

In earlier work, Li et al.'s Virtual Shelves system (Li et al., 2009) realized a virtual circular hemisphere around a user. Within this volume, they implemented a 'shelf' metaphor: each 'cell' on the 'shelf' is programmed to map to different mobile shortcuts. Building upon their solution, I designed *Body Cobweb*, an imaginary cobweb around a person that allows her to 'stick' web pages on it. Essentially, it adopts the Spherical model where each web page is associated to an *orientation* value measured in relation to the entire body (i.e., indicating which direction the device is situated relative to the person's body). An association is created or specified by orienting and holding the device around the body. Along a given orientation, the device's *position* (i.e., its distance to the body) is used to specify different operations with an associated web page. As shown in Figure 5-9 & 5-10, *Body Cobweb* uses two distances to delimit the around-body space, where those distances from two imaginary layers: near and far. The basic interaction of *Body Cobweb* consists of holding the device and moving it to pass through these layers. The system keeps track of the passes and determines the associated operations with a web page, which can be illustrated using a simple flow chart (Figure 5-10):

$\boldsymbol{0}$. A person is holding the device and browsing a web page X.

$\boldsymbol{1}$. A typical interaction starts by point the device outward the body, specifying a body-centric orientation.

$\boldsymbol{2}$. Passing through the near layer displays any existing web page associated to that orientation;

$\boldsymbol{3a}$. Retracting the device and passing through the near layer again (but in the opposite direction) retrieves the displayed web page (which overwrites web page X);

$\boldsymbol{3b}$. Continuing to pass through the far layer update the cobweb by associating the orientation to the web page X (and possibly rewriting existing bookmarked web pages).

Figure 5-11 illustrates a usage scenario. Larry is browsing news on the web (Figure 5-

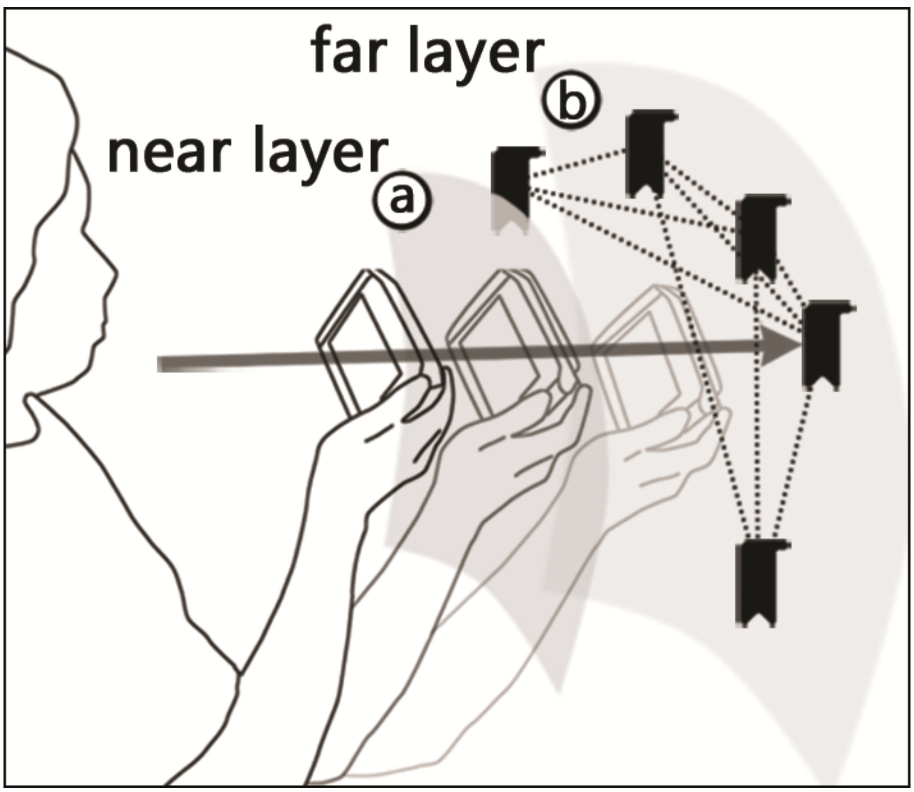


Figure 5-9. *Body Cobweb* lets people bookmark web pages by sticking them to an imaginary cobweb surrounding them. The interaction is based on two virtual layers: touching the ‘near’ layer retrieve a bookmark while reaching to the ‘far’ layer adds a new one. Details of designing such interactions are given in the corresponding sections..

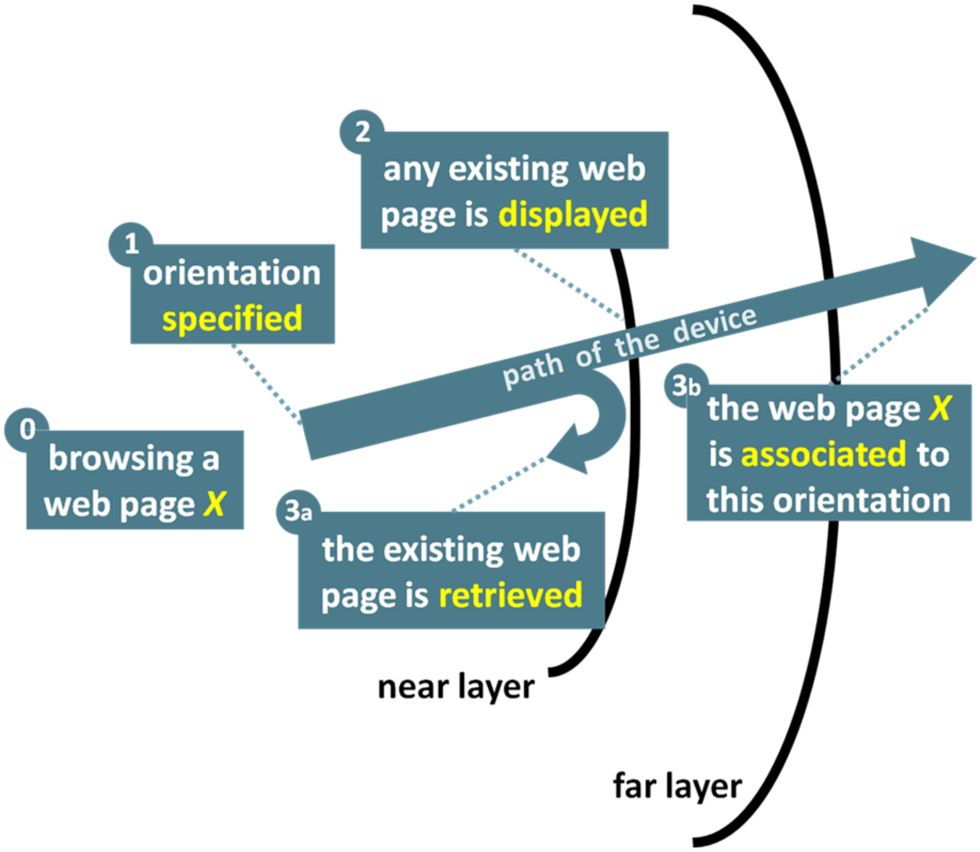


Figure 5-10. A flowchart showing how the two layers (near and far) delimit the around-body space and frames the operations with a web page.

11 1a). To bookmark the current page, he moves the device to his front to touch the far layer (Figure 5-11 2a and 3a). Later, to show this news to his friend, Larry simply revisits the previous location (Figure 5-11 1b and 2b) where the device shows the earlier-bookmarked web page (Figure 5-11 3b).

Body Cobweb was implemented using the Vicon motion capture system (details in Chapter 4). In particular, the cameras track 1) the person's location and forward direction, and 2) the device's location. This information is further used to construct a spherical model based on the person' location, where it indexes bookmarked web pages at particular coordinates, and where it infers the placing/retrieving operations

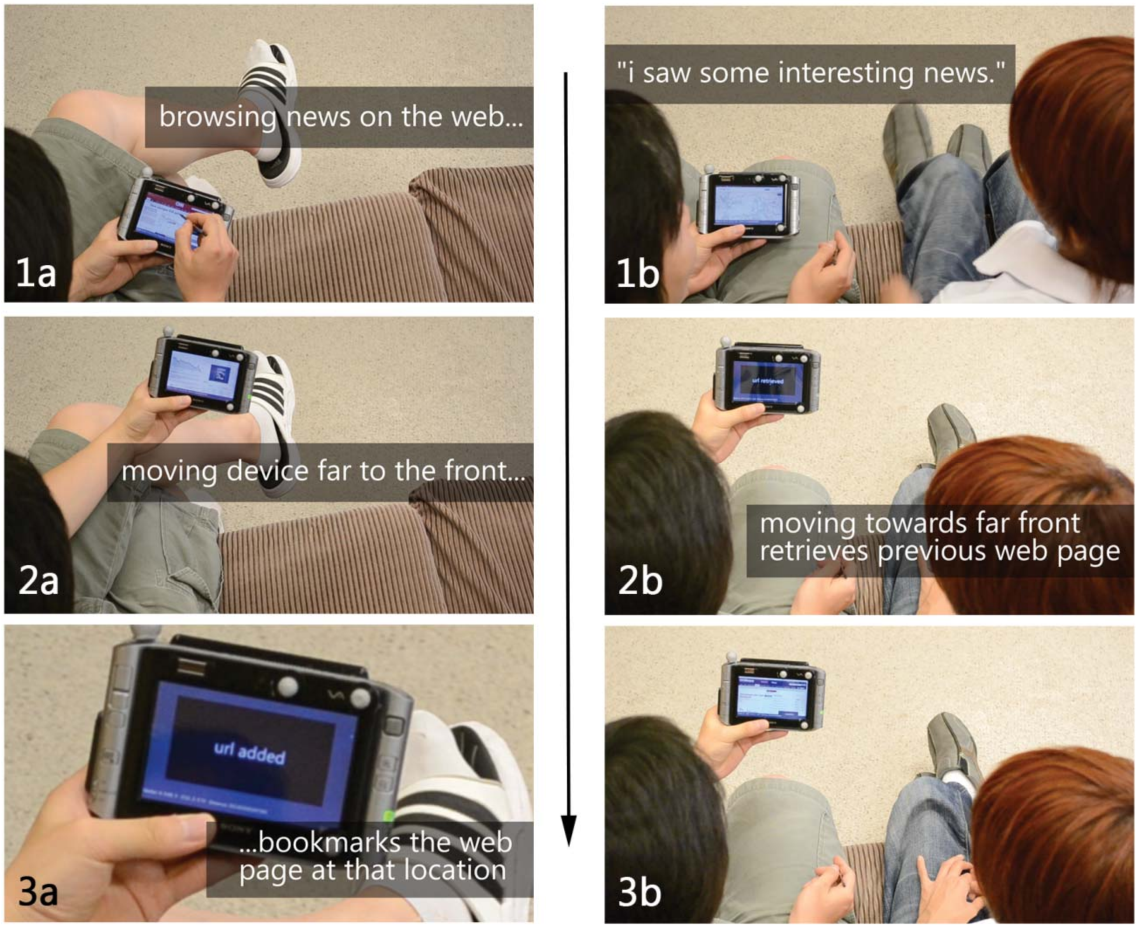


Figure 5-11. *Body Cobweb* is an imaginary cobweb surrounding a person whereon he can attach a web page (1a-3a) and later retrieve it (1b-3b). Also see video body-cobweb.wmv

of those URLs by tracking the device's movements through the layers as defined by those coordinates.

5.5.3 Summary

This section explored how we can place/retrieve digital objects to/from the space ***around*** the body. This is achieved by considering how this around-body space can be perceived (Planar, Spherical, or Cylindrical), and on how digital objects can be associated to that space. The *Body Cobweb* prototype implements the Spherical model – the device's movement around the body's vertical axis specifies *orientation* values that are used to index web pages, while its *position* (hence the distance) relative to the body axis specifies two operations (placing/retrieving) with these web pages. Relating back to the *Body Viewer* design, *Body Cobweb* pushes the boundaries of interactions outward to include the space around the body. This shift of locus also changes how the device-body spatial relationship is tracked. While the device used to be tracked relative to particular body parts, it is now best considered as a point relative to the entire body. The mapping of interactions from the body also changes as a consequence. First, the arm's motor characteristics (*physical constraints*) suggest rotation around the body's vertical axis as a primary action. While *spatial memory* is still important for one to recall and retrieve, say, a web page on the cobweb, various metaphors (shelf (Li et al., 2009), cobweb, etc.) can leverage people's associative experience to help them understand the mapping and the interaction.

5.6 Placing/Retrieving Digital Objects on the Body→Wearables

The related work in Chapter 3 suggests that a *body-centric* approach can also be applied to interactions 'worn' on the body (computational clothing, smart jewelry, wearable devices, etc.). This motivated me to explore alternate ways of interacting with on-body space with a mobile device. Specifically, can the device interact with, not the body per se, but the ***wearables*** attached to body parts? In our everyday life, we routinely interact with wearables, such as pockets, glasses, a wrist watch, a purse, gloves. Some of these can be thought of as 'semi-fixed features' (cf. (Hall, 1982)) of the body. For example, pockets and watches are affixed to certain locations. Others are more 'mobile', such as a purse. Some vary between the two, such as glasses or gloves which are normally worn at a particular location, but are occasionally taken off the body. In terms of BCI, wearables add to the interaction possibilities on the body. In particular, wearables are meaningful spatial and associative landmarks on one's body. A wrist watches connects the concept of time to one's wrists, while the body locations of pant pockets relate to the storage of personal belongings.

The remainder of this section explore a particular type of wearable – clothes pockets. The basic idea is that people can place and retrieve digital objects to and from their clothes pockets, similar to how they deal with their physical belongings. This idea is demonstrated in the *Pockets* prototype where one can retrieve, for instance, an electronic business card by moving the device towards his pocket.

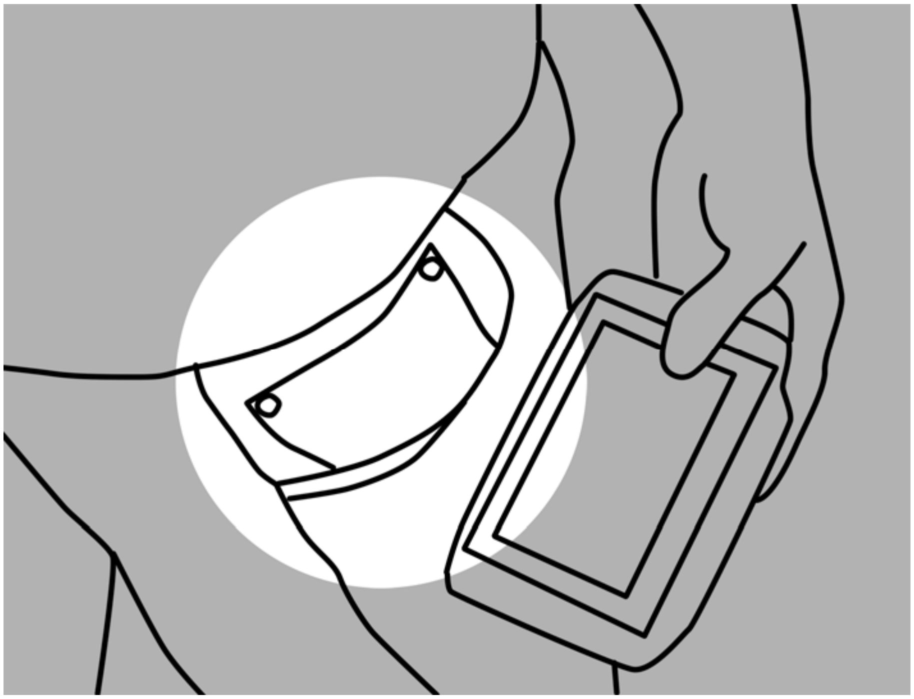


Figure 5-12. *Pockets* prototype allows people to place/retrieve their digital belongings (business card, access card, identification, etc.) ‘in’ their physical pockets. For example, to get one’s digital business card, he orients the device towards the right front pocket (where he previously placed the business card). The device will show all the ‘stored’ digital object where one can see and picks up the business card.

5.6.1 Example: Pockets

Essentially, the *Pockets* prototype creates virtual storage space that is mapped to the physical space of a pocket (Figure 5-12). Consider an interaction scenario where two people meet for the first time (Figure 5-13a). Steve wants to show George his business card. He holds his smart phone over his right pants pocket (Figure 5-13b). The screen reveals part of the storage space corresponding to which part of the pocket the device is positioned at (Figure 5-13c). Steve then moves the device around the pocket to navigate through its virtual space. It is as if the device is a looking glass that reveals what is ‘inside’ the pocket. Steve sees his business card (Figure 5-13d), taps it to anchor it to the display, and shows it to George (Figure 5-13e-f).

To implement *Pockets*, I used several RFID tags to mark the circumference of a pocket (shown in yellow in Figure 5-14 left). The device reads a particular tag, and thus knows which part of the pocket it is located over. The digital space of the pocket is thus partitioned into 'cells', each of which is registered with an RFID tag, where each cell can host a digital object (Figure 5-14 right). Upon detecting an RFID tag, the corresponding cells will show up on the device' screen. For example, when Tag 3 is detected, four 'cells' (shown in red frames in Figure 5-14 right) will appear on the screen where a person can see the digital objects stored in this area of the pocket.

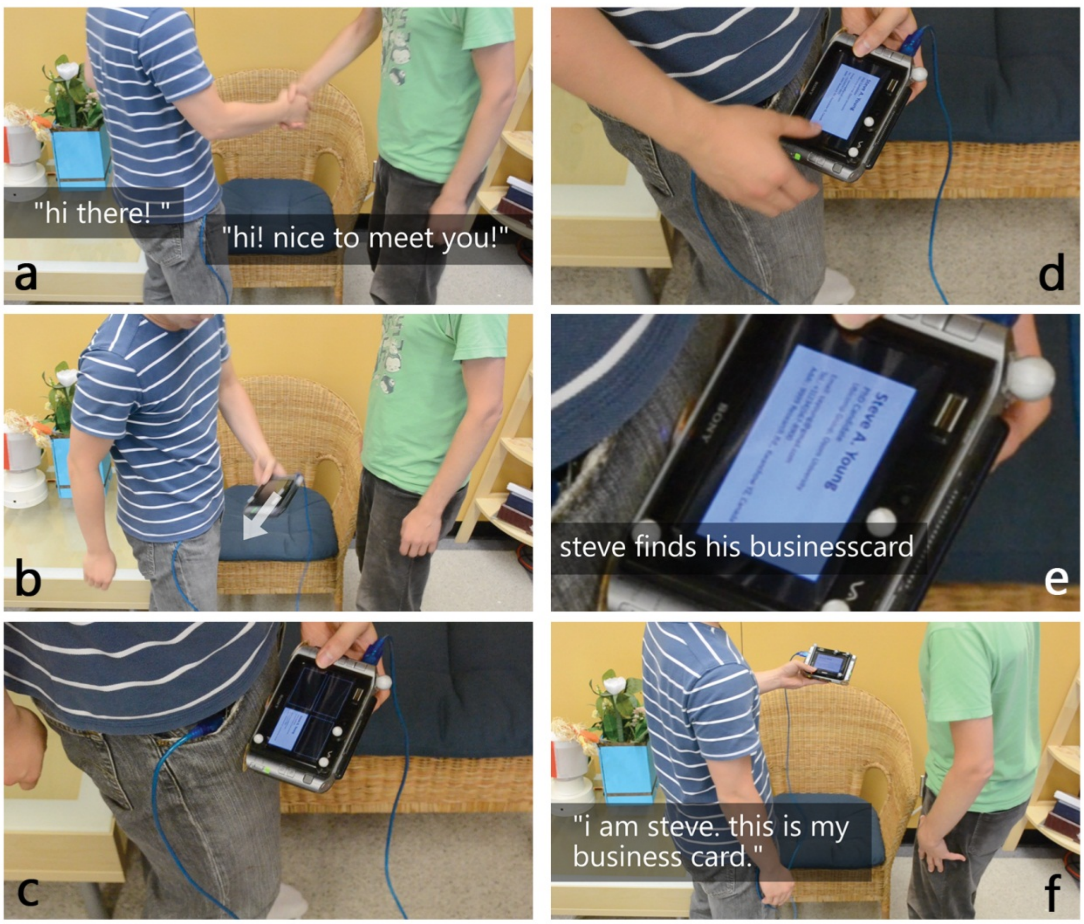


Figure 5-13. The *Pockets* prototype allows Steve to get and show his (electronic) business card by positioning the device at his pockets. Also see video pockets.wmv.

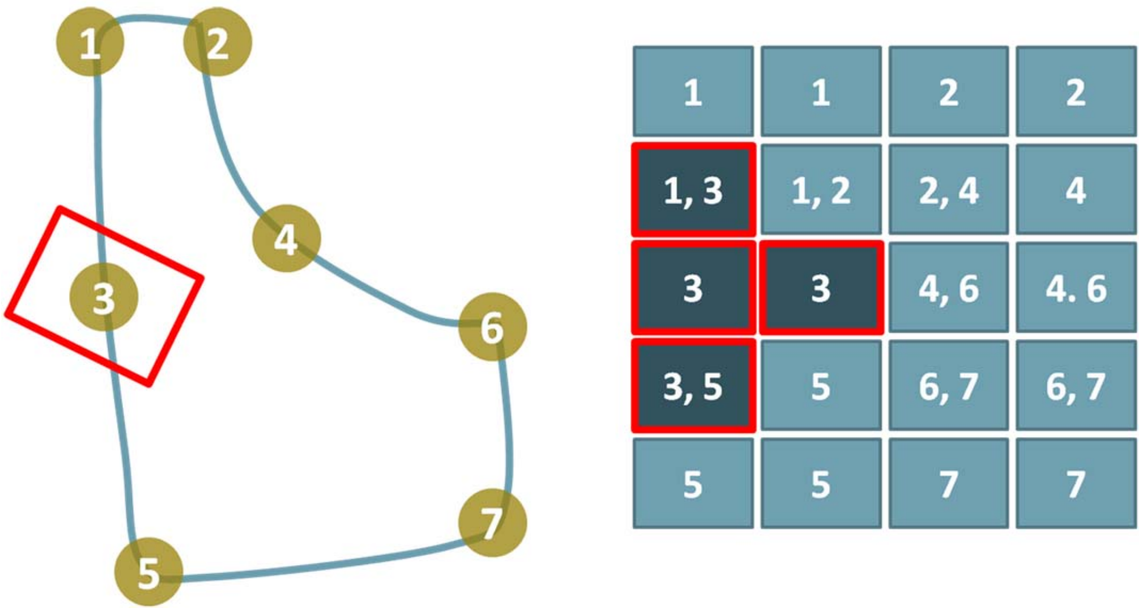


Figure 5-14. RFID tags mark the circumference of a pocket and map to different 'cells' wherein digital objects are stored.

5.6.2 Summary

This section explores how we can place and retrieve digital objects to and from the ***wearables*** (focusing on clothes pockets) on the body. This is achieved by considering people's associative experiences of normally using clothes pockets: what are/can be put in the pockets, how people delegate different pockets to sort their personal belongings, and how pockets' contents change based on occasions, etc. These considerations have turned into three design ideas, one of which is demonstrated in the *Pockets* prototype. Using RFID tags, different parts of the pocket are mapped to different virtual spaces wherein the digital objects are placed and retrieved. Realizing that BCI can also take place via the wearables on the body, we can expand the horizon of mapping interaction from the body by, for example, incorporating the *associative experience* developed from using physical pockets, as well as the *visual cues* they provide.

5.7 Triggering Digital Objects→Actions on/around the Body

The previous examples illustrate using BCI to switch between various digital objects (images, web pages, electronic business cards). However, digital objects might also involve triggering ***actions***, e.g., calling a contact, finding a location on a map, locating a page in an eBook. Some of these actions may require people to explicitly perform them, a topic that will be discussed in the next chapter. Other actions are more routine and can be packaged for quick execution. This section illustrates how body locations can trigger digital actions, as demonstrated in the *Body Shortcut* prototype.

5.7.1 Example: Body Shortcuts

Consider the daily use of a mobile map application, where a person routinely queries it for transit and schedule information between the home and workplace. *Body Shortcuts* is designed for speeding up such routine digital actions. Essentially, it packages operations as a macro, and allows a person to trigger them by positioning the device over different body locations. The design is partially inspired by the work of (Guerreiro et al., 2009); but in this prototype the concept of 'shortcut' is generalized from 'app shortcuts' to any programmable digital actions on the device. Figure 5-15 shows three typical Body Shortcuts, all of which make use of certain associative experience from the user. In Figure 5-16 Left, the wrist wears a watch, hence triggering a calendar. In 5-15 Center, the stomach digests food hence triggers finding nearby restaurants. In 5-15 Right, knees are used for walking and hence search for nearby hikes. With *Body Shortcuts*, daily routine tasks can be triggered by a single movement towards certain body location. Figure 5-16 shows the usage scenario of triggering a calendar application from the wrist (1a and 2a) and a map application from the knee (1b and 2b).

The implementation of these shortcuts is straightforward, similar to that of *Body Viewer*. RFID tags mark different body parts and, upon detection, tell the device to start executing certain programmable digital actions.

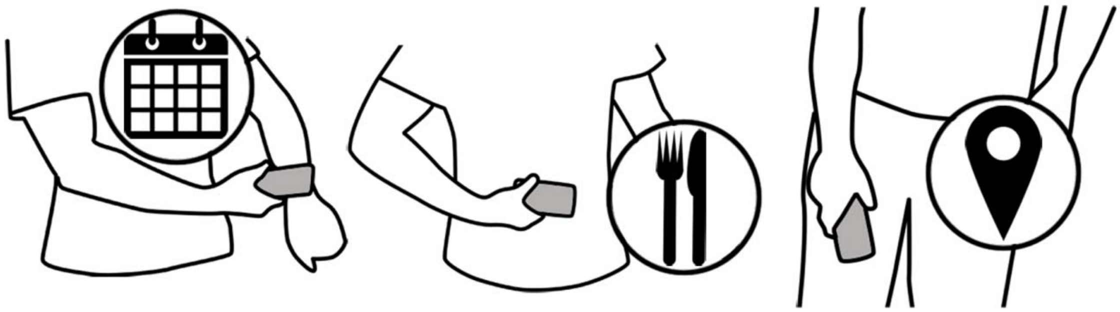


Figure 5-16. *Body Shortcuts* program different body parts to trigger the device to execute certain digital actions. Left: the wrist wears a watch hence triggers a calendar; Center: stomach digests food hence finds restaurant; Right: knees are used when walking hence searches routes, and so on.

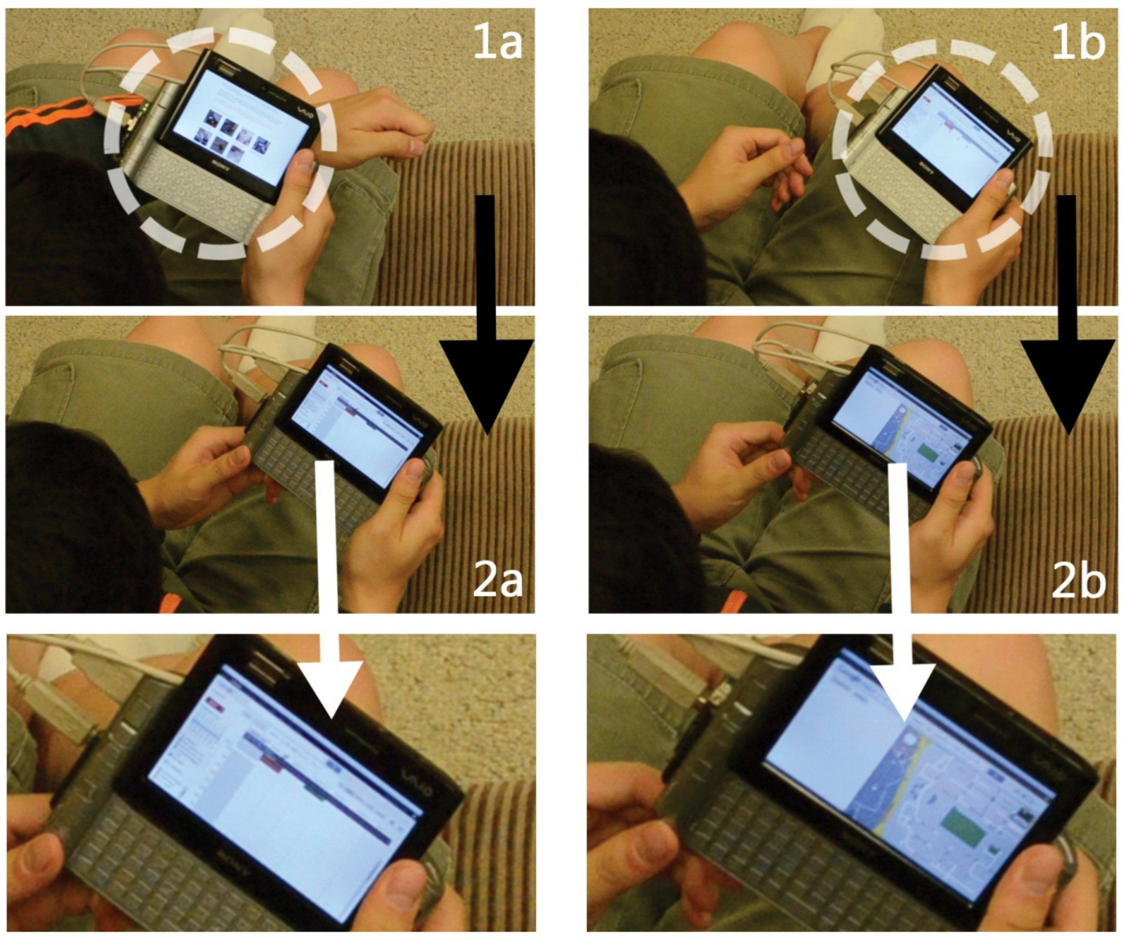


Figure 5-15. Usage scenario of *Body Shortcuts*: triggering a calendar application from the wrist (1a and 2a); starting a map application from the knee (1b and 2b). Also see video body-shortcuts.wmv.

5.7.2 Summary

This section explored how we can trigger digital ***actions*** from the body. This is achieved by considering that: 1) some operations on a mobile device are routine, and therefore better chunked in integral, self-contained units; 2) these units can be meaningfully associated to different body locations from which a person can find and trigger these digital actions via a mobile device. To illustrate these ideas, I built *Body Shortcuts* – a prototype where a person can trigger various digital actions by moving the device towards the corresponding body parts.

5.8 Summary and Discussion

A handheld device has to fully exploit its limited screen space only to display a limited amount of digital contents. *Switching between screens of contents*, therefore, becomes a critical task for handling the information flow in the mobile context. To accomplish this task, this chapter has pursued a BCI approach. In particular, it follows a bottom-up path of prototyping and implementation, from asking a fundamental design question – placing/retrieving digital objects to/from the body – to 'stretching' this question and considering its various extensions. While addressing new questions, the three above-mentioned design themes emerge.

1. Interactions situated *on* the body can be 'pushed' outward to the space *around* the entire body;
2. This switch of locus causes the change of tracking method that calculates the device's *position* and *orientation* relative to the body; further, extending the measurement from *discrete* to *continuous* often yields more interaction possibilities;
3. When finally mapping the body to interactions, we can 1) simply rely on people's *spatial memory* to memorably associate (on-/around- body) space to digital contents, or 2) leveraging their *associative experience* to reinforce any existing association, or 3) sometimes, consider their body's *physical constraints*, the *kinesthetic sense* brought by their actions, and whether *visual cues* are available at the interaction locus.

Figure 5-16 summarizes the formation of these extensions and themes reflected on them: **scalability** (one→multiple objects) is explored through varying the tracking granularity (Theme 2) and considering new ways of mapping interactions (Theme 3); the **boundaries** of the body is extended (on-→around- body) (Theme 1); Pockets (the body →wearbles) also create new ways of mapping interactions by providing visual cues, and by leveraging people's associative experience (Theme 3); to increase the vocabulary of interaction (digital objects→ actions), we can develop meaningful associations between these actions the different body locations (Theme 3).

Design issues also emerge, such as how one can (or should) deal with scalability. How many digital objects can be actually associated with one's body space? How can people recall an increasing number of objects? How can one search and find them? These and other questions will also be revisited and summarized later in Chapter 7.

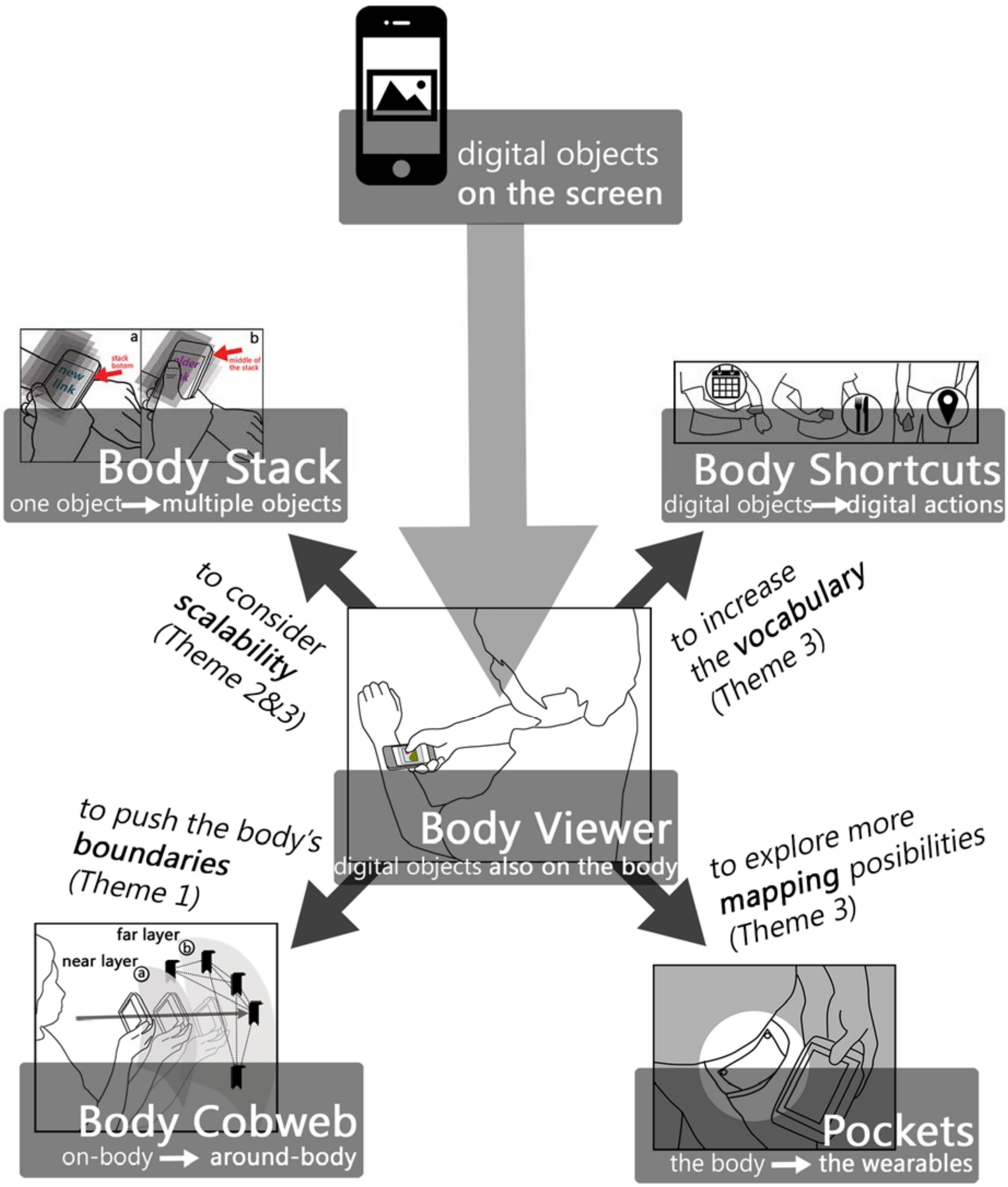


Figure 5-17. An overview of the prototypes presented in this chapter, how they evolve, and how this process echoes the above-mentioned design themes.

Chapter 6 Designing the Body to *Interact* with Contents in the Screen

Larry is showing a prospective grad student how to get to the department's main office. He tries to use a sketch application from his smart phone to draw a simple roadmap. He holds the device with his left hand and uses the right hand to do the drawing. He first draws the hallway that leads to the main office, as well as the relative locations of several buildings on the way. Then he wants to highlight some key locations with more striking color. By default the screen shows no color palette aside. To change to a different color, Larry moves the device up along his right arm. As the device is moving along the arm, a color palette shows up on the screen. Each arm location is mapped to part of the palette which is presented in a fish-eye view consistent with the device's movement. Larry stops at the red color and then moves the device away from the arm. The application remembers the last visited color and updates it to the pen tool. Larry then uses this color to highlight some key locations on his sketched roadmap to help the prospective student find his way to the main office.

6.1 Interacting with Contents on the Screen

At the beginning of Chapter 5 I described two typical phases when using a mobile device: *switching* between screens of contents, and *interacting* with contents in the screen. While chapter 5 focused on the first *switching* phase, this chapter turns to the *interacting* phase. The basic question is: once a person *switches* to the right screen, how can BCI continue to help her interact with the contents on the screen?

Typical on-screen interaction scenarios include various activities: sharing a web page (via social networks), checking one's schedule in a calendar app, sketching and taking notes, controlling a music player, panning and zooming in/out a map, and so on. Accomplishing these tasks on a mobile device can be challenging because the screen limited space for auxiliary controls for performing such operations. While a few may be placed on-screen (e.g., a few buttons on the edges), most require navigating to additional screens or menus. Direct manipulation, while a partial remedy, is typically applicable to only a few interactions (e.g., panning and zooming a map). Thus mobile devices impose an extra interaction burden on the user, as they have to locate, identify and trigger certain control items.

To address this problem, BCI can provide an alternate way to accomplish these tasks without subjecting a user to these micro-scaled on-screen operations. To set the scene, consider how many interaction tasks fall into the following two categories, which suggests that at least two distinctive BCI design solutions are needed.

1. *Object manipulation*, inherited from Shneiderman's Direct Manipulation (Shneiderman, 1983) concept, describes people's actions to manipulate visual objects on their mobile screen, e.g., panning and zooming a mobile map;
2. *Mode switching* can be thought of as the action to *frame* object manipulations, e.g., a calendar app can switch between a few modes (day, week, month, etc.), which defines the granularity of time units a person can manipulate.

While other tasks are possible (e.g., text entry), this chapter focuses on *object manipulation* and *mode switching* as a starting point to introduce BCI into the interaction with on-screen contents. With this focus, we see a person using a mobile device involving sequences of screen switching, mode switching, and object manipulation. For example, consider a person using a mobile device to navigate to a new place. She first locates the map app (screen switching). Then she switches to the search mode and looks for that place on the map (mode switching). As the location is specified, the map switches to direction mode and shows the driving routes. The user then pans and zooms in and out the map to see how she should drive there (object manipulation). Many interactions are involved in this sequence – screen navigations, button clicking, target selection, continuous positioning, etc. The problem is they all take place on a small screen with limited input area, which motivates me to think of an alternate approach where object manipulation and mode switching can be 'unlocked' from the screen. To achieve this goal, I take two design strategies as detailed below.

6.2 Two Design Strategies

In Chapter 5, the basic design strategy is to think of the body and the space around it as a canvas where people can place/retrieve digital objects between the device's screen and that space outside the screen. This strategy can be transferred and adopted to object manipulation and mode switching as well by situating controls and action on the virtual space around the body, as reflected on the two strategies described below.

Extending the screen's boundaries. Here I follow a strategy established in previous chapters, i.e., creating virtual screens on and around the body that extend the physical boundaries of a mobile device. Prior work is somewhat related (Fitzmaurice, 1993; Yee, 2003; Cao and Balakrishnan, 2006) yet their focus of interaction is on seeing the virtual space with the device simply acts as 'peephole' into that space. In my strategy, the focus is still on the device's screen (i.e., interacting with contents of the screen); but this screen is spatially extended to the space on/around the body (e.g., the current screen is the canvas and the 'arm screen' is a color palette). As another example, we can design a larger screen behind the device and by leaning to that space the device switches from the current screen to the virtual one (e.g., the current screen is the editor window and the virtual screen shows recently-opened files). Later I will demonstrate the usefulness of appending these virtual screens to the real one.

Appropriating actions on/around the body differs in that it maps the larger-scaled, coarser-grained actions on/around the body to the otherwise smaller-scaled, finer-grained manipulations on a device' screen. Shoemaker's work has shown two similar examples where he maps a user's scrolling the arm to the scrolling of a slider, and the positioning in their torso to the selection in a 2D color picker (Shoemaker et al., 2010). My strategy develops these two ideas and explores a larger space of associating body-centric actions to digital actions on a UI. For example, holding the device and rotating the arm around the body maps to a continuous quantification (one of the substasks proposed by Foley, 1984), such as specifying a day of the current week in a calendar application.

Consider how these two strategies meet the above-mentioned tasks. Table 6-1 maps out examples of four possible 'combinations' of strategy and task. First, extending screen boundaries has been used in Peephole Displays for object manipulations (Yee, 2003). In the next section I develop the other usage – mode switching. By placing controls/menus in the peripherals (on-body screen) we can enable mode switching in parallel with working on the main screen. The section after next discusses a third 'combination' – how coarse arm rotations can be used to navigate a mobile calendar. Finally, the last 'combination' can be found in the LightSpace project where lifting/lowering the device in front of the body to go through a list of control options (Wilson and Benko, 2010) (Figure 3-2c).

6.3 Extending Screen Boundaries for Mode Switching

People develop natural and habitual postures of holding, viewing and interacting with a handheld device. These patterns of postures spatially correspond to a 'comfort zone' located within the around-body space (typically in front of a person and within eye-reading distance). The basic approach of extending screen boundaries for mode switching is to exploit the space adjacent to this 'comfort zone' (e.g., the space on one's arms that hold the device). In particular, we can place menus and controls in the peripherals and then append them to the left/right/top/bottom/front/back of the device's 'comfort zone'. These design details are presented right afterwards, followed by a proof-of-concept prototype.

General task / Design strategy	**Object manipulation**	**Mode switching**
Extending Screen Boundaries	Increasing the size of a map while using the device as a 'peephole' (Yee 2003) (Figure 3-7b).	Placing controls/menus peripherally off the screen (to the best of my knowledge not found in prior work).
Appropriating actions on/around the body	Navigating a mobile calendar with coarse arm rotation around the body (shown shortly in a prototype).	Lifting/lowering the device in front of the body to go through a list of control options (see LightSpace (Wilson & Benko 2010)).

Table 6-1. Examples of how the two design strategies (Column 1) can be used to design for the two general tasks (row 1).

6.3.1 Exploring Design Possibilities

The development of the prototypes in Chapter 5 has suggested that the three design themes summarized in Chapter 2 can help structure the design ideas of BCI and discover new interaction possibilities. I apply these design themes to explore the richness of extending the device's screen to a person's body.

Body's proximal space suggests two ways of extending screen boundaries. First, the body's surface can extend the device's screen, particularly the space on the arm since this space is usually closest to the device itself (when holding/touching the device). The promises of arm space were also demonstrated in *Skinput* (Harrison et al., 2010) and *PUB – point upon body* (Lin et al., 2011), where both used touch directly on the arm to enable always-available input. Aside from body parts, the space around the body (which also bounds the device) allows for extending the device's screen (assuming it is normally held in the user's field of view) to its left/right/top/bottom/front/back. This, for example, can enable a new way of structuring mobile interface: the toolbars or sidebars are instead placed atop/aside the space that bounds device's normal 'range of motions'. To reach a button, one simple shift the device upwards, or left-/right- wards to unveil the off-screen toolbars/sidebars.

The device-body spatial relationship can be developed to allow for rich interaction with these extended screens. The solution can learn from existing designs in Chapter 5 where the device is *positioned* on this surface and opens a small window into the extended screens, or in addition, hovering the device over body parts can mimic a bird's-eye view where one can have a glance of the extended screens. For the space around the entire body, *orientation* and *position* are used to identify the location on a given extended screens. More nuances can be explored by considering the various models of perceiving the around-body space (these models – Spherical, Planar and Cylindrical – were detailed in Chapter §5.5).

Finally, it is important to keep aware of various ***considerations for mapping the interaction*** from the extended screens. One possible approach mimics GUI conventions for locating controls. For example, because tabs in a web browser are usually located above the web page, such tabs can be placed upwards from the handheld device (i.e., where one moves the device upwards to see those tabs). Likewise, in a drawing application, toolbars/sidebars can be placed on the left or right arms, mimicking the location of palettes in their desktop counterparts. Another approach leverages people's associative experience to inspire new design ideas. For example, 'time' can be thought of as flowing spatially backwards from the present to the past. Thus pushing the device away hosts a flow of screens showing recently-opened files ordered by time. The spatial memory along with their associative experience can help them 'make sense of' the interaction and reinforce the association between their body and the application's interface.

I now present a proof-of-concept prototype that illustrates some of these design possibilities.

6.3.2 Example: Body Toolbar

The full functionality of desktop applications are difficult to transfer to mobile platforms, in part because it is impractical for a small device's interface to host the many menus and controls required to operate them. To partially address this problem, I develop the concept of *Body Toolbar* in a sketching application prototype. The main idea is to preserve the device's screen as the main canvas (Figure 6-1a) for sketching while leaving the other (less important) UI elements (e.g., an icon representing a pen

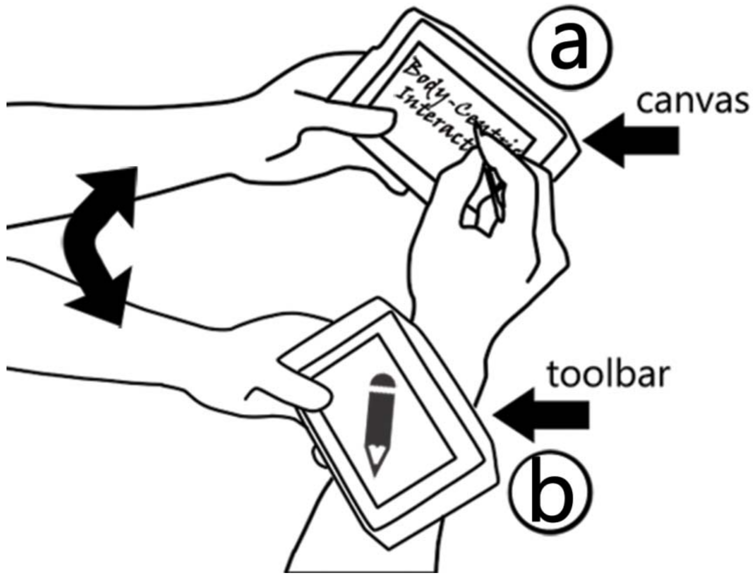


Figure 6-1. The *Body Toolbar* prototype. Top: a sketch of the basic idea – the toolbar is placed on the arm, leaving the main canvas intact. Bottom: a scenario shows how to use such toolbars – orienting the device to the right arm shows a fish-eye view of tools, aligned to the length of the arm.

tool, see Figure 6-1b) on a person's body surface. Specifically, the screen by default contains sketching area only: no menu bar, toolbar, status bar, etc. Conceptually, these control items are instead placed on the user's two arms. To switch to a 'pen tool', for example, one moves the device along the surface of her right arm. While she does so, a toolbar slides out from the right side of the screen, overlaying the main canvas (Figure 6-2a). The tools are presented in a fish-eye view with the focus mapped to device's position on the arm. Scrolling on the arm goes through the list of tools. The focused tool is considered 'semi-selected' and retracting the device from the arm finalizes the selection (with the last focused tool confirmed as selected). Hence to switch to a 'pen tool', one just moves the device to the corresponding position (Figure 6-2a) and then simply retracts the device back to sketching (Figure 6-2c). Similarly, the other arm can be used as a color palette (Figure 6-2b) that enables either discrete color picking or continuous color value quantifying.

This prototype was implemented using RFID technology – each tag marks one of the controls or colors. In essence, *Body Toolbar* embodies a technique that outsources the many menus and controls to the peripherals of the main workspace. When complex applications arrive at mobile platforms, *Body Toolbars* provide for a way to ‘flatter’ an application by tiling its menus and controls aside the main working screen and right on a person’s body surface. Admittedly, it can only affords a selective scale of interface hierarchy; that is, it is better at situating on the body a short list of frequently or recently used tools, than unlimitedly populating all the existing menus and controls onto the limited area on the body.

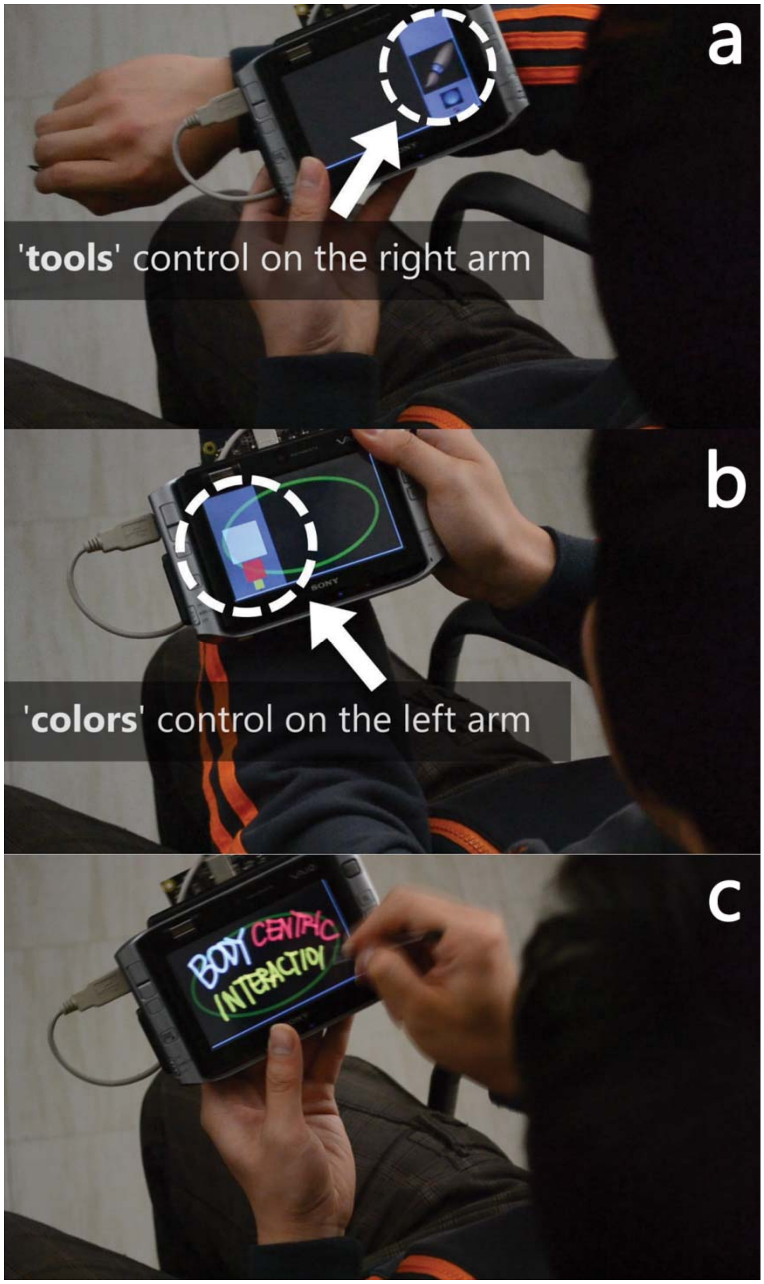


Figure 6-2. Usage scenario of the Body Toolbar: (a) first moving the device to the right arm to elicit a toolbar and select a pen tool; (b) then moving the device to the left arm to select a color; (c) finally going back to sketching on the canvas upon the device leaves the arms. Also see video body-toolbar.wmv.

6.4 Manipulating Objects with on/around Body Actions

The main idea of appropriating actions on and around body for object manipulation is to implement the original small-scaled, fine-grained on-screen actions with large-scaled, coarse-grained on/around body actions. For example, the action of using an on-screen slider to locate a page in an eBook can be replaced by scrolling on one's arm whose locations map to the locations in the eBook. In the previous section, similar on-/around- body actions are mapped to pointing and selection on a virtual extended screen. Here, such actions are instead mapped to the manipulation of digital objects on the current physical screen. The remainders of this section follow two steps: first I explore the design possibilities surrounding this topic; then I embody the idea in a proof-of-concept prototype that uses arm rotation around the body to navigate in a mobile calendar application.

6.4.1 Exploring Design Possibilities

To discover potential design possibilities, I follow the three design themes to elicit different ideas.

Body's proximal space suggests that actions can either follow the surface of the body (e.g., scrolling along the arm) or take place in mid-air around the entire body (e.g., lifting/lowering the device in front of the body).

Accordingly, ***the device-body spatial relationship*** should be measured as the footprint of the device on the body's surface, or its position/orientation relative to the entire body. For example, consider a map application. Positioning the device on the right lap pans the underlying map while scrolling it on the left lap zooms in/out the map. As another example, when viewing a calendar application, reaching out and orienting the device around the body navigates days of the current week.

Finally, ***considering mapping the interactions*** from these actions, natural constraint plays an important role. For example, the shape of the arm naturally suggests scrolling along its length (as opposed to its width) whereas, in the space around the body, arm's motor range naturally suggests orientation (in relationship to the entire body) might be the desired metric. Also, associative experience functions when people can relate the actions to those typically used on a traditional user interface, e.g., rotation around the body mimics actions with a knob, arm scrolling reminds users of slider, and leaning the device away or closer reminds them of zooming -in /-out.

These design possibilities are selectively illustrated in the following prototype.

6.4.2 Example: Rotating Watch

The *Rotating Watch* prototype uses arm rotation around the body to serve as a natural action to view events in one's schedule. The device is a small LCD display simulating a watch-like mobile device. This 'watch' shows the user's calendar when lifted to the reading distance from the eyes (Figure 6-3). Instead of giving the user a default calendar view, the 'watch' jumps to a particular time of the day based on the orientation of the arm in relationship to the main body. Specifically, in front of the torso it shows the closest calendar event (Figure 6-3a); rotating it away clockwise/counter-clockwise shifts to the next/last events (Figure 6-3 b and c). In Figure 6-4, a person lifts the watch in front of his torso (Figure 6-4 a) and is prompted with the closest event (10 – 11am, Ubicomp Class, Figure 6-4 b); then rotating the watch to the right shifts to the next event (2 – 4pm, iLab Meeting, Figure 6-4c).

The prototype was implemented in the Vicon motion capture system with the user and the LCD display as two interaction entities. A computer connected to the LCD display receives positional data and alters the calendar information accordingly. Even though *Rotating Watch* is just a prototype, it envisages the richness of interaction with a spatially aware device, not only in revealing a larger interaction palette (as shown in prior work, e.g., (Yee, 2003)), but specifically in controlling and manipulating its digital contents.

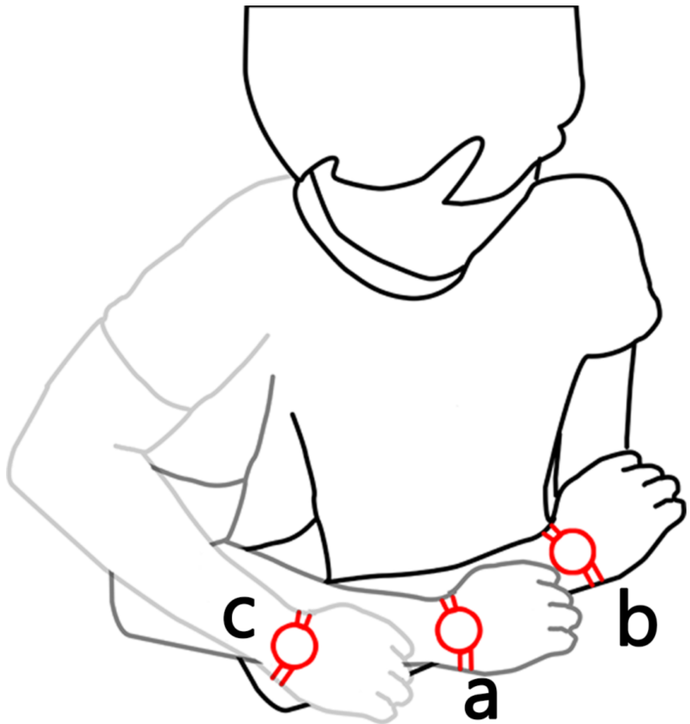


Figure 6-3. The Rotating Watch concept shows how a person rotates the device to shift from one calendar event to another.

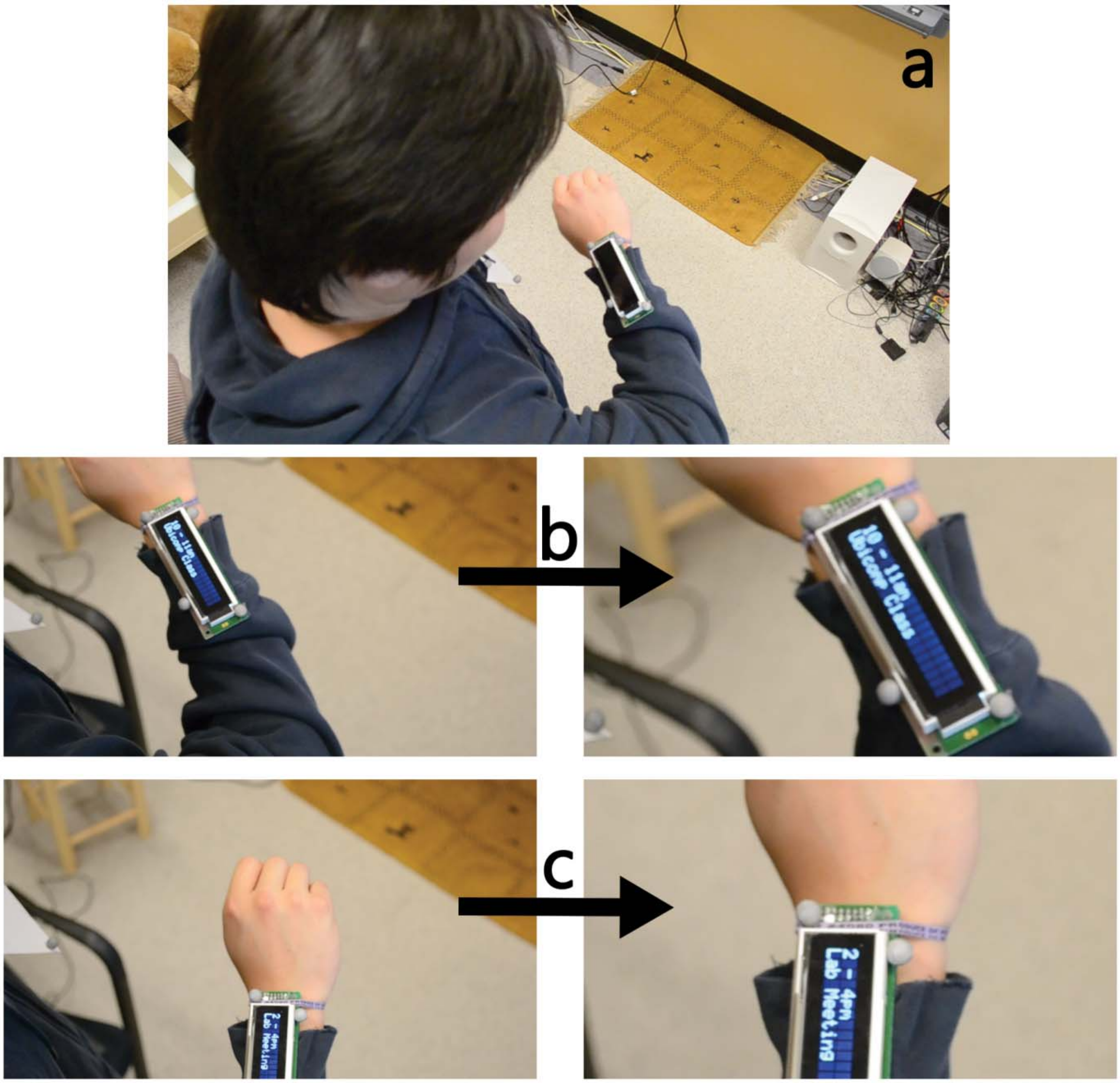


Figure 6-4. Usage scenario of the Rotating Watch: a person lifts the watch in front of his torso (a) and is prompted with the closest event (10 – 11am, Ubicomp Class, b); then rotating the watch to the right shifts to the next event (2 – 4pm, iLab Meeting, c). Also see video rotating-watch.wmv.

6.5 Summary

Following the phase of *switching screens of contents*, this chapter discuss designs for *interacting with contents on a screen* using the space on/around the body as the interaction platform. To explore the spectrum of this interaction phase, I consider two basic tasks: *mode switching* and *object manipulation*. The goal is to enable these two tasks beyond asking the person to perform touch on the small screen (Figure 6-5 Top-middle). To attain this goal, the first design idea is *extending screens' boundaries*, where I imagine the entire space on/around the body can be appropriated as the virtual extension of the physical screen (Figure 6-5 Bottom-left). Second, appropriating actions on/around the body creates a new input vocabulary based on a person's hand/arm movements (while holding the device) relative to her body (Figure 6-5 Bottom-right). The basic idea is to map such movements to the manipulations of on-screen objects. The three design themes are embedded in the formation of these strategies, e.g., borrowing people's associative experience with GUI conventions ((Norman, 1999)) (Theme 3), and measuring their actions as the position and orientation of the device on/around their bodies (Theme 2).

Altogether, Chapter 5 and 6 take a body-centric approach to re-design the way a person uses a mobile device. A person first switches to certain screen of contents which can be placed and retrieved on or immediately around her body. Then, as she uses touch to interact with the contents on the screen, her body extends the screen space where she can pick up a tool or trigger a mode immediately on her body parts. Meanwhile, by moving the device relative to her body, she can manipulate the objects on the screen, such as going through a time line of calendar events. While the primary input techniques (e.g., touch) are preserved in this context, the space on and around the body serves as an alternate channel in which one can communicate with the mobile device by positioning/orienting it in that space.

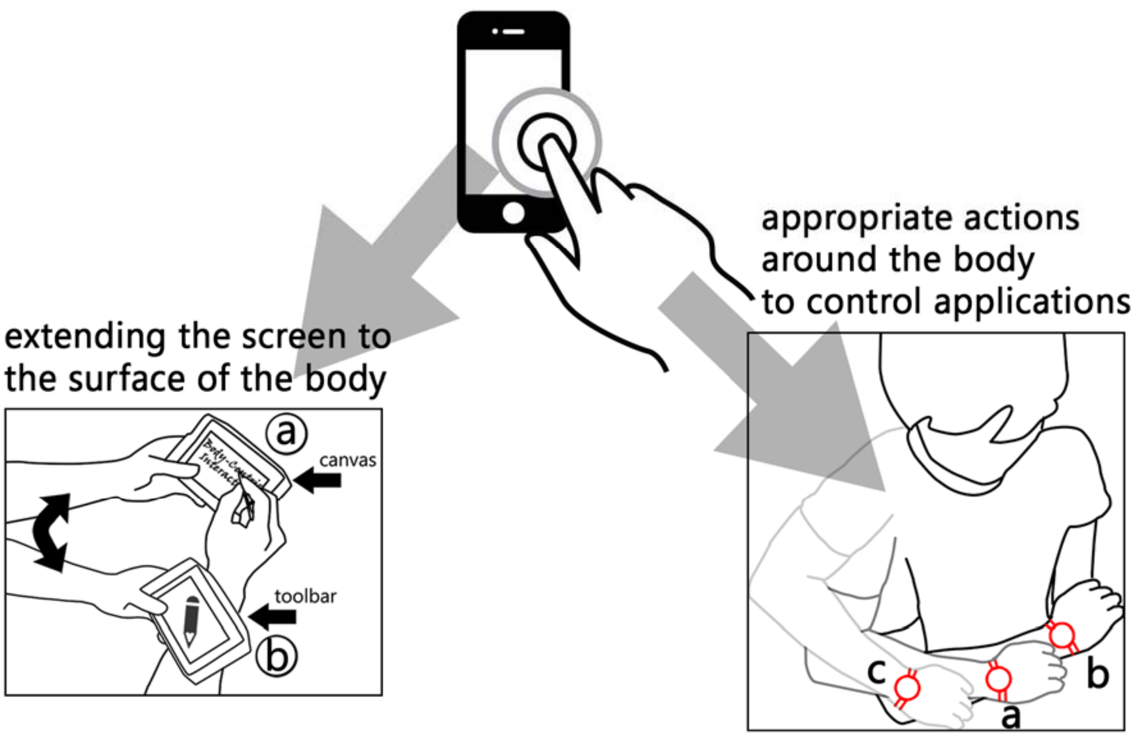


Figure 6-5. Overview of this chapter. To enabling interaction beyond touching the screen, I first extend the screen space to the surface of the body. Further, I also appropriate actions around the body as a way to control applications.

Chapter 7 Discussion, Conclusion and Future Work

The last chapter of this thesis critiques, concludes and considers future work in BCI. First I present a final prototype system that embodies and integrates the essence and ideas of BCI. I then summarize my thesis contribution, and discuss design issues and limitations that arise from the above-mentioned prototyping explorations, and that suggest future work and improvements. Finally I conclude and close this thesis.

Looking chronically, BCI was built from a host of prior work where a *body-centric* approach (see Chapter 1) was applied to a mobile device for interaction. BCI connects and develops this prior work into a class of interaction techniques illustrated by a set of proof-of-concept prototypes and summarized as three recurring and reusable design themes. As BCI grows, design issues emerge, and new research opportunities will be discovered, opening up various spaces for future improvements and explorations.

7.1 BCI Creates New Experience of Using Mobile Applications

Touch has created a new paradigm of how we can ‘engage in a dialogue’ (Card et al., 1990) with a computer, which is proved especially intriguing in the mobile context. But touch can only happen in a limited-sized screen (or in some cases extended to the other surfaces of the device (Baudisch and Chu, 2009)). To further increase the bandwidth (Wigdor, 2011) between the device and the person, this thesis proposes BCI – a new way of composing input to a mobile device. Seeing as a whole, the ideas of BCI can be applied in the design of mobile application that yields new experiences. I demonstrate this in one final prototype – the body-centric browser.

7.1.1 The Body-Centric Browser

Tabbed browsing – a useful feature in most desktop browsers – is more difficult to perform in the mobile setting. For example, the Apple iPhone’s Safari browser (circa 2012) requires users to press a button, which leads them to a queue of thumbnails representing all the open web pages. Then they flip through these pages (thumbnails) until they locate the one in search for. In (re)designing a mobile web browser, we apply our ‘Body-Centric’ approach to enhance the manipulation and navigation of browser tabs in the mobile context. Specifically, our designed body-centric browser is driven by three functional requirements: displaying and managing opened tabs, bookmarking web pages on the tabs, and providing controls to work with these. We now describe how our three design themes helped us apply BCI to implement these functional requirements that yield new experience of using a mobile application.

Displaying and managing opened tabs: the tab navigating zone. To fulfill this requirement, we wanted to keep the browser’s design of tab bar easily seen and retrieved by the user. When thinking of potential design ideas, we found people normally hold and view the device in their field of view (i.e., a ‘viewing zone’ at an eye reading distance in front of their upper body). First, it made sense that our tab navigating zone should be close to this position while not interfering with it. Thus we placed the tabs in front of the user’s waist, which is immediately below this ‘viewing zone’.

Figure 7-1 shows a person lowering the device to reach the tab navigating zone. This layout exploits people's associative experience of the 'tab bar' widget in desktop browsers. Further, it is situated *around* the body, where the semi-circular queue of tabs is shaped to match the motor characteristics of the arm (*physical constraints*). Thus the *orientation* of the device maps to parts of the queue that are then displayed on the screen. This leverages ideas found in *Rotating Watch* (Chapter 6), as the tabs are normally in time-order, and panning around them navigates across time. For example, one would go straight to the left to look for an earlier-opened tab, or to the right to visit a recently-opened tab.

Bookmarking tabbed web pages: the bookmark zone. We needed to allow users to bookmark a tab by 'pinning' it somewhere for future reference. Similar to how we considered tab navigation (and leveraging the *Body Cobweb* design in Chapter 5), we chose the space behind the viewing zone (i.e., further in front of one's upper body), as we wanted people to be able to easily bookmark a page immediately after viewing it, where they could freely pin, move, and unpin a web page anywhere within it. Our space is modeled as a cylindrical canvas, matching a cylindrical coordinate system. We measure the device's *continuous orientation* and height (y-axis *position*) to keep track of its location on the canvas (e.g., somewhat similar to (Li et al., 2009)). Figure 7-2 shows a person holding the device to position at the virtual canvas. Upon 'touching' the web page when in this bookmark zone (i.e., the canvas), the web page displayed in the device can be pinned on it by a single tap. It is then anchored to that location and shown as a web page thumbnail during navigation (Figure 7-2 callout). Tapping an existing bookmark (i.e., a web page thumbnail) selects it, after which one can pin it somewhere else or return to the viewing zone to browse the page. Because these bookmarks stay at the same location, interaction with this bookmark zone exploits users' spatial memory to recall the spatial mapping between the canvas and the bookmarks.

Providing control options with tabs: control zone. Our last requirement is to provide basic control options, such as those that operate on the currently web page (e.g., 'email', 'refresh', etc). These controls are used intermittently, so we decided to place them somewhat off the body's main viewing axis, just as a palette of tools in a GUI are typically at the edges of the window rather than its center. As a result (which also leverages ideas in *Body Toolbar* in Chapter 6), we designed a band of 'control buttons' that is virtually worn on the user's wrist (Figure 7-3). To choose a control, the user *positions* the device on the wrist, and *orients* them relative to each other. The changing orientation leads to different control options seen on the screen. A single tap then selects and executes that option. Figure 7-3 shows a person locating the 'email' (emailing the current page URL) option before he taps the button to confirm the selection.

In summary, the body-centric browser integrates the ideas of BCI in designing new experience of using a mobile application that crosses the boundaries of the screen and that leverages a person's actions of positioning and orienting a device on/around her body.

7.2 Thesis Contributions

This thesis has contributed a class of *Body-Centric Interaction* techniques with *a Screen-based Handheld Device*. In particular, these techniques are delivered as:

- *A set of reusable design examples* – I designed and implemented a set of prototype systems, each of which demonstrates a particular BCI idea and technique. Further, as shown in the evolution of prototypes, these examples can be reused and integrated to compose interactions that yield new experience of using a mobile application.
- *Three generalized design themes* – following the bottom-up path of prototyping, I summarized three higher-level themes from the individual prototype systems. Foremost, these three recurring themes encapsulate the key aspects of designing BCI – identifying the body's proximal spaces, tracking device-body spatial relationship and mapping interactions to the device.

These two deliverables work reciprocally, altogether contributing to a new design direction for interacting with mobile digital contents where the paradigm shifts from the device's screen to the user's body, thus creating more space to situate, compose and perform interaction beyond the limited physical form factor of the device.

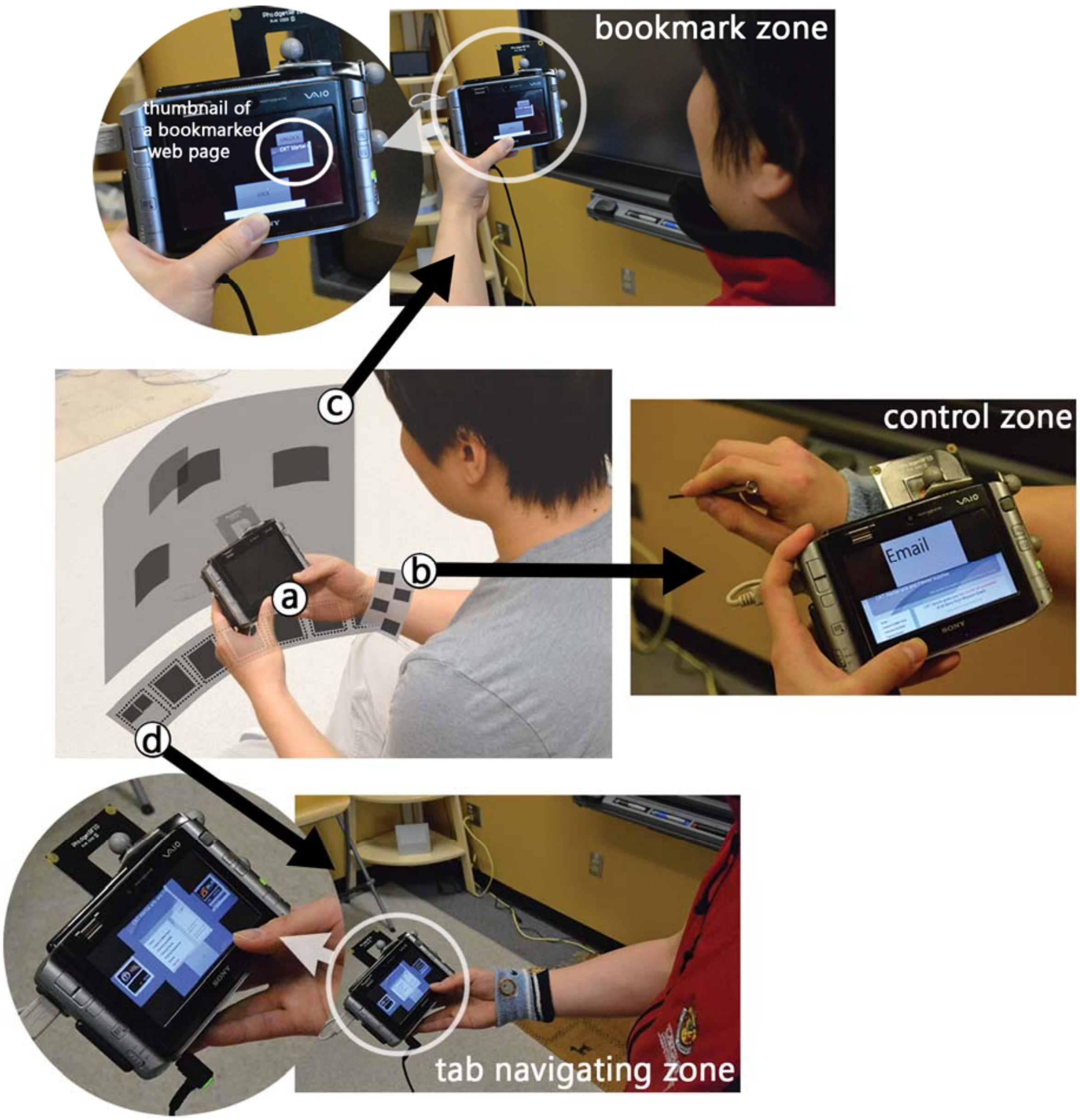


Figure 7-1. Interaction scenarios of body-centric browser: the user positions/orients the device on and around his body to navigate and manipulate browser tabs. Also see video body-centric-browser.mp4.

7.3 Future Work

Now I discuss three design issues that arise from the prototyping process: search and find, scalability, and social/cultural concerns.

7.3.1 Search and Find

In all the BCI prototypes, a challenge occurs when people cannot quite remember where something was placed – how can they search and find digital contents they had previously placed on and around the body? Our current designs require them, for instance, to move the device and to ‘scan’ their bodies in order to locate an item (e.g., a sketching tool located on the right arm). This is, of course, suboptimal as a full search would require scanning a considerable body area. Information visualization approaches suggest various ways of improving upon this. One example is an overview mechanism for the body-centric browser. When moving the device towards (say) a bookmark zone, the screen first shows an overview of the entire canvas, perhaps with items altered to best represent them at their small size (i.e., semantic zoom). As the device gets closer, it gradually zooms in the overview until finally focusing on a particular area. Another approach is to enable ‘coarse’ selection. The idea is that people do not have to perform a one-step recall of the exact on-/around- body locations. Instead, they start with specifying a coarse range on/around their bodies, such as quickly swiping the entire arm to ‘pick up’ to the screen all the digital objects located in that range. Then they search on-screen for the target within this smaller set of digital objects. If there are too many of them to discern between each other, the person can change the range by swiping a narrower regions (e.g., the forearm). In so doing, she picks up half of the arm-associated digital objects at a time and searches for the target among each of them.

Admittedly, the solutions discussed above are not perfect. The problem is that the screen size of a mobile device is only a fraction of the large space on and around the user’s body, making it difficult to perform visual search-and-find with the small display area. As displays become more and more ubiquitous, this problem might eventually be solved, for example, by showing one’s personal digital belongings on large displays situated in the environment – similar to looking at one’s body image in the mirrors.

7.3.2 Scalability

Another challenging issue is scalability – where will BCI break down as the number of digital objects/actions increase? The resolution of BCI will be limited by several factors, such as the resolution of the sensing devices to body location, the number of digital items that need to be found, displayed and accessed, and the ease that a person can hold a device at an exact position. For example, in the *Body Cobweb* prototype, as the number of web pages increases, it will become more and more difficult to identify, locate or retrieve a particular bookmark from the 'cobweb'. Of course, larger zones can fit more items, but the space for these zones is fairly limited (bounded by the arm's reach on/around the body). The scalability issue forces us to limit the scope of BCI: instead of trying to scale it up to meet the level of a file system, we need a more critical view of what BCI can achieve and what it cannot. Essentially, the greatest benefit of BCI comes from reserving the large (albeit with upper limits) on-/around- body space for a modest number of important digital objects and actions. Examples include quickly placing content for later retrieval, accessing frequently done actions, navigating to favored places, repeating recently done actions or viewing recently visited content (i.e. a history list), and a place to customize favored actions as shortcuts.

When scalability issues arise, one possible approach is to provide mechanisms to transition from BCI to the conventional mobile interaction paradigms. Consider again the example of placing digital objects on the forearm. As introduced in Chapter 5, the basic approach is to enable a one-to-one mapping between arm locations and the digital objects. As the number increases and exceeds the resolution of arm locations, one-to-many mapping comes into play, or the extra space above the arm can be appropriated to enable stacking up multiple digital objects. When the number becomes so big that none of these approaches can yield reasonable usability, we would probably start packaging digital objects and create hierarchies. In particular, the person can only view or retrieve a package of digital objects from the arm where she has to open that package on the screen to further manipulate these digital objects. However, the usability of this approach is yet to be determined

In brief, BCI is good for interacting with a modest number of important digital objects and actions. When scalability hinders usability, BCI is no longer an optimal solution;

instead, it should transitions to a more desirable interaction style where the data is indexed and easily retrievable on command.

7.3.3 Social and Cultural Concerns

BCI should also account for social and cultural concerns.

The first social concern is about private and public spaces. Most of the prototypes presented in Chapter 5 and 6 assume the person has ample private space to use without being observed by others (Hall, 1982). But this is not always the case when interacting with a mobile device. Consider a crowded bus, or a restaurant with cramped seats. In such contexts, our body is constrained and thus people are limited in performing required actions. Thus many BCI methods may become difficult or even impossible. A second issue concerns social appropriateness. Even if space is not a problem, people might feel reluctant to perform BCI in public, as some actions might seem odd to the others, e.g., waving the device around one's body (cf. (Rico and Brewster, 2010)). The implication is that the way people perceive the space on/around their bodies is socially biased. On-body space might be 'safer' for interactions – in that it does not invade others' personal spaces, and it can avoid inappropriateness by limiting the interaction to a selective set of body locations (e.g., the two arms). In general, when designing BCIs, one also needs to consider the scenarios in different social settings, and to test whether the actions involved will cause invasion of personal spaces or social inappropriateness.

Cultural concerns present another challenge. As people are asked to reach on and around their bodies (and possibly in public places), their cultural understanding of the body will affect whether they will accept such interaction styles. The exploration of the 'cultural body', however, sits beyond the scope of this thesis and remains as future work.

7.3.4 An Analysis of Input Tasks of BCI

As briefly introduced in Chapter 2 §2, many researchers have performed analysis of input tasks (Foley et al., 1984), input devices (Card et al., 1990; Fitzmaurice et al., 1999), or input techniques (Buxton, 1983, 1986), mostly focusing on a desktop setting.

Ballagas et al. redid such analysis on a mobile device with a premise that it can be used as a ubiquitous input device (Ballagas et al., 2006). All this work shares a common goal of abstracting and parameterizing interactions to advance the understanding of their nature. To achieve a similar goal with BCI, future work should include an analysis of the input tasks performed by BCI. In particular, we need to find out what the various techniques in each prototypes share in common. Is there a set of 'BCI tasks' with which we can expressively compose certain interactions with a mobile device, e.g., *selecting* a digital object, *scrolling* through digital objects, *entering* text? Heading towards such direction would yield a deeper understanding of BCI beyond specific techniques rendered by example prototypes.

7.3.5 Exploring Different Form Factors and Ergonomic Issues

Future work can also experiment with different form factors: tablet, desktop computers, interactive surface and large display (Shoemaker explored BCI with a wall-sized display (Shoemaker, 2010)). It is important to note that the interactions introduced in this thesis cannot simply be 'migrated' to a different sized device. For example, consider Body Toolbar, it becomes somewhat cumbersome to hold a tablet and scroll it along one's arm. And how about interacting with an interactive surface (a demonstrative example is presented in Appendix C)? What accompany these form factors related problems are the ergonomic issues. It would be interesting to look at these form factors side by side under a framework of ergonomics. Each kind of device is likely to have a 'comfort zone' on/around one's body, and a set of ergonomically feasible ways to interact with these areas. Knowing these differences can help us make a better design decision where the interaction is physically comfortable.

7.3.6 Identifying Application Niches

In their book Brave NUI World, Wigdor and Dixon point out that each emerging interaction paradigm will produce one of the three outcomes in relations with existing paradigms: dominant (taking over existing paradigms), assimilation (staying in symbiosis with existing paradigms), and niches (defining and taking on new roles) (Wigdor, 2011). BCI is likely to stay in assimilation with existing mobile interaction paradigms where the basic touch screen based input is preserved and the body becomes an 'add-on' input channel. However, it remains a question how BCI, while staying in assimilation with conventional input, can find its own niche and present its value beyond what a touch screen can offer. There are situations where touch is less available such as in a cold weather where gloves are needed outdoor. It also often happens when the semantics of touch (i.e., what touch does) needs to be specified before the touch can be performed, which suggests instead BCI can be used to frame the touch before/while it is being performed. For example, by positioning the device at different body locations, a touch on an email might 1) open it, 2) archive it, or 3) delete it. It is important to keep looking for such niches as they sum up to a better understanding of why BCI is valuable and, subsequently, how we can realize such value when designing it.

7.4 Conclusion

Screen-based interaction, with its ever realized limited interaction space, has become a motivation for a host of recent work that sought to provide optional input channels between a person and a mobile device. This thesis has been trying to use a person's body and the space immediately around it as a new locus for situating, tracking and mapping interaction beyond a mobile device' screen. To attain this goal, I take a bottom-up approach, starting with designing and implementing prototype systems that contribute to an emerging concept of *Body-Centric Interaction*. To define this interaction, my unique focus is on allowing a person to navigate and manipulate *on-screen* digital content with *off-screen* actions of positioning and orienting the mobile device on and immediately around her body. One prototype after another gradually illustrates and shapes this idea, and eventually reveals three recurring design themes: First, proximal spaces on and around the body are identified and delimited to situate interactions. Second, within these spaces, the spatial relationship between the body and the device serves as 'raw input'. Third, given such 'raw input', various considerations influence the mapping of interactions from the space on and around the user's body. The knowledge of these themes allows a designer to stimulate and structure her idea, or to branch from one idea to various alternatives. At the beginning of this chapter, I show a specific instance of taking a BCI approach in (re)designing a mobile browser that yields new experiences beyond the conventional approaches. The primary contribution of BCI is opening, defining and illustrating this new mobile interaction design approach, all presented and concentrated in a set of reusable prototype systems and a summary of recurring design themes. Admittedly, more iterative design and testing are required to further pursue these new interaction techniques – this is considered one of the most important future work items.

Appendix A Hardware Configuration

To help the readers understand the fundamental mechanisms that enables the BCI prototypes, this appendix collects information about the hardware I use in creating these prototypes.

Radio Frequency Identification (RFID) Technology

In this thesis, I used PhidgetRFID[5] readers (Figure 4-1b) for building prototypes. This type of readers uses the EM4102 protocol and works only in close proximity (typical read distance ranges from 6 to 11 cm) to the RFID tags. In most of my designed prototypes, a reader was connected and/or attached to an Ultra Mobile Personal Computer (UMPC, Figure 4-1a) via USB cables.

The RFID tags used are passive sticker tags (Figure 4-2). This allows for attaching these tags to the body (usually to the clothes instead) in a lightweight manner. For example, Figure 4-2 shows a sleeve with RFID tags attached inside, physically mapping the tags to one's arm locations.

RFID technology, while sufficient for rapid prototyping, is limited as a sensing system. First, because the readers we use can only read a single tag at a time, the tags must be placed a certain distance apart to avoid interference. This limits the location resolution. Second, tags are attached to the body's surface or clothes, which means that a person can only exploit locations directly on their body (personal space) but not around it (peripersonal space). Third, tags only provide a binary measure – they are either in range and readable, or out of range. No distance measure is provided, nor are there other built-in measures available that may help tune the interaction (e.g., the orientation of device). I will return to these limitations in another enabling technology in the next section.

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[5] PhidgetRFID http://www.phidgets.com/products.php?category=14&product_id=1023_1

Motion Capture (mocap) System

Motion Capture Systems (mocap) use photogrammetic tracking. These systems were originally developed for animation in cinematography. They were used to record and analyze object movements, which can be further translated into digital models. This technology has evolved in its uses, where it has been applied as a biomechanical analysis tool, to athletic training applications, and to a wide adoption in HCI community for designing novel user interfaces.

I used the commercial Vicon Motion Capture System[6], as set up in a room-sized space (Figure 4-3a). Currently I use eight infrared cameras. A set of passive retro-reflective markers in a particular spatial arrangement are attached to a person's clothing (e.g., the hat worn by a person as illustrated in Figure 4-3c). Similarly, a different set of markers are attached to the handheld device. These markers are illuminated with infrared light generated near the cameras' lens (Figure 4-3b), thus reflecting back the markers' positions in the cameras' field of view. As the cameras capture the markers from different angles, their synthesized image of the markers and their known spatial arrangements can be used to calculate the entity being tracked, and their 3D spatial information such as location, orientation and motion. In this way, the person or the device's spatial information can be derived (though usually with some adjustments, as markers cannot perfectly represent their geometric structures, e.g., there is always certain offset between the calculated geometric center and the actual one).

While mocap serves as a powerful and efficient tool for rapid prototyping and exploring proofs-of-concept, we should be aware of its limitations when choosing it as an enabling technology. Foremost, the heavy environmental setup and expense prevents it from becoming a real practical solution. Another limitation is the need to coordinate with cameras' line of sight. Since it is possible that the markers are sometimes (partially) occluded by a person's body or the device, the system, at such moments, will temporarily lose track of these entities. Further, the use of markers is also limited. For example, in order to identify different entities, any given two sets of markers must be sufficiently different in geometric structure (even though they both

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[6] http://www.vicon.com/index.html

represent, say, arms). Finally, entities must maintain certain distance in between to avoid ‘merging’ their markers and interfering with each other.

Appendix B Software Implementation

Based on the hardware configuration listed in Appendix A, I now briefly explain the implementation in the software layer that receives and process sensory data from these sensing hardware.

Software Implementation Using RFID Technology

While the PhidgetRFID interface supports multiple programming frameworks, I chose C#/WPF as the programming interface for the hardware.

With RFID technology, the tracking model is quite straightforward. Consider tracking body locations on the arms. To start, select a number of tags and align them along the length of the arm as a 1D array. These tags are then configured in an XML file to associate their ID with a name or number that reflects their layout. For example, the tag '**`1000257fc1`**' is named '**`wrist`**' or '**`arm-0`**' to indicate that it marks the wrist location. I use a simple .xml file to associate and store the tags' data strings with these names and numbers. With this setup the reader can 'scan' the arm and infer the discrete change of location simply by matching the tag ID with its name (and possibly with other data associated with it).

The steps above are just a simple example, as the RFID setup can be altered to provide more flexibility. For example, we can have tag arrays on different sides of an arm location (i.e., a 2D array of tags) where one can rotate her arm while holding the reader still. This slightly altered setup can yield interesting interaction design, as shown earlier in the body-centric browser prototype in Chapter 7.

Software Implementation Using Mocap System

There are three software layers built atop the current Vicon mocap system. First, the Vicon Nexus[7] software that reads raw input from the cameras and provides a toolkit that, among the others, returns to programmers the 3D locations of different entities (i.e., the markers). Second, I use the Proximity Toolkit (Marquardt et al., 2011) to gather and, through the Vicon Nexus, process the lower-level data obtained from the Vicon mocap system. This can supply programmers with higher-level finer-grained proxemic information between interaction entities. This toolkit has greatly simplified the building of the BCI tracking model, as introduced below.

Following one of the design themes discussed in Chapter 2, I build up two models with mocap to track the spatial relationship between the device and the body: device on the body, and device around the body. Each of them, however, is not purely 'software' –it usually requires configuring markers (or choosing from existing sets of markers) that are relevant to the BCI one is trying to realize.

First, mocap can track how the device is spatially associated to particular ***on-body*** locations. To enable this, it requires adding markers to the device and body parts that represent their geometric structures. This can be achieved variously, such as adding a number of markers along one's forearm, or just two or three at the joints (wrist, elbow, etc.). The next step is to adjust the geometric models inferred from the markers, e.g., identifying their geometric centers for tracking the *locations*, adding vectors representing certain pointing *directions*. The resultant tracking mechanism is similar to, but well beyond, the capability of RFID technology. For example, consider the marker-augmented arm and device. We can obtain or calculate the followings (also see Figure 4-4):

- ***I***dentity of a the arm location;
- ***D****istance* between a device and an arm location;
- ***O****rientation* of a device relative to a given arm location;
- *Motion* of the device relative to an arm location – represented as the device' **V**elocities (which can be also be obtained from the Proximity Toolkit).

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[7] Vicon Nexus http://www.vicon.com/products/nexus.html

Further, mocap can also track how the device is oriented ***around the body*** (as opposed to local body parts), similar to the Virtual Shelves model where the user triggers shortcuts by orienting a spatially-aware mobile device within the circular hemisphere in front of her (Li et al., 2009). To enable this, it only requires adding markers to represent the entire body and the device. There are also various ways to 'mark' the body, such as wearing a marker-augmented cap (also see Figure 4-3c), or wearing a vest attached with markers, both of which represent a person's entire body in the environment. Then following similar steps, we can calculate the location and direction information of the body and the device, as well as the device's spatial relationship with the body. In other words, we create a body-centric coordinate system whereby we calculate the device's spatial information in this system (also see Figure 4-5):

- *The body-centric coordinate system* is decided by 1) a *location* representing the entire body in space (e.g., the body's geometric center), and 2) a 'forward' pointing *direction* (i.e., the direction we are facing) telling the front, the back, the left and the right of the person.
- *The device's spatial information*, as discussed earlier in Chapter 2 §2, consists of 1) its *position* P2 (in relations to a person's body P1, Figure 4-5); 2) its *orientation*, calculated from the body-device vector (V = P2 – P1, in relations to the body's 'forward' direction V1, Figure 4-5).

While mocap serves as a powerful and efficient tool for rapid prototyping and exploring proofs-of-concept, we should be aware of its limitations when choosing it as an enabling technology. Foremost, the heavy environmental setup and expense prevents it from becoming a real practical solution. Another limitation is the need to coordinate with cameras' line of sight. Since it is possible that the markers are sometimes (partially) occluded by a person's body or the device, the system, at such moments, will temporarily lose track of these entities. Further, the use of markers is also limited. For example, in order to identify different entities, any given two sets of markers must be sufficiently different in geometric structure (even though they both represent, say, arms). Finally, entities must maintain certain distance in between to avoid 'merging' their markers and interfering with each other.

Appendix C Other Prototypes

There are prototypes that were not reported in the chapters. Some did not quite work and remained as an intermediate product during the iterative design process. Others diverged away from the scope of using a screen-based handheld device. However, valuable lessons can be learnt from them such as experience that informs the next steps of design and implementation, or pointers to future work.

'Image Hand'

'Image Hand' is an earlier version of Body Viewer (see Chapter 5 §3). It represents many other 'intermediate products' that offered valuable lessons for the next steps of design and implementation and finally led to a working prototype systems.

'Image Hand' learns from the classic 'pick-and-drop' technique (Rekimoto, 1997) and allows a person to pick up images from, say, the desktop computer by hands, and to drop them on, say, a large display where she can share the images with the other viewers.

Two Phidget Proximity sensors[8] detect the 'picking' gestures towards a desktop computer, which associates the images to the two hands (the underlying data structure is a stack where one image is pushed in at a time). At a different location, the mocap system can track the same person's 'dropping' gesture; that is, a short and quick hand 'push' movement towards a vertical display. The images are then popped out from the two stacks and shown on the display.

While this prototype allows a person to have two 'handfuls' of images, it simply uses the hands as two 'pickers' (similar to two styluses) and ignores the possibilities of interacting with the space on the body. As a result, it is difficult and cumbersome to retrieve a particular image – one has to 'drop' all the images atop the one she is looking for. BCI should afford more than such 'two-state' (pick and drop) interaction.

[8] http://www.phidgets.com/products.php?category=2&product_id=3520_0

And the idea that emerged from this ‘failed’ prototype is to consider the larger on-body space beyond the two hands, which led to the design of Body Viewer, then Body Shortcuts, and then Body Toolbar.

Body Surface

The prototyping process is also a process of finding and defining the scope of BCI. While a number of other prototypes finally fall out this scope, they, on the other hand, suggest interesting future work opportunities. Below I report one such example where I designed BCI for an interactive surface.

One of the problems of surface computing is the direct manipulation by touch can only afford a limited semantic/syntactic (Buxton, 1983) complexity. For example, it is somewhat difficult to touch and gesture a ‘copy’ command for which one can easily resort to a right-click menu in a conventional desktop setting. The idea of Body Surface is to use the surface of the body (e.g., the arms) as an extension of the interactive surface but specifically just to serve as a palette of control options. As shown in Figure A-1, the touch on one arm surface frames the semantics of touch performed by the other arm on the interactive surface. Closer to the wrist is ‘move’ where a contact point causes an object to move following its path (Figure A-1 Top). Mid-forearm is ‘copy’ where a dragging gesture starting from an object copies it and the copy moves following the path of the contact point. (Figure A-1 Middle). Closer to elbow is ‘delete’ where a single tap on an object deletes it (Figure A-1 Bottom).

This idea was extended from the Body Toolbar prototype and also learnt from the Skinput project (Harrison et al., 2010). While I did not develop it further in this thesis, I consider it as an opportunity for future work where BCI can be introduced to other computing form factors like an interactive surface.

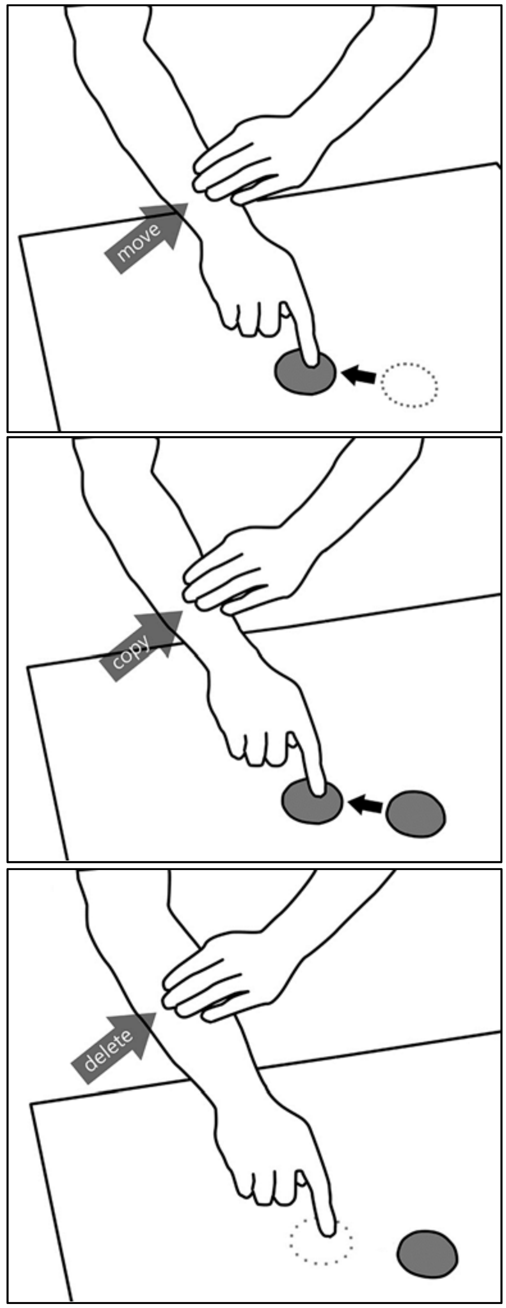

Figure A-1. Body Surface lets a person touch different parts of the arm to specify the actions perform by touch on an interactive surface such as closer to the wrist is ‘move’ (Top), mid-forearm is ‘copy’ (Middle), and closer to elbow is ‘delete’ (Bottom).

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