Mobile and Physical User Interfaces for NFC-based Mobile Interaction with Multiple Tags

Gregor Broll
DOCOMO Euro-Labs
Munich, Germany
broll@docomolab-euro.com

Doris Hausen
Media Informatics Group, Ludwig-Maximilians-Universität (LMU), Munich, Germany
doris.hausen@ifi.lmu.de

ABSTRACT
Near Field Communication (NFC) is an emerging technology for mobile interaction with everyday objects and associated digital resources. Apart from simple interactions with single tags, NFC has the potential for more elaborate interactions with physical objects that comprise multiple tags and serve as physical user interfaces (UI). This paper investigates the design of mobile and physical UIs for the interaction with multiple NFC-tags. It focuses on three basic interactions that qualify for multi-tag interaction - the navigation between parts of an application, the selection of items and the combination of items. Two user studies compare different configurations of mobile and physical UIs for these interactions in order to evaluate the allocation of application features and UI elements to mobile devices and tagged objects. The results advocate the continuous interaction on the latter, instead of splitting interactions between mobile and physical UIs.

Categories and Subject Descriptors
H.5.2 [**Information Interfaces and Presentation**]: User Interfaces –input devices and strategies, interaction styles

General Terms
Design, Human Factors

Keywords
Near Field Communication, NFC, single-tag interaction, multi-tag interaction, physical user interface, usability, evaluation

1. INTRODUCTION
As Mobile Computing becomes part of our daily lives, its technologies affect the way we access and use information. Mobile devices can be used for physical interaction with tagged, everyday objects in order to facilitate the interaction with associated information or services. Users can interact with the latter by touching wireless NFC/RFID tags or by taking pictures of visual markers with their mobile devices [2]. Tagged objects like posters, leaflets or advertising columns can serve as physical user interfaces (UI) that advertise ubiquitous information or services and facilitate their discovery. Physical UIs can adopt features of mobile UIs, complement them and thus compensate constraints of mobile devices. Instead of browsing nested menus on small screens, application features and options can be mapped to physical UIs from where users can select them directly.

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An emerging technology for *physical mobile interaction* [14] is Near Field Communication (NFC) [20], a radio-based technology for short-range data exchange between reading devices, e.g. mobile phones, and passive wireless tags. Many applications take advantage of the touch-like interaction between them to facilitate mobile payment, ticketing or information retrieval. These and other examples benefit from the simple interaction with single tags but neglect the potential of tagged objects for further physical interaction. Nevertheless, NFC can be used for more elaborate interactions with physical UIs that comprise multiple tags. Examples are posters for mobile ticketing [2], menus for home delivery [5] or control panels for multimedia players [15].

While the interaction with physical objects and multiple NFC-tags can facilitate mobile interactions, the separation of mobile and physical UIs affects the interface and interaction design of mobile applications. The focus of interaction shifts from mobile devices to physical objects, splitting the application UI and the users´ attention between them. This separation raises questions regarding the logical and spatial allocation of application features and UI elements to mobile and physical UIs. Different aspects such as control, privacy, intuitiveness or convenience may influence the preferences of the users for different UI configurations: S*ingle-tag interactions (STI)* that use single tags as physical hyperlinks [16] and keep the focus of interaction on mobile devices, *multi-tag interactions (MTI)* that map application features and UI elements to multiple tags on physical objects, and hybrid configurations that split features between tagged objects and mobile devices.

This paper investigates the design of mobile and physical UIs for the interaction with multiple NFC-tags by comparing different allocations of application features and UI elements to mobile devices and tagged objects. It focuses on three basic interactions of mobile applications that qualify for MTI: the navigation between parts of an application, the selection of items and the combination of items. In order to evaluate the allocation of application features and UI elements for these basic interactions, two user studies compare different configurations of mobile and physical UIs for each of them, including STI, MTI and hybrid configurations. The results provide insights about the mapping of application features and UI elements to mobile and physical UIs as well as the applicability of STI and MTI.

The next section summarizes related work on physical UIs and NFC-based mobile interaction. Section 3 analyses the latter to point out basic interactions with multiple tags. Sections 4 and 5 present two user studies that compare and evaluate different configurations of mobile and physical UIs for these interactions Section 6 summarizes the results of the studies and section 7 concludes the paper.

2. RELATED WORK

Physical mobile interaction [14] has emerged as a paradigm for mobile interaction that uses mobile devices for physical interaction with (tagged) everyday objects. Among others, NFC and RFID (Radio Frequency Identification) [20] have become popular enabling technologies for physical mobile interaction. In 1999, Want et al. [19] have presented some of the first examples for linking objects (e.g. books, documents, business cards) and digital information (e.g. electronic documents, URLs, email-addresses) through RFID-tags. Today, many applications take advantage of the simple interaction with NFC or RFID for mobile payment (e.g. i-mode FeliCa [10]), ticketing (e.g. Oyster Card [12]), identification or information retrieval, using contactless smartcards or NFC-enabled mobile devices. In Ubicomp research, NFC and RFID are used for mobile interaction with tagged objects and associated digital resources, e.g. in the Internet of Things [8]. Another example is the SmartTouch project [18] that has investigated NFC in different use cases, such as ticketing, access control, home care or entertainment.

Most of these and other examples take advantage of the simplicity of single-tag interaction that facilitates interactions on mobile devices by reducing their various steps to the simple physical interaction of touching one tag. Such tags often serve as physical hyperlinks [16], but STI can be used in many different ways: Geven et al. [3] point out four categories of NFC-based mobile interactions: *"reading from passive objects"*, *"verification for services"*, *"payment"* and *"peer to peer sharing"*. Herting and Broll [6] also point out *"information retrieval"*, *"physical hyperlinks"*, *"tagging"* and *"tag emulation"*.

Although the simplicity of STI is one of the biggest advantages of NFC-based mobile interaction, it neglects the potential of tagged objects to serve as physical UIs that support further physical interactions. While STI reduces the complexity of mobile interactions, MTI maps different features of mobile applications to multiple tags and spreads them on physical UIs, from where users can select them directly: The PERCI project [2] has developed smart posters that comprise multiple tags to let users invoke Web Services for mobile ticketing. Sanchez et al. [15] use a physical UI to operate a multimedia player whose controls have been mapped to RFID-tags that users can touch with their mobile devices. In [5], the authors present a home care service that allows elderly people to order meals for home-delivery by touching RFID-tags on a menu. Reilly et al. [13] explore mobile interaction with tagged paper maps where users can select different actions and apply them to different areas of the map by touching their RFID-tags. In [4] and [17], the authors use grids of NFC-tags as physical UIs that users can touch to manipulate dynamic application UIs that are projected onto the physical UI or presented on a laptop display.

So far, evaluations of mobile interaction with NFC or RFID have focused on the comparison of NFC and visual markers, e.g. [9] and [11], or its general usability. A field study by Mäkelä et al. [9] showed that people are usually not familiar with RFID, visual markers and how to trigger the interaction with them. Due to the lack of familiarity with these technologies, the mental model about them is very vague. Similarly, Geven et al. [3] have found out that novice users often do not know how to initiate the interaction with NFC. They were also not sure about how to align mobile devices and tags correctly, since the position of the NFC-unit was not marked on the devices. Broll et al. [1] have compared different approaches to improve the learnability of NFC-based interactions. They found out that a dedicated start-tag facilitates the first step in NFC-based mobile interactions and that users preferred an implicit guidance through the interaction process. Häikiö et al. [5] have found out that an NFC-based interface was useful for elderly people who suffered from trembling hands and could hardly use the small keys of mobile devices.

3. ANALYSING BASIC INTERACTIONS WITH MULTIPLE TAGS

Overviews of NFC-based mobile interactions, e.g. in [3] or [6], show a strong preference for STI, due to its directness, simplicity and convenience. On the other hand, the previous section showed that applications and interactions may comprise several features or options that cannot be reduced to the interaction with a single tag. Instead, these applications can take better advantage of NFC-based interaction by mapping features and options to multiple tags on everyday objects and by using them as physical UIs. In order to comply with these applications, this section points out three basic interactions that qualify for MTI. The studies in sections 4 and 5 build upon them to implement different configurations of mobile and physical UIs for mobile applications and to compare different allocations of their features and UI elements.

3.1 Navigation

Mobile applications can use MTI to facilitate the navigation between their different parts. Physical UIs with multiple tags can give a better overview of available features and provide multiple entry points to an application. The tags provide direct access to application features on the mobile device, where the interaction continues. Instead of browsing nested hierarchies of screens, pages or forms on mobile UIs, users can directly jump to different parts of an application and switch between them by touching their NFC-tags on a physical UI.

3.2 Selection of Items

The selection of items also suffers from mobile UIs with nested menus or long lists that require tedious scrolling. Just as MTI can facilitate the top-level navigation between the screens, pages or forms of mobile applications, it can also support the selection of the items and options they contain. Instead of putting them into crowded lists, they can be mapped to tags on physical UIs, from where users can select them directly, e.g. to fill out a form on the mobile UI. Again, physical UIs provide more space for an overview of multiple items and prevail over mobile UIs as the number of available items grows. Examples are tagged posters for mobile ticketing that comprise several groups of options [2]. Each option is tagged with an NFC-tag and users can touch it with their mobile devices to collect the associated option.

3.3 Combination of Items

Mapping features and options of mobile applications to NFC-tags and spreading them on a physical UI can also facilitate their accumulation and combination for a complementary purpose, increasing their solitary value. That way, information items can be accumulated for a service invocation or actions can be applied to different objects and vice versa. Compared to STI, MTI can greatly reduce the number of tags required to implement all possible combinations of a number of items. Instead of mapping each combination of *m* x *n* items to single tags, MTI only needs *m* + *n* tags for the single items, whose combination is achieved through physical interaction. Collect&Drop [2] for example maps items for actions and parameters, respectively URLs of Web Services and information for their invocation, to different tags. Users can invoke a service by collecting its action item and a choice of suitable information items. In [13], users can interact with a tagged map to select actions from a menu and apply them to an area of the map, e.g. to look for coffee shops in this area.

4. EVALUATING NAVIGATION AND THE SELECTION OF ITEMS

The first study investigated mobile and physical UIs for navigation and the selection of items, which often complement each other in mobile applications. Their evaluation is based on a use case for browsing different categories and selecting items from them. Its interaction workflow serves as the blueprint for the design, implementation and comparison of four prototypes whose UI configurations map features and UI elements for navigation and selection to mobile and physical UIs in different ways.

4.1 Use Case and Interaction Workflow

This use case is inspired by applications for ordering food and complies with both navigation and selection. Users can browse different categories (appetizer, main course, dessert and drinks) and select items from them. For an equal comparison of different UI configurations for navigation and selection, the prototypes that implement them always comprise the same steps of the use case interaction workflow:

- **Start:** Users start the mobile application from the menu of the mobile phone or by touching an NFC-tag with it.
- **Welcome-screen:** The first screen of the mobile application tells users how to perform the next step in the workflow by either pressing a key or by touching a tag.
- **Navigation:** Next, the users can switch between the four categories, either on the mobile UI or by touching different tags on a physical UI.
- **Selection of items:** In each category, users can select items to compose their order, again on either UI.
- **Summary:** From this overview of selected items on the mobile device, users can either submit their selection or go back to the different categories to change it.
- **Submission:** Users confirm their order either by pressing a button on the mobile device or by touching an NFC-tag.
- **Confirmation:** The final screen of the mobile application confirms the submission of the order.

4.2 Prototype Design and Implementation

In order to compare all combinations of navigation and selection on mobile and physical UIs, four prototypes implement the same steps of the use case workflow, but map them to mobile devices and tagged objects in different ways. Each prototype comprises a Java ME application on a Nokia 6131 NFC and a tagged object. The positions of the NFC-tags on the back of these objects are indicated by symbols on the front. The successful reading of a tag upon touching it with the mobile device is confirmed by a short vibration feedback. The design of the prototypes is deliberately plain in order not to distract the subjects during the study.

- **Single-tag interaction (STI)** maps both the navigation and the selection of items to the mobile UI. Users start the mobile application by touching an NFC-tag on a leaflet (Figure 1a). All further interactions are performed on the mobile device including the linear traversal of the four category-screens using the left and right softkeys, the selection of items from a list of radio buttons for each category (Figure 1b) and submitting the order from the summary (Figure 1c).

a) b) c)

Figure 1: Tagged leaflet to start the mobile application (a), the screen for selecting items from a category (b) and the summary (c)

- **Multi-tag interaction (MTI) #1** maps the navigation to the physical UI and the selection of items to the mobile UI. The physical UI was implemented as a cardboard stand, similar to the "Restaurant Pannu" use case from SmartTouch [18]. It comprises six tags for starting the application, switching between the four categories and submitting the order (Figure 2). Users can touch the tags to perform actions or to access screens for each category on the mobile device. Opposite to STI, users can access them arbitrarily and not in a fixed, linear order. Similar to STI, the selection of items is performed on the mobile device, where users can select them from a list of radio buttons for each category (Figure 1b).

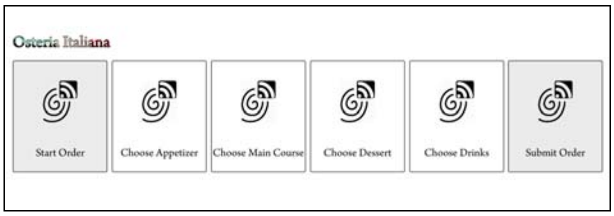

Figure 2: Tagged physical UI for navigation via MTI

- **Multi-tag interaction (MTI) #2** maps the navigation to the mobile UI and the selection of items to the physical UI. To keep the navigation completely on the mobile device, the application is started from its menu and uses a wizard-like navigation to guide users, telling them when to select an item from which category. All items are mapped to NFC-tags on a poster (see Figure 3 – without the grey tags on the top of the poster). After each selection, the summary gives an overview of collected items on the mobile device. From here, users can change an order or submit it by pressing a key.
- **Multi-tag interaction (MTI) #3** maps both the navigation and the selection of items to the physical UI. Users can start

the application, select items and submit their order by touching NFC-tags on the poster (Figure 3). Since the navigation between the categories is merged with the selection of items on the physical UI, the mobile UI comprises only one screen for the summary (Figure 1c).

Figure 3. Tagged, physical UI for the selection of items in MTI #2 and #3 (poster for MTI #2 only comprises tags for items)

4.3 Experimental Design and Procedure

In order to evaluate mobile and physical UIs for navigation and the selection of items, the study compared the four prototypes and their different UI configurations. It was conducted with 16 subjects (9 male, 7 female) with an average age of 25.1 years. Most subjects were students with a background in computer sciences who rated their technical expertise and their expertise with mobile device as quite high (4.5 and 3.8) on a Likert-scale from 1 (worst) to 5 (best). 14 subjects have already heard about NFC or RFID, but only 4 have used them before the study. The study tested three independent variables to gather results about the interaction with single and multiple NFC-tags:

- The first variable reflects the different UI configurations and has four levels (STI, MTI #1 - #3).
- The second variable reflects the number of items that can be selected from a category and has two levels - 7 and 14 items. The latter causes the additional effort of scrolling long lists on mobile UIs and scanning physical UIs to find a specific item. STI and MTI #1, that allocate the selection of items to the mobile UI, implement two different lists with 7 and 14 items for each category. MTI #2 and MTI #3 each use two posters of different sizes for the different numbers of items.
- The third variable reflects the complexity of tasks and has two levels. It has the subjects complete tasks with and without making two corrections which require them to go back in the interaction workflow.

The study used a repeated measures design within subjects. Each subject had to carry out the same four tasks with each of the four prototypes. Each task covered one of the four combinations of low and high task complexity and the two numbers of items. The basic task (low complexity) was a straight walk through the interaction workflow. It asked the subjects to start the application, go through the four categories, select an item from each of them, look at the summary and submit the order. For tasks with high complexity, the subjects had to go back in the workflow from the summary to make two corrections. To test low and high numbers of items, the subjects had to select from a choice of 7 and 14 items.

A balanced Latin Square design was used to counterbalance the order of the independent variables, resulting in 16 combinations – one for each subject. At the beginning of the study, each subject was introduced to NFC-based interaction, the topic of the study and the prototypes. Before a subject performed the four tasks with one of the prototypes, he carried out a trial order to familiarize himself with the application and the NFC-based interaction.

The dependent variables were task execution time and the number of attention shifts [7] between the mobile device and physical UIs. During the study, the subjects were recorded on video for a post-hoc analysis of attention shifts. This analysis did not explicitly investigate errors, since the subjects had become familiar with the prototypes before the tests. The task execution time was recorded by the mobile applications from touching the first tag to start the application until submitting the order. An exception is MTI #2, which was started on the mobile device and whose time was measured with a stop watch. At the end of the study, the subjects had to fill out a final questionnaire to compare the prototypes.

4.4 Results

4.4.1 Task Execution Time

Figure 4 shows how the configuration of mobile and physical UIs, the task complexity and the number of selectable items affected the task execution time for navigation and the selection of items. STI was faster than MTI #1 for simple tasks and about as fast for more difficult ones, making MTI #1 the slowest of the four configurations. STI performed better than MTI #1 regarding low task complexity/low number of items (m=22.0; sd=5.4 vs. m=30.6; sd=8.0; all times in seconds) and low task complexity/high number of items (m=34.5; sd=8.1 vs. m=43.2; sd=17.3). Both UI configurations performed similarly regarding high task complexity/low number of items (m=45.3; sd=7.6 vs. m=48.4; sd=10.2) and high task complexity/high number of items (m=69.2; sd=15.8 vs. m=70.2; sd=17.9).

Among the four UI configurations, MTI #3 was clearly the fastest one for all tasks: low task complexity/low number of items (m=18.9; sd=6.8), low task complexity/high number of items (m=19.6; sd=5.9), high task complexity/low number of items (m=31.1; sd=7.1) and high task complexity/high number of items (m=40.2; sd=14.1). UI configurations that mapped the selection of items to physical UIs (MTI #2 and #3) often performed better than UI configurations that mapped it to mobile UIs (STI and MTI #1), with a few exceptions. While MTI #2 was slower than STI regarding low task complexity/low number of items (m=26.3; sd=5.4), it was slightly faster regarding low task complexity/high number of items (m=30.2; sd=8.9), about as fast regarding high task complexity/low number of items (m=44.9; sd=9.7) and much faster regarding high task complexity/high number of items (m=48.5; sd=12.2). In summary, MTI #2 was faster than STI for high numbers of items.

The results for the mapping of navigation features are less clear. The comparison of MTI #2 and #3 clearly advocates mapping the navigation to the physical UI. Opposite to the rigid navigation of

MTI #2, MTI #3 benefits from the possibility to select tags in arbitrary order. On the other hand, the comparison of STI and MTI #1 shows that mapping the navigation to a physical UI does not make the interaction faster. These contradicting results are probably due to the number of attention shifts, which slightly drops in the comparison of MTI #2 and MTI #3, but significantly increases in the comparison of STI and MTI #1 (see next section).

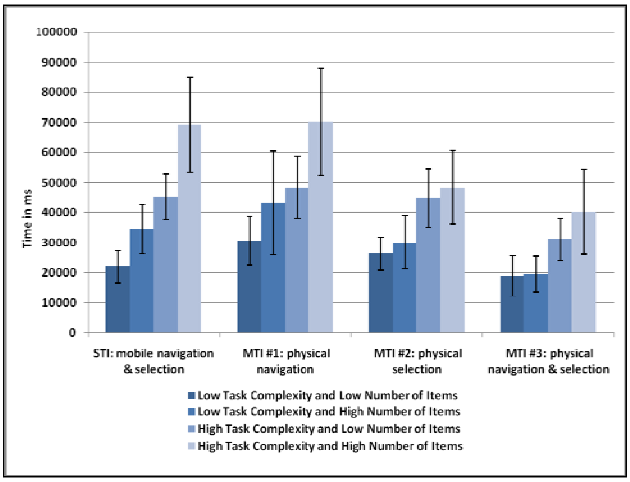

Figure 4. Task execution times for navigation and selection

These results show that hybrid UI configurations that are split between mobile devices and tagged objects often performed worse than UI configurations that are completely mapped to either one of them, especially for simple tasks and interactions with few items. In addition, mobile applications benefit more from mapping the selection of items to physical UIs than mapping navigation features to them. While the task complexity and the number of items clearly affected the performance of the different UI configurations, the results for MTI #2 and #3 show that the physical selection of items clearly reduced the impact of the number of items.

A three-way repeated measures ANOVA was used to analyze the results. Regarding within-subject effects, all (combinations of) independent variables were significant, except for the total combination of UI configuration, task complexity and number of items. Regarding their pairwise comparison, all UI configurations, task complexities and numbers of items were highly significant and had a strong effect on the task execution time, except for the comparison of STI and MTI #1.

4.4.2 Attention Shifts

Figure 5 shows the number of attention shifts for the different UI configurations. The constant values for STI and MTI #1 comply with the mandatory number of attention shifts for the different tasks. After touching the tag to start the mobile application, STI only needed one attention shift to continue on the mobile UI. MTI #1 needed 9, respectively 13 more attention shifts to have the subjects look at the tags for the four categories, to look back at the mobile UI and finally to find the last tag to submit the order. These results were not affected by the task complexity or the number of items, except for MTI #1 which needed four additional attention shifts to carry out two corrections.

Mapping the selection of items to a physical UI (MTI #2 and #3) clearly caused less attention shifts than mapping the navigation to a tagged object (MTI #1). For the physical selection of items, the subjects did not have to shift their attention between the mobile and the physical UI as often as for the physical navigation in MTI #1. Instead, they were able to focus on the interaction with the tags and rely more on the vibration feedback to confirm it, instead of glancing at the mobile UI for that purpose. Since the selection of items was performed on the physical UI, the number of attention shifts was not much affected by the number of items but by the task complexity. This was confirmed by an ANOVA within subjects which was highly significant for UI configurations and task complexity, but not for the number of items.

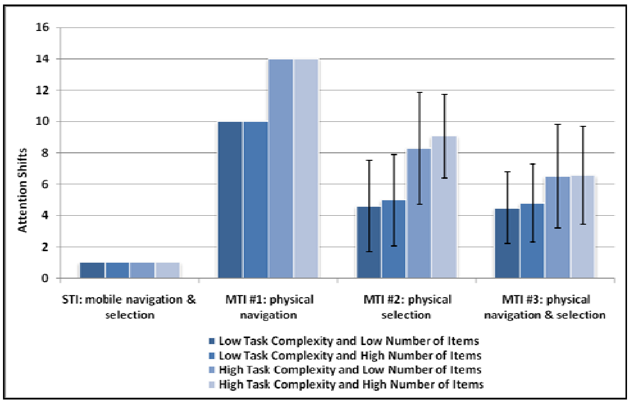

Figure 5. Attention shifts for navigation and selection

MTI #2 and MTI #3 show almost identical results for low task complexity with low numbers of items (m=4.6; sd=2.9 vs. m=4.5; sd=2.3) and with high numbers of items (m=5.0; sd=2.9 vs. m=4.8; sd=2.5), whereas MTI #3 has less attention shifts regarding high task complexity with low number of items (m=8.3; sd=3.6 vs. m=6.5; sd=3.3) and with high number of items (m=9.1; sd=2.7 vs. m=6.6; sd=3.1). MTI #3 seems to benefit from the complete mapping of navigation and selection to the physical UI, especially for more complex tasks that are not slowed down by rigid navigation on the mobile UI. Pairwise comparisons of UI configurations with Bonferroni Correction of the ANOVA were significant, except for MTI #2 and #3. While the comparison was not significant for the number of items, the task complexity has a significant influence on the number of attention shifts. Similar to the results for task execution times, hybrid UI configurations that split interactions between mobile devices and tagged objects often performed worse and caused more attention shifts than UI configurations that map all features for navigation and selection to either the mobile or the physical UI.

4.4.3 User Feedback

At the end of the study, the subjects had to fill out a final questionnaire to compare the prototypes and to evaluate the allocation of features for navigation and the selection of items. All 16 subjects voted for MTI #3 as the most suitable UI configuration for accomplishing the tasks and regarded it as the easiest and most intuitive design. Reasons for this preference were the continuous interaction with NFC-tags without having to shift the attention to the mobile device, the physical UI that is larger and more comfortable to use than the mobile UI, the arbitrary order of interaction on the tagged poster or its suitability for carrying out more complex tasks like corrections. MTI #3 gave the subjects the feeling of being in control instead of being controlled and limited by the application. Regarding the least suitable prototype, seven subjects voted for STI because of the fixed order of navigation and the tedious scrolling through long lists of items on the mobile device. Six subjects disliked MTI #1 for the scrolling and for the high number of attention shifts during the navigation. Three subjects disliked MTI #2 because of the rigid wizard-like navigation.

In general, most subjects (13) preferred the interaction on the physical object which was fast and intuitive, caused less attention shifts and had a more clearly arranged UI, especially for large numbers of items. It was also seen as easier to use for people who are unfamiliar with mobile applications. No subject preferred the interaction on the mobile device, but three subjects voted for a combined interaction on both UIs. They appreciated the feedback from the mobile device and felt more in control of critical actions, like submitting an order, for which they could press a key on the phone, instead of just touching a tag on the poster.

Regarding their preferences for carrying out different parts of the interaction workflow, the subjects clearly preferred the interaction with the physical UI for starting the application, navigating between its categories, selecting items and making corrections (see Table 1). They were undecided about the execution of more critical actions like submitting an order. Seven subjects did not mind whether actions are executed by pressing a key on a mobile device or by touching an NFC-tag, but more subjects preferred the interaction with the mobile UI (6) than with the physical UI (3).

Table 1. Preferences for the allocation of features for navigation and selection to mobile devices, tagged objects or both

Feature	Physical UI	Mobile UI	Both
Starting the application	11	1	4
Navigation	12	0	4
Selection of items	14	1	1
Execution of actions	3	6	7
Corrections	10	4	2

5. EVALUATING THE COMBINATION OF ACTIONS AND OBJECTS

The second study followed the approach of the first one to evaluate different configurations of mobile and physical UIs for the combination of different kinds of items - actions and objects - through physical interaction. It used the interaction workflow of a basic use case as the blueprint for the implementation and fair comparison of different allocations of application features and UI elements to mobile devices and tagged objects.

5.1 Use Case and Interaction Workflow

The interaction with a map was inspired by [13] and serves as the use case for the combination of actions and objects. It comprises a poster that highlights several sights of a city and uses the mobile device to apply different actions to them. The workflow of this use case always includes the following steps which will later be mapped to physical and mobile UIs in different ways:

- **Start:** The mobile application is always launched by touching an NFC-tag on the physical UI.
- **Welcome-screen:** The first screen of the mobile application tells the user how to perform the next step in the workflow either by pressing a key or by touching a tag.
- **Selection of object:** Depending on the prototype, the user has to select an object, respectively a sight, from a list on the mobile UI or by touching its NFC-tag on the physical UI.
- **Selection of action:** Next, the user selects an action in order to apply it to the previously selected object. Actions and objects are combined by the mobile application as a result of their subsequent selection from either the mobile or the physical UI. Depending on the prototype, users can select items in a fixed or an arbitrary order. The "*Information*"-action retrieves details about a sight on the mobile UI. "*Route*" allows the selection of further sights to calculate an itinerary between them. "*Email*" lets users send an email about a sight to contacts from a list on the mobile UI.
- **Confirmation**: The last step of the workflow concludes the different actions on the mobile UI individually: Users see additional information about a sight, get a confirmation for having sent an email or see an itinerary between sights.

5.2 Prototype Design and Implementation

Following the same steps of the interaction workflow, five prototypes were designed and implemented to cover all combinations for mapping objects and actions to mobile and physical UIs. Each prototype comprises a Java ME application on a Nokia 6131 NFC and a tagged poster with a map of a city centre and its sights. Each poster features an NFC-tag to start the mobile application. The posters also comprise NFC-tags for objects, respectively sights, and actions, depending on the tested UI configuration (Figure 6).

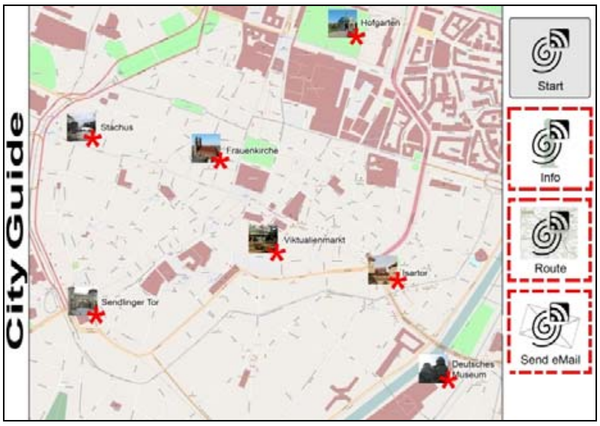

Figure 6. Physical UI for the combination of actions and objects. Asterisks and dashed boxes mark the positions of NFC-tags for objects and actions on posters for different prototypes (map from www.openstreetmap.de)

- **Single-tag interaction (STI)** maps objects and actions to the mobile UI. The poster for STI only comprises one NFC-tag to start the mobile application (Figure 6 without any other tags). First, users select one of seven sights from a list on the mobile UI (Figure 7a). The next screen highlights the selected sight (Figure 7b) and users can apply one of the three actions from the "Options"-menu.

a) b) c)

Figure 7. Mobile UI screens for selecting objects on the mobile device (a), highlighting selected objects (b) and actions (c)

- **Multi-tag interaction (MTI) #1** maps objects to the physical UI and actions to the mobile UI. The sights on the map are tagged (Figure 8a) and can be selected by touching their NFC-tags with the mobile device. Similar to STI, selected objects are highlighted on the mobile UI (Figure 7b), where users can select actions from the "Options"-menu.

a) b)

Figure 8. NFC-tags to select objects for further interaction (a) and to apply actions to individual objects instantaneously (b)

- **Multi-tag interaction (MTI) #2** maps objects to the mobile UI and actions to the physical UI. Opposite to MTI #1, this prototype does not tag objects on the poster, but provides NFC-tags for the three actions below the "Start"-tag (Figure 6). In order to combine objects and actions, users first have to select a sight from a list on the mobile UI (Figure 7a, b) and then apply an action by touching its tag on the poster.
- **Multi-tag interaction (MTI) #3** maps objects and actions to the physical UI. This UI configuration combines MTI #1 and #2 to map all actions and objects to NFC-tags on the poster (Figure 6). Users can select them in arbitrary order by touching the tags with their mobile devices. The selected object or action is highlighted on the mobile UI (Figure 7b, c) and users can simply touch another tag on the poster in order to combine an action with an object or vice versa.
- **Multi-tag interaction (MTI) #4** combines objects and actions on the same NFC-tag on the physical UI. This design was inspired by the idea of hybrid tags from Collect&Drop [2] that put the URL of a Web Service and information for its invocation on the same tag. MTI #4 reduces the design of MTI #3 to the interaction with single tags as it provides individual action-tags for each object (Figure 8b). This approach implements the combination of items by putting them on the same tag, instead of having them selected one after another. This design is not strictly MTI and will provide additional insights about STI.

5.3 Experimental Design and Procedure

The study used a repeated measures design within subjects to compare the five prototypes and to evaluate the influence of their UI configurations on the combination of items. The study was conducted with 15 subjects (8 males, 7 females) with an average age of 23.1 years. Most of them were students of computer sciences and thus rated their technical expertise and their expertise with mobile devices as quite high (3.8 and 3.8) on a Likert-scale from 1 (worst) to 5 (best). Eleven subjects have heard about NFC or RFID before the study, but only three of them have actually used it. The study tested two independent variables to evaluate mobile interaction with single and multiple tags:

- The first variable reflects the different configurations of mobile and physical UIs and has 5 levels (STI, MTI #1 - #4)
- The second variable reflects the complexity of the actions, respectively the tasks that the subjects had to carry out with the prototypes. This variable has three levels, presenting different ways of combining items with each other: For "*Information*", the subjects only had to combine one object with one action. For "*Route*", the subjects had to combine one action with four sights to build an itinerary. "*Email*" had the extra effort of selecting an email-address from the mobile device, causing more attention shifts.

During the study, each subject had to carry out the three tasks with each of the five prototypes. The order in which the subjects tested the prototypes and the tasks was counterbalanced according to a balanced Latin Square. The tasks reflect different levels of complexity on which items can be combined. For the first task, the subjects had to select a sight and apply the "Information"-action to look up more details. For the second task, the subjects had to select four sights and apply the "Route"-action to create an itinerary. For the third task, the subjects had to select a sight, apply the "Email"-action and look up an email-address from the mobile device.

Similar to the first study, the subjects started this one with an introduction to NFC-based mobile interaction and familiarized with each prototype right before performing the three tasks with it. During the study, each subject used each of the five prototypes to carry out all three tasks. The task execution time was measured by the application from touching the NFC-tag to start the application until the task was finished. The number of attention shifts was counted during the analysis of the video that was recorded during the study. Again, errors were not counted, since the subjects had already become familiar with the prototypes before the actual execution of tasks. At the end of the study, the subjects had to compare the prototypes with a final questionnaire.

5.4 Results

5.4.1 *Task Execution Time*

The comparison of task execution times across all UI configurations for combining actions and objects (Figure 9) confirms the complexity of the different tasks: the simple retrieval of information was the least elaborate task, followed by the more complex sending of an email and finally the creation of an itinerary that involved the selection of four sights.

The comparison shows that STI and MTI #2 required the most time to carry out the tasks. The results of STI for "Information" (m=10.0; sd=2.8), "Route" (m=33.3; sd=7.6) and "Email" (m=16.7; sd=6.9) are most likely due to the continuous interaction on the mobile device. MTI #2 suffered from the uncommon selection of actions from tags on the poster while the objects were selected on the mobile device. The comparison between MTI #1 and MTI #2 shows that the opposite configuration which maps objects to the physical UI and actions to the mobile UI is clearly faster. This is supported by the task execution times for "Information" (m=7.9; sd=5.1 vs. m=9.8; sd=2.2), "Route" (m=22.6; sd=10.7 vs. m=35.1; sd=10.7) and "Email" (m=12.7; sd=5.0 vs. m=19.0; sd=7.5).

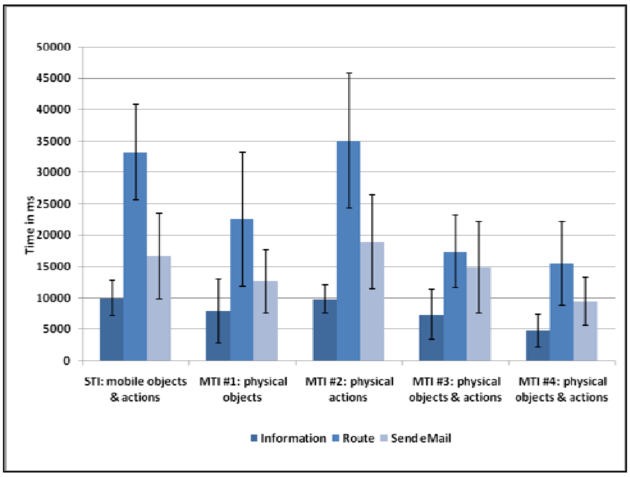

Figure 9. Task execution times for the combination of items

The more features a prototype maps to the physical UI, the faster can subjects carry out the different tasks. Although MTI #1 only maps objects to the poster, it was faster than STI and MTI #2. As MTI #3 and MTI #4 mapped all features to the physical UI, they performed even better than MTI #1 in most cases. MTI #4 performed better than MTI #3 regarding the tasks "Information" (m=4.8; sd=2.6 vs. m=7.4; sd=4.0), "Route" (m=15.5; sd=6.7 vs. m=17.4; sd=5.7) and "Email" (m=9.5; sd=3.9 vs. m=14.9; sd=7.2), making it the fastest of the five UI configuration. Similar to the first study, mapping all features to tagged objects usually performed better than hybrid configurations that split interactions between mobile and physical UIs and required users to switch between them more often.

A repeated measures ANOVA was used to analyze within-subject effects for the independent variables and showed that their effects on the task execution times were highly significant. Pairwise comparison with Bonferroni Correction showed that the combinations of STI and MTI #2, MTI #1and MTI #3, MTI #1 and MTI #4 as well as MTI #3 and MTI#4 were not significant. In contrast, the comparison of tasks showed that this variable was highly significant in all cases.

MTI #4 reduces most of the multi-tag interactions of MTI #3 to single-tag interactions by combining objects and actions on the same tag. Instead of selecting two tags for an action and an object, users only need to touch one tag for information retrieval and emailing. The comparison of MTI #3 and #4 points out an advantage of multi-tag interaction: While MTI #3 only needs 7 + 3 tags to cover all combinations of actions and objects, MTI #4 needs 7 x 3 tags to provide each object with individual actions. STI and MTI #4 show different ways to use single-tag interaction: The STI-prototype uses single-tag interaction on a physical UI with one tag to implement a physical hyperlink that launches the mobile application. The MTI #4-prototype uses several single-tag interactions on a multi-tagged physical UI to implement the combination of actions and objects. The comparison of STI and MTI #3 or #4 only evaluates whether users prefer the interaction with a mobile or a physical UI. The direct comparison of single- and multi-tag interaction for the very same purpose – the combination of actions and objects – is carried out between MTI #3 and #4 and shows that both interactions can perform equally well. These observations can lead to a refinement of the definition and the comparison of single- and multi-tag interactions.

5.4.2 *Attention Shifts*

The number of attention shifts for the five prototypes (Figure 10) again reflects the different complexities of the three tasks: information retrieval needed the least attention shifts, followed by sending an email and building an itinerary from four sights. Apart from the single attention shift across all tasks for STI, the results for MTI #2 are among the best for "Information" (m=2.1; sd=0.5), "Route" (m=4.1; sd=0.4) and "Email" (m=3.3; sd=0.7). The number of attention shifts for this UI configuration should be constant as well, because it only maps actions to the poster and keeps the rest of the interaction on the mobile device. However, the results are distorted by different errors, e.g. touching the "Route"-tag several times or trying to add information to the email by touching the "Information"-tag.

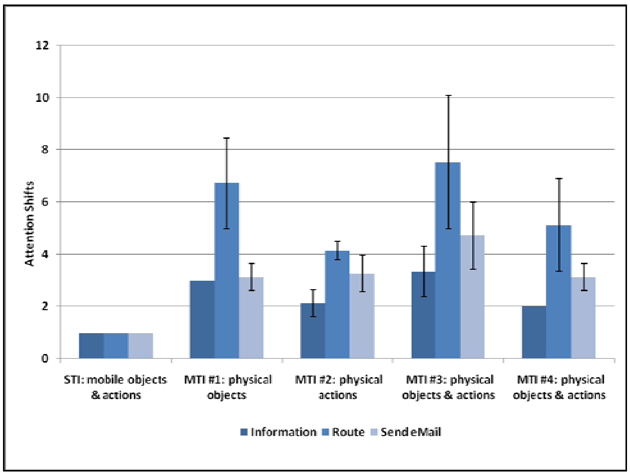

Figure 10. Attention shifts for the combination of items

Among the three UI configurations that map the selection of objects to the physical UI, MTI #3 needed the most attentions shifts for the different tasks, followed by MTI #1 and MTI #4 ("Information": m=3.3; sd=1.0 vs. m=3.0; sd=0.0 vs. m=2.0; sd=0.0; "Route": m=7.5; sd=2.6 vs. m=6.7; sd=1.7 vs. m=5.1; sd=1.8; "Email": m=4.7; sd=1.3 vs. m=3.1; sd=0.5 vs. m=3.1; sd=0.5). The constant numbers of attention shifts for information retrieval with MTI #1 and #4 result from the interaction with only a single tag. In many cases, the number of attention shifts could have been constant as well, but subjects made mistakes or looked at the mobile UI for feedback. It is also surprising that MTI #3 which maps actions and object to the physical UI performs even worse than MTI #1 which only maps objects to the poster.

The ANOVA shows that the values of the within-subjects effects were significant for all independent variables. The pairwise comparison with Bonferroni Correction of the ANOVA shows that the UI configuration had a signification effect in most cases. Changing between MTI #1 and MTI #3 as well as between MTI #2 and MTI #4 was not significant and did not have an influence on the number of attention shifts.

5.4.3 User Feedback

A final questionnaire asked the subjects to compare the different UI configurations of the five prototypes. The subjects preferred MTI #4 (6 votes) for carrying out the tasks, followed by MTI #3 (5), MTI #1 (3), STI (1) and MTI #2 (0). The subjects liked MTI #4 because it was fast and facilitated the selection of items, especially for the “Route”-task. MTI #3 was regarded as quick and easy to use and scored with the arbitrary order in which tags could be selected. Subjects who preferred MTI #1 liked the selection of actions from the mobile UI. Regarding the least appropriate UI configurations, ten subjects disliked MTI #2 because it was slow, cumbersome and unintuitive due to the unfamiliar selection of actions from the physical UI and the long list of objects on the mobile UI. Four subjects disliked STI because they had to carry out most of the interactions with the mobile device and its small screen and keypad. Three subjects disliked MTI #3 and #4 because of their high number of tags.

Eight subjects preferred to carry out the tasks on the poster because it was fast and easy to use, caused few attention shifts and reduced interactions with the keypad. Five subjects preferred a combination of tagged posters and mobile devices to accomplish the tasks as this approach allowed a more flexible design of the whole application. Only two subjects preferred the mobile device, because no knowledge about NFC was needed and because people did not have to share a poster to interact at the same time.

The questionnaire compared MTI #3 and #4 in more detail and asked the subjects whether they preferred separate tags for actions and objects (MTI #3) or individual action-tags for each object (MTI #4). Eight subjects preferred the latter design, because they had to touch fewer tags and did not have to remember an order of selection. This design was also considered to be faster and more clearly arranged. Seven subjects liked the separate tags for actions and objects better, although they had to combine them themselves. They preferred the step-by-step order of interaction which let them choose actions and objects freely. They also liked the smaller and thus less confusing number of tags.

Next, the subjects were asked whether they preferred to carry out the different steps of the interaction workflow on the physical UI, on the mobile UI or on both. Table 2 shows that the subjects were undecided about how to start the application, but preferred the mobile UI to close it. In line with previous results, the subjects preferred the physical UI for the selection of objects and the mobile UI for the selection of actions. However, they again preferred the physical UI for their combination. The subjects seemed to prefer one UI over the other depending on the kind of interaction they performed with it. Surprisingly, the subjects preferred to correct their interactions on the mobile device, opposite to the results for navigation and selection.

Table 2. Preferences for the interaction with actions and objects on mobile devices, tagged objects or both

Feature	Physical UI	Mobile UI	Both
Starting the application	6	5	4
Selection of objects	10	2	3
Selection of actions	4	8	3
Combination	8	3	4
Closing the application	2	11	2
Corrections	2	11	2

6. SUMMARY

In two studies, we showed that the physical interaction with multiple NFC-tags can facilitate mobile interactions regarding the navigation between different parts of a mobile application, the selection of items and their combination, with a few caveats.

UI configurations that map features for navigation and selection to either mobile or physical UIs often performed better regarding task execution times and attention shifts than hybrid UI configurations that split interactions between mobile devices and tagged objects. Interactions with multi-tagged physical UIs worked best for the selection of items and the accomplishment of more complex tasks, especially when the navigation was also mapped to the physical UI. In this case, the mobile device became less important and users could focus their attention on the physical UI, where they could arbitrarily interact with tags and only look at the mobile UI for casual feedback.

The feedback of the users confirmed the preference for multi-tag interactions with physical UIs which were seen as fast, intuitive and easy to use, causing the least attention shifts, providing a larger and more clearly arranged UI and allowing arbitrary interactions with tags instead of fixed navigation or tedious scrolling. The users preferred to carry out most parts of navigation and the selection of items on the physical UI, except for more critical actions, like submitting an order. In this case, the interaction with the mobile device seemed to provide more privacy and a greater feeling of being in control.

These results are complemented by the second study about the configuration of mobile and physical UIs for the combination of actions and objects. Again, the hybrid configurations that split these interactions between tagged objects and mobile devices often performed worse, along with the continuous interaction on the latter. Mapping objects to physical UIs may increase the number of attention shifts, but it allows users to carry out interactions faster than on the mobile UI. Similar to the previous results, the users benefitted from mapping as many features to the physical UI as possible. They could focus on the interaction with the tags and were less distracted by the mobile device, facing less attention shifts and spending less time on the whole interaction. The users preferred the UI configurations that mapped the most features to physical UIs, as the interaction with them was easy, fast and caused less attention shifts. Complementary, they disliked the UI configurations that mapped the combination of objects and actions to the mobile device. Regarding the allocation of interaction steps to mobile and physical UIs, the users preferred the mobile UI for the selection of actions and the physical UI for the selection of objects and their combination with actions.

7. CONCLUSION

This paper has investigated to which degree features or UI elements of mobile applications can be mapped to mobile and physical UIs, how they can complement each other and which aspects influence the preferences of the users. In the process, the comparison of different UI configurations for mobile interaction with tagged objects can lead to a comparison of STI and MTI in general. However, such a comparison can be contorted as these interactions are often used for specific purposes. Since this paper has focused on MTI and has investigated interactions that comply with it in the first place, the studies can only provide limited results regarding the direct comparison of STI and MTI for the same purpose. In fact, it can rather help to understand whether and under which circumstances users prefer STI, MTI, mobile or physical UIs for certain interactions.

Nevertheless, the second study showed how to use STI beyond physical hyperlinks and provided new arguments for refining the definition and the comparison of STI and MTI in general. So far, STI and MTI have been loosely categorized according to the number of tags on physical UIs and the way they support mobile applications by either reducing mobile interactions to a single tag or by mapping features of mobile applications to multiple tags. However, the second study showed that STI not necessarily depends on the number of tags on a physical UI and can also be carried out on physical UIs with multiple tags. Therefore, it seems reasonable to define STI and MTI not according to the number of tags on physical UIs, but according to the number of tags that are actually used to carry out and complete an interaction. Future work in this area will have to consider these aspects for more elaborate, direct comparisons of STI and MTI.

8. REFERENCES

[1] Broll, G., Keck, S., Holleis, P., and Butz, A. 2009. Improving the accessibility of NFC/RFID-based mobile interaction through learnability and guidance. In Proc. of MobileHCI´09. ACM, New York, NY, 1-10.

[2] Broll, G., Rukzio, E., Paolucci, M., Wagner, M., Schmidt, A., and Hussmann, H. 2009. Perci: Pervasive Service Interaction with the Internet of Things. IEEE Internet Computing 13, 6 (Nov. 2009), 74-81.

[3] Geven, A., Strassl, P., Ferro, B., Tscheligi, M., and Schwab, H. 2007. Experiencing real-world interaction: results from a NFC user experience field trial. In Proc. of MobileHCI '07, vol. 309. ACM, New York, NY, 234-237.

[4] Hardy, R. and Rukzio, E. 2008. Touch & interact: touch-based interaction of mobile phones with displays. In Proc. of MobileHCI '08. ACM, New York, NY, 245-254.

[5] Häikiö, J., Wallin, A., Isomursu, M., Ailisto, H., Matinmikko, T., and Huomo, T. 2007. Touch-based user interface for elderly users. In Proc. of MobileHCI '07, vol. 309. ACM, New York, NY, 289-296.

[6] Herting, T. and Broll, G. Acceptance and Usability of Physical Mobile Applications. MobileHCI 2008 workshop on Mobile Interaction with the Real World (MIRW 2008). Amsterdam, Netherlands. September 2008.

[7] Holleis, P., Otto, F., Hussmann, H., and Schmidt, A. 2007. Keystroke-level model for advanced mobile phone interaction. In Proc. of CHI '07. ACM, New York, NY, 1505-1514.

[8] ITU Internet Reports 2005: The Internet of things (ITU 2005 7th edition).

[9] Mäkelä, K., Belt, S., Greenblatt, D., and Häkkilä, J. 2007. Mobile interaction with visual and RFID tags: a field study on user perceptions. In Proc. of CHI '07. ACM, New York, NY, 991-994.

[10] NTT DOCOMO i-mode Felica, http://www.nttdocomo.co.jp/english/service/imode/make/content/felica/index.html

[11] O'Neill, E., Thompson, P., Garzonis, S., and Warr, A. 2007. Reach out and touch: Using nfc and 2d barcodes for service discovery and interaction with mobile devices. In Proc. of Pervasive'07, volume 4480 of Lecture Notes in Computer Science, 19-36. Springer, 2007.

[12] Oyster Card website: https://oyster.tfl.gov.uk/oyster/entry.do

[13] Reilly, D., Welsman-Dinelle, M., Bate, C., and Inkpen, K. 2005. Just point and click?: using handhelds to interact with paper maps. In Proc. of MobileHCI '05, vol. 111. ACM, 239-242.

[14] Rukzio, E., Broll, G., Leichtenstern, K., and Schmidt, A. Mobile Interaction with the Real World: An Evaluation and Comparison of Physical Mobile Interaction Techniques. In Proc. of AmI´07, Darmstadt, Germany. 7-10 Nov, 2007.

[15] Sánchez, I., Riekki, J., and Pyykknen, M. 2008. Touch & control: Interacting with services by touching RFID tags. In Proc. of IWRT 08, June 12-13 2008.

[16] Schwieren, J. and Vossen, G. 2007. Implementing Physical Hyperlinks for Mobile Applications Using RFID Tags. In Proc. of IDEAS`07. IEEE Computer Society, Washington, DC, 154-162.

[17] Seewoonauth, K., Rukzio, E., Hardy, R., and Holleis, P. 2009. Touch & connect and touch & select: interacting with a computer by touching it with a mobile phone. In Proc. of MobileHCI '09. ACM, New York, NY, 1-9.

[18] SmartTouch website. www.smarttouch.org

[19] Want, R., Fishkin, K. P., Gujar, A., and Harrison, B. L. 1999. Bridging physical and virtual worlds with electronic tags. In Proc. of CHI '99. ACM, New York, NY, 370-377.

[20] Want, R. 2006. An Introduction to RFID Technology. IEEE Pervasive Computing 5, 1 (Jan. 2006), 25.