Mediated Tabletop Interaction in the Biology Lab Exploring the Design Space of The Rabbit

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ABSTRACT
Interactive surfaces like diffuse illumination tabletops (DIT) identify and track objects using multiple techniques like shape and color recognition, fiducial markers, electronic components, and RFID tags. However, tracking becomes more complex when dealing with multiple small objects of similar form. We propose to use tangible mediators for integrating such objects to tabletops. This paper reports on our initial explorations of *mediated tabletop interaction* consisting of a mediator prototype and a design space definition. We built a mediator, the *Rabbit*, a device that translates the value of an RFID tag into a visual 2D code. The *Rabbit* rests on the interactive surface, holds the object, reads its passive RFID tag, and converts the read value into a 2D code that can be read by the DIT's built-in camera. When handling multiple objects, the Rabbit iterates through the generated 2D codes. Through a series of participatory activities with end users (molecular biologists), we collected initial feedback from participants and defined a design space for mediated tabletop interaction.

Author Keywords
Mediated Tabletop Interaction, The Rabbit, Tabletop, Tangible, Interactive Surfaces, RFID

ACM Classification Keywords
H.5.2 Information Interfaces and Presentation: User Interfaces: Input Devices and Strategies, Interaction Styles

General Terms
Design, Human Factors

INTRODUCTION
One of the interesting features of interactive surfaces is the merging of input and output into a single space. This dual-space allows designers to go beyond simple touch interactions, to integrate physical objects as interactive tools on the surface; either to augment objects with digital information and/or use objects as a controllers of the digital system. To achieve this level of integration, objects have to be identifiable by the system, for which several techniques have been proposed: shape and color recognition, RFID tags, active electronic components, and fiducial markers.

By working with tabletops in a biology laboratory setting, we uncovered several unexpected constrains for deploying interactive surfaces. Besides supporting extreme usage conditions like radioactivity, designing with reduced UI space and pervasive clutter on the surface, a difficult problem that we faced was the tracking of small objects. Small objects like test tubes are at the core of laboratory work: they do not only contain physical substances, but are now often related to digital information. When biologists order samples from a commercial supplier they also receive spreadsheets describing what they ordered and links to detailed descriptions of the materials. Therefore, integrating test tubes with an interactive laboratory bench could bring to the biology lab some of the benefits the Ubicomp community has explored elsewhere like, for example, better support for the processes of information access and situated data capture. However, test tubes and interactive surfaces cannot be integrated by using existing techniques, because tubes are both too small for attaching fiducial markers to them, too similar and numerous for shape and color recognition, and too expendable for adding active electronic components. These constrains are not unique to biology labs and can also be found elsewhere, e.g. the electronics world where components are also small and have PDF documents or web pages describing them.

In this paper we explore an alternative for integrating everyday objects and tabletops called *mediated tabletop interaction*. In this approach a *mediator* is used to convert the object's tag ID into one that the tabletop can read and use to determine its location and orientation (figure 1). Mediated tabletop interaction derives from our observations that in many cases users engage with small objects through a holder object. Thus, we seek to instrument the holder with communication capabilities in order to enable its integration with the tabletop. In this paper we make three contributions: (1) introduce the notion of mediated tabletop interaction, (2) present a first mediator prototype implementation called the 'Rabbit', and (3) present a collectively defined design space

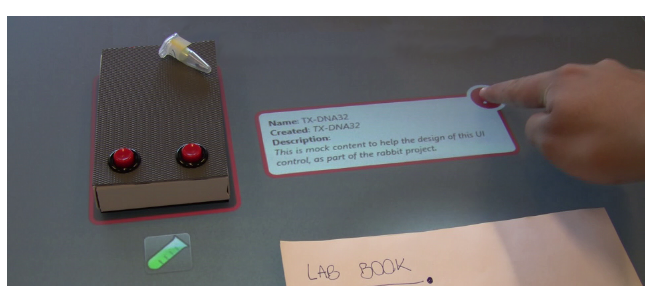

Figure 1. The Rabbit is a *mediator* prototype for integrating small RFID-tagged objects and tabletops.

for mediated tabletop interaction in the biology lab. The paper ends with a discussion on the implications of mediated tabletop interaction, and the conclusions.

RELATED WORK

For integrating physical objects and interactive surfaces (identification and tracking) researchers have looked into different techniques using static means, active means, and RFID tags.

Tracking solutions through static means

Static means relate to the use of physical properties, or passive and un-powered components of objects to determine their identity, location and orientation on an interactive surface. Seminal work in this direction was the DigitalDesk [16] and the metaDESK [13], introducing shape and color recognition for the tracking and augmenting of physical objects. These systems are camera based, and through computer vision algorithms detect physical properties like the color and the 2D contour of the object, which can be used to query a repository in order to determine the object's identity.

Other projects have added special passive components to the objects to aid their recognition. The SenseTable [7] uses electromagnetic pucks to communicate the presence and identity of an object to the interactive surface. Other projects attach fiducial markers to the objects, so they can be recognized with a bottom or overhead camera. A more detailed account of camera-based recognition and tracking techniques can be found in Moeslund et al. [5].

Tracking solutions through active means

Active means relate to the use of dynamic mechanisms in the objects, physical or electronic, that help the interactive surface track them, or that execute the tracking themselves. The SurfaceWare uses a drinking glass with a built-in prism to determine when a refill should be offered [2]. The PhotoelasticTouch uses the elastic properties of transparent materials to enhance touch interaction [11]. Using both static markers and the elastic properties of transparent materials, the SLAP widgets provide controls (keyboard, check box, slider, etc) to interact with the interactive surface [15]. The Madgets maintain the haptic properties of the SLAP widgets and add magnets to them, so that together with an array of electromagnets behind the screen, they become actuators that can change state and even move on the surface [14].

More complex interactions are achieved via electronic active means. For example, the Anoto[1] and Anoto-based projects [3] use a reference grid and a built-in camera into the object, to determine its position on the interactive surface. The QualiTrack system combines IR capable pens with a synchronized IR camera-emitter system to query the ID of the pens [4]. The BlueTable combines BlueTooth and IR light of a cellphone, to enhance the handshaking when establishing a connection between the interactive surface and the phone [17]. In this way the table can match the cellphone's BlueTooth ID with the detected shape on the table. A more comprehensive account of active means and interactive surfaces can be found in Dietz and Eidelson [2].

[1] http://www.anoto.com – Anoto Pen.

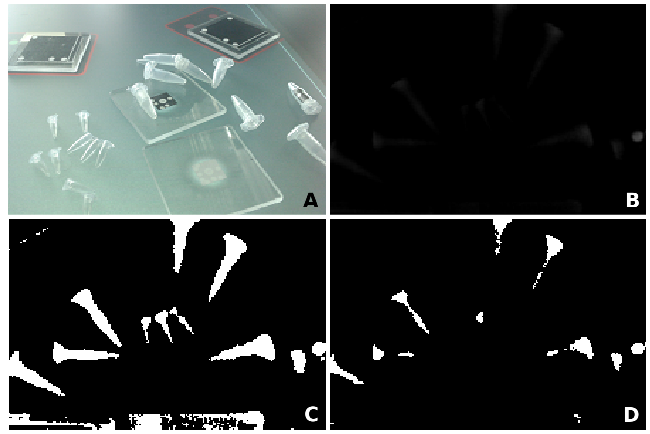

Figure 2. (A) Small objects like test tubes are too small to hold a fiducial marker that can uniquely identify them, and still be readable by the camera. (B) Their reflection in IR light is very poor, and even with a threshold value of (C) 1 and (D) 20, test tubes are indistinguishable by means of shape and color.

Tracking solutions through RFID technology

Radio-frequency identification (RFID) uses radio waves to exchange data between a reader and an electronic tag attached to an object with the purposes of identifying and tracking. RFID-based solutions use the tag's ID, signal strength, and optionally, computer vision to determine the identity, location, and orientation of objects on an interactive surface. The Marked-up Maps project uses RFID tags to mark places of interest in a map, so users can access the information with a hand held RFID reader [9]. The interaction thus takes place in the handheld device and the interactive surface simply acts as an input mechanism. The ePro Board [12] and DataTiles [10] projects use a matrix of readers behind the interactive surface. Objects are tagged with RFID tags, and can then be brought on to the table. However, these configurations of readers cannot determine the objects' orientation.

SurfaceFusion combines activity detection in the RFID and computer vision domains, to establish the identity of the shapes in the scene [6]. SurfaceFusion introduces *Frame Difference Algebra* (FDA) to provide robust and fast detection of objects under the constrain that only one object is manipulated at the time. A more comprehensive account of RF and RFID-based approaches and their integration with interactive surfaces can be found in Olwal and Wilson [6].

Small Objects and Tabletops

Current approaches to object tracking for tabletops do not provide efficient means to identify small objects. For instance, objects like test tubes are too small to carry any static identification like fiducial markers. Figure 2 shows how current vision-based approaches to object tracking in tabletops behave with small indistinguishable objects. Color and shape recognition are not viable, as the tubes' reflection of infra-red light is very poor, and their visual footprints are equal (figure 2B-D). Using active means of identification, like powered electronic components, are too expensive for the mundane and expandable test tubes used in a laboratory environment. Existing RFID-based techniques could be used to identify the objects, but they do not allow for precise location and orientation tracking on the interactive surface. Moreover, the integration small objects with tabletop interaction could extend the reach of applications to new areas. In the biology lab, where biologists work with test tubes, tabletop applications could provide advanced tracking during and after experiments.

MEDIATED TABLETOP INTERACTION

Figure 3 illustrates our proposed notion of *mediated tabletop interaction*, as a way to support tabletop interaction with small objects. The main components of mediated tabletop interaction are *object tags* and the *mediator*. Small objects should be tagged with unique identifiers, in a way that their physical appearance is not radically altered. The mediator acts as a bridge between the physical tag and the tabletop; it can be seen as a conversion mechanism between an object-friendly tagging technology and a technology the tabletop can read. Moreover, the mediator conveys information about the location and orientation of the physical object on the tabletop. With this dataset (location, orientation, and tag value) the tabletop interaction can occur. Optionally, the mediator can communicate information regarding its own state (like battery levels), or user interaction with it (like button pressings).

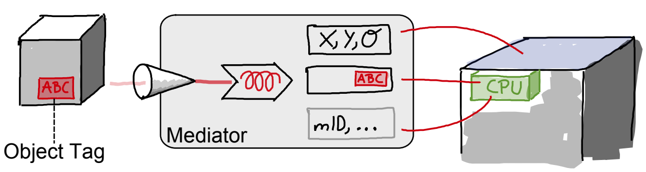

Figure 3. Mediated Tabletop Interaction: The integration between and object and the tabletop is aided by a *mediator*. The mediator reads the object's tag, and interacts with the tabletop to convey location, orientation, the tag value, and optionally, data specific to the mediator.

RESEARCH APPROACH

The goal of our research is to explore both the technical implementation as well as the design implications of *mediated tabletop interactions*. For this purpose, we have engaged in a three-phase research approach. In the first phase, we engaged in an open-ended participatory design process, investigating the need for biologist to integrate physical and digital information while working at the laboratory workbench. In this phase, a series of observations, interviews, and prototyping sessions were conducted. This lead to the design of an artifact for mediating between physical objects – like test tubes – and interactive surfaces – like a future electronic lab bench – as described above.

In the second phase, we did a prototype proof-of-concept implementation of the mediator designed in phase one. This implementation – called *The Rabbit* – is further described below. The aim of this implementation is to prove that such a mediator between physical objects and an interactive surface can actually be implemented in a technical sound manner.

In the third phase, we returned to the explorative participatory design process. In this phase we wanted to explore the design space of mediated tabletop interaction. Our goal was to explore how such a technology could be used in everyday work in a biology laboratory. Therefore, rather than performing a focused usability evaluation of the technical prototype developed in phase two, we decided to deploy mediator design probes in a real biology environment. These probes were not Rabbits, but simple mock-ups. This approach was necessary because the interactive surfaces on which the Rabbit is dependent to run on top of are simply not available in the laboratories yet. This research approach enabled us to map the design space of this kind of technology in much greater details for others to consider in the design of mediators for other application areas.

THE RABBIT

Figure 4 shows *The Rabbit*[2], a mediator device that dynamically converts the value of an object's RFID tag into a 2D code that can be identified and tracked by an interactive surface. The rabbit aims to support objects that cannot be normally augmented on interactive surfaces, because they are very small, yet can hold a passive RFID tag. The key components of the rabbit are an RFID reader and the 2D code display. The rabbit allows the application to present the user with digital information related to the object, and to locate the information according the its location and orientation on the interactive surface.

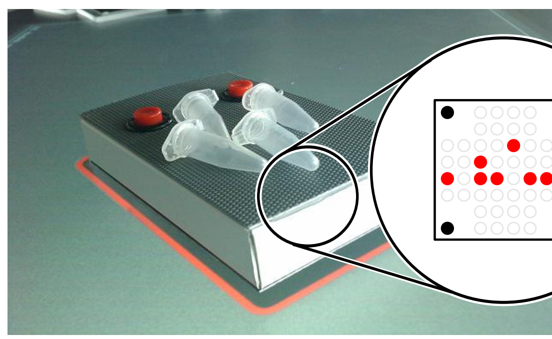

Figure 4. The rabbit is a device that dynamically conveys the value of an object's RFID tag, its location and orientation to tabletop.

The call-out in Figure 4 illustrates the structure of the 2D code: it's called the *SquareCode*. Similar to other fiducial markers, the SquareCode encodes a value, and its static regions (the three black-dots at square angles) help determine its location and orientation. We created the SquareCode as a new kind of fiducial marker that we could generate dynamically with common electronic components (IR LEDs). Figure 5A shows an RFID-tagged object (●:●) approaching the rabbit, the RFID tag is read, and the corresponding 2D code is shown toward the interactive surface. Figure 5B shows a capture of how the SquareCode is seen and recognized by the interactive surface. In addition, as a rabbit can hold multiple RFID-tagged objects, the *SquareCode* provides means to iterate through multiple codes. When an object is no longer sensed within the antenna range, the rabbit removes its code from memory and no longer communicates it to the table. The RFID-tags can be read by one single antenna (with anti-collision support) or by multiple fine-grained antennas. The number of objects that can be tracked is only limited by the RFID reader used and the antenna configuration. Moreover,

[2]*The Rabbit* is the internal code-name for the project seen as the tabletop equivalent to the desktop's *mouse*.

in contrast to the Audiopad [8] and others, the rabbit uses off-the-shelf unmodified passive RFID tags.

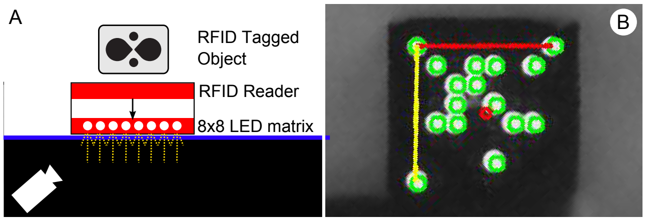

Figure 5. (A) The rabbit translates an RFID code into a SquareCode and displays it to the DIT via infrared LEDs. (B) The DIT reads the code and determines its value, location and orientation.

Another key characteristic of the rabbit is that it can be brought off-the-table to read RFID tags of objects that cannot be brought onto it. The rabbit reads the tag, stores the read code in memory, and communicates it to the tabletop once it is brought back onto the surface. In this kind of rabbit the code remains in the rabbit's memory until it's overwritten by a new code. Also, the rabbit itself uses the interactive surface to communicate issues of its own functioning like low battery levels.

Implementation

The rabbit was built with an *Arduino Pro Mini*, an *Innovation's ID-12* RFID reader, a serial backpack from Sparkfun for LED matrices, a custom IR LED matrix at 850nm (shown in Figure 6), and two buttons. We used standard Eppendorf test tubes with 125kHz RFID glass capsules. The tabletop was a Microsoft Surface, with an API in C# using the Open Computer Vision Toolkit *OpenCV*. The LED matrix encodes values according to the SquareCode, as shown in Figure 7.

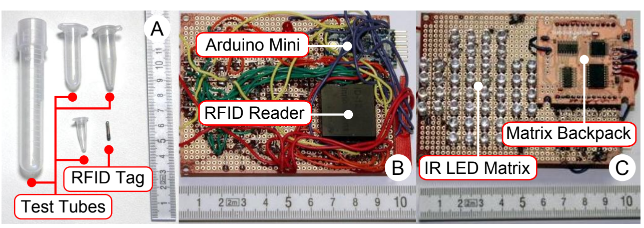

Figure 6. (A) Test tubes, and the 125kHz RFID Glass Capsule. (B) Top-view of the rabbit showing RFID readers and Arduino Mini Pro. (C) Bottom-view of the rabbit showing the serial backpack from Sparkfun, and infra-red LED matrix.

In the current implementation, each test tube is tagged with an RFID glass capsule. The rabbit, normally resting on the Microsoft Surface, continuously reads for nearby RFID tags. When a test tube comes within reading range of the RFID reader (1cm approximately), its RFID identification and checksum are acquired by the reader and transmitted to the Arduino board. The Arduino processor checks the validity of the read identification against the checksum and, if valid, generates a corresponding SquareCode to display through the custom IR LED matrix. The SquareCode also contains information about the state of the buttons (pressed, released). As the IR LED matrix faces down toward the Microsoft Surface, the projected SquareCode can be captured by the surface's infrared camera system.

On the application side, a rabbit-enabled application registers a series of listeners to the provided API (*RabbitObjectEntered*, *RabbitObjectLeft*, *RabbitButtonPressed*, *RabbitButtonReleased*). To trigger these events the API maintains a list of object codes associated with each rabbit. Every captured input image is handed over to the surface application, and from there to our API which processes the image looking for SquareCodes. Then, the API notifies the application about object and button-related events. The object-related events, contain location, orientation, and an object code corresponding the RFID identification of the test tube. Application developers can use this object code to fetch data from local or remote repositories and update the user interface correspondingly.

The LED matrix approach taken for this implementation is not the only possible one, and presents problems when the amount of data to transmit is greater than the capacity of the SquareCode. We considered alternatives to build rabbits; for example using static fiducial markers and BlueTooth to communicate the value of the RFID codes. However, this approach also has several disadvantages compared to the technologies we chose. First, using static markers and BlueTooth requires pairing between the table and the device. Second, wireless connections present interference problems when using multiple rabbits. Third, the static markers and the BlueTooth data are transmitted over different channels, requiring handling of channel fusion (image + wireless).

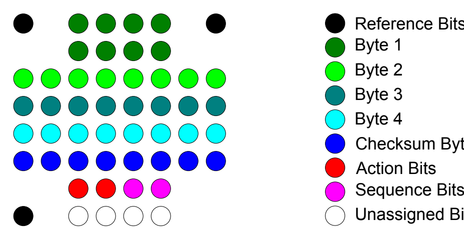

Figure 7. The *SquareCode* contains a 4 byte code value, 1 byte for checksum, 2 action bits for button events, 2 sequencing bits, and 4 unassigned bits.

TECHNOLOGY EXPLORATION

Designing mediators between physical objects and tabletops opens up a whole new design space for bringing surface computing to places like the biology laboratory. In this section we present the user-centered exploration of this new design space involving a group of biologists using 'Rabbit' technology probes in their own biology lab while doing real experiments. This exploration happened in the context of a project with the same biologists devising the design of interactive laboratory benches. Based on this exploration we defined a set of design dimensions along which these tabletop mediators can be designed.

Process

The user-centered design exploration aimed at uncovering factors involved in the application of mediators in a biology laboratory context. In order to introduce the rabbit and tabletop technologies to the biologists, we carried out one participatory design workshop and one focus group. After gathering feedback on our initial designs, we gave a set of *mock* mediator probes to the biologists for them to use during their laboratory work.

Workshops: 6 participants were involved in an early participatory workshop on digital laboratory benches and 12 participants took part in a focus group (8 PhD students and 4 post-docs). All were experienced in laboratory work, and were familiar with digital technologies. In the first workshop, participants created videos whose ideas we used to create video prototypes of possible usages of mediators.

Our video prototypes presented two mediators: the *augmented rack* and the *mobile* mediator. The *augmented rack* is a 4x5 test tubes rack-shaped mediator that can be used as a normal rack and integrates to the interactive surface to support biologists on their interactions with test tubes. The *mobile* mediator reads the RFID code attached to shared laboratory machines allowing biologists to virtually “bring” the machines to the tabletop and access their related digital information. We discussed our videos with the focus group, and invited people to participate in a probe activity.

Probes: In order to have more naturalistic data on how people could use such mediators we gave mock devices (a mock augmented rack and a mock mobile mediator as shown in figure 8) and a disposable film camera to 6 . The devices did not have any electronic components or other functionalities, and were to be used over their existing lab benches. Their physical appearence, however, imitated the rabbit designs we presented in the video prototypes. We asked participants to take pictures during the course of their work, if they had any idea on how to use mediators on a digital bench. The purpose of the mock devices was to inspire and provoke the biologists to come up with ideas in the middle of their daily lab work. Participants received movie tickets for their participation and we asked them to return the cameras within 3 weeks.

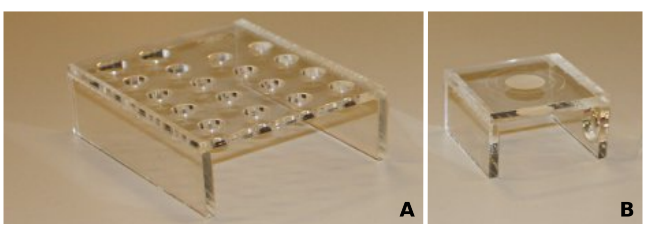

Figure 8. Probes handed to participants A) A rack mediator, shaped as a rack for test tubes. B) A mobile mediator, shaped as a small RFID reader.

Analysis method: Two participants never returned the camera. Overall participants took 35 pictures (avg: 8.7, max: 16, min: 4), out of which 32 had a good enough quality (illumination, focus, etc). To interpret the pictures, we followed a process inspired by grounded theory coding. We attached tags describing the salient characteristics of every picture. For example, the first picture had the following tags: *rabbit in picture*, *multiple racks*, *marked tubes*, *15+ tubes*, *small tubes*, *big tubes*, *rack with lid*, *live zone*, *rack case*, *storage*, and *rabbit label*. After finishing tagging, we listed the tags and grouped them by topic. Each picture was processed again in order to add missing tags. We created a tag matrix and counted the occurrences of each picture tag. Table 1 shows the 44 tags and 5 categories created during the coding.

Category	Tags
Support Info	physical protocol (6), notebook (3), scrap paper (8), documents (10), digital protocol (2), digital work-flow (1), digital document (3)
Interactive UI	experiment interface (4), sample interface (1), grid like interface (1), text access (10), data analysis (1), linking (3)
Usage Conditions	rack (22), mobile mediator (5), rack empty (3), rack on ice (4), multiple racks (11), mixing (5), marked tubes (23), note-taking (7), 15+ tubes (9)
Tools	small tubes (22), big tubes (5), rack with lid (7), gloves (5), ice box (5), flasks (7), burner (2), machine (14)
Bench	live area (20), lab bench (13), machines bench (8), hazardous bench (1), office bench (3), spacious (10), non-spacious (14)
Storage	rack case (1), storage (3), desk storage (13), freezer (3), rabbit label (13)

Table 1. Tags used to classify the pictures collected (and the number of appearances), and the categories in which they are grouped.

DESIGN DIMENSIONS

Based on our discussions with participants and the categories and tags of the probe activity, we define a series of design dimensions along which mediated tabletop interaction can vary, and which we group in three main themes: (i) mediator design, (ii) object+mediator+surface integration, (iii) and integration with other devices.

Mediator Design

These dimensions present the different ways in which the mediator in itself can be designed. Its form will depend on the content it mediates, or how appropriate a physical shape is for the task at hand.

Capacity

This first dimension refers to objects that are mediated simultaneously. Figure 9 shows the three values for this dimension: *Single* means only one object is mediated at a time. *Bag-like* means that many objects are mediated at once, but without order, and physical location inside the mediator. *Batches* means that multiple objects are mediated simultaneously, with information about the order in which they are read, and their location within the mediator.

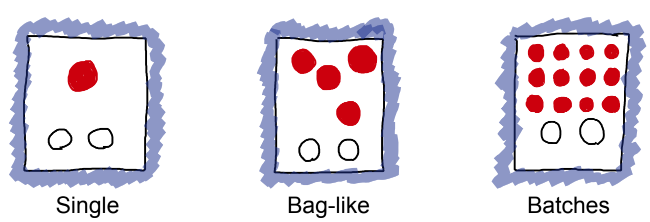

Figure 9. Capacity dimension. A *single* mediator. A *bag-like* mediator. A *batched* mediator.

Figure 10 was taken during the probe-phase and shows a biologist with two racks, each containing two lines of 10 tubes. In this case the location of each tube within the rack is important, as their physical location impacts that way tubes relate to each other. As one biologist explained: *You can divide the tubes between archive, primers, and the ones you use to mix.* The different groups of tubes are located in specific parts of the rack for easier handling. Thus, it is meaningful for biologists to keep track of the tubes and their locations.

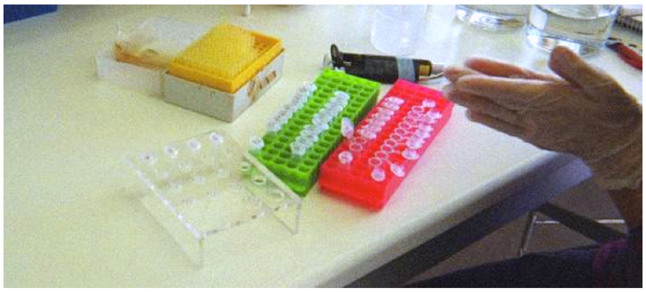

Figure 10. Batches of test tubes in the rack. Biologists organize the tubes inside the rack according to the different conditions they are experimentally testing. In the picture, each line contains a different component, and each tube a different concentration of it.

Embeddedness

This dimension describes the level of replacement of an existing object intended with a specific mediator. This is a continuous value with extremes on *new element* and *replacement*, as shown in figure 11. When a rabbit-like device is a completely new element, alien to the existing uses, users have to incorporate it into their routines. In such situations designers can leverage the mediator to introduce users to new practices. At the other extreme is replacement, which happens when the rabbit is designed to augment an existing object, adding to it the ability to integrate with the interactive surface. Adoption is easier as the object is already part of the work practice. Designers should determine existing practices/objects upon which to build in order facilitate adoption while leaving room for innovation and possibly new activities.

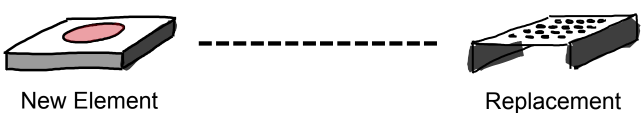

Figure 11. Embeddedness dimension. A new element is completely novel to the users. A replacement element augments an existing tool.

In our technology exploration we saw instances of both extremes. Our proposed idea of augmenting a test tubes rack was well received, with biologists suggesting multiple ways in which the information could be displayed, stored, and related. The fact that integration between the tabletop and the test tubes is through a familiar object increased the biologists interest as they didn't have to adopt yet another technology for their already overloaded space. Moreover, the idea of the *mobile mediator* also received attention, with discussions about new forms of interactions with the existing physical infrastructures in the lab. For instance, a biologist suggested the mobile mediator could be used to move information between lab machines, the tabletop, and his personal computer, as illustrated in figure 20C.

Form Factor

This dimension describes the variety of mediator forms to be supported by the interactive surface (see figure 12). The simplest of cases is for the interactive surface to support mediators with a single physical shape. However, designers might find the need to support objects of different sizes on their interactive surface applications, and therefore building mediators with different physical forms.

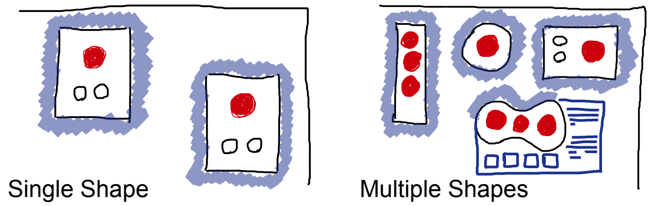

Figure 12. Form factor dimension. It describes the multiplicity of mediator shapes that the interactive surface application needs to handle.

Support for multiple shapes has been discussed by authors like Baudisch et al. [1]. In our specific case, we could observe it with test tubes of different sizes and therefore different racks biologists work with. For example, participants captured the diversity of tubes in figure 13, and the diversity of racks can be seen in figures 15A and 10.

Figure 13. An interactive surface application should support mediators of different forms, as they should hold objects of different sizes. The picture shows small size tubes together with bigger ones. Both sizes are normally used in the execution of experiments.

Object+Mediator+Surface Integration

These dimensions present the different ways in which the mediation between tagged-objects and the surface can take place; the mediated objects can be the reference point of the interaction or just additional data to a central digital object. A mediator can also link objects to digital data in different ways, from manual input to embedded sensors.

Reference

This dimension refers to the way that physical objects and digital information are related and the prevalence between them. Figure 14 shows the two values of this dimension: *physical reference* and *digital reference*. Designing for a physical reference, the physical object acts as a container or indexer for the digital data; a common approach in tangible interaction with tabletops. Designing for a digital reference, physical objects are indexed around a digital document.

In our design space exploration we encountered situations where the physical object is one of many resources related

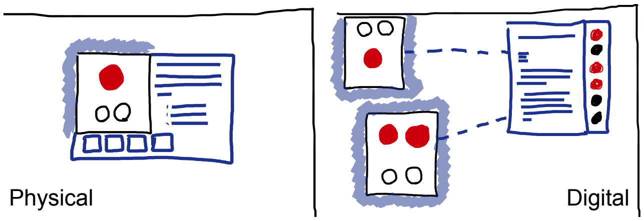

Figure 14. Reference dimension. With *physical* reference, digital information is attached to the physical object. With *digital* reference, physical objects and other digital data are attached to the digital document.

to a master digital object (corresponding to the *digital* reference). Figure 15A shows a biologist relating multiple tubes to a single protocol in his notebook. This relation is later migrated to a digital protocol, and it is this digital protocol which they would refer to when they want to know about the contents of a tube. Figure 15B shows another instance of a digital reference. The image presents a sketch (created by a participant in the probe-phase) representing the protocol as a work-flow showing how each tube was used in the flow.

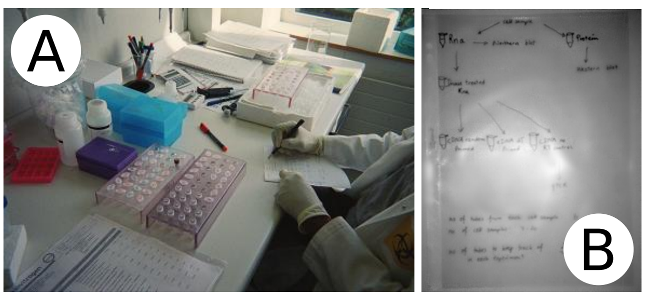

Figure 15. Reference dimension. A) Biologist keeping track of multiple tubes related to a single experiment. B) UI sketch made by a participant of a experiment work-flow interface, with multiple tubes coming into play at different moments.

Finally, the following quote from the focus group shows how associating several physical objects (test tubes) around a digital one (an agarose gel image) can ease the analysis of information later on:

> *"We normally work with 10 to 20 tubes, and they are all on one [DNA] gel [image]. So, in that way it doesn't make sense to track each small tube. It's the gel that's the focus point now... So, sort of that you click on a band on the gel and you see the tube, and what happened to the tube in history."*

Information Source

This dimension describes the ways in which information is associated to the *reference object* (previous dimension). Figure 16 shows the four association methods: *manual input*, *data integration*, *object integration*, and *contextual*. Manual input requires the user to type in the relevant information. Data integration makes use of existing digital information that a user could simply drag-and-drop. This information can be as simple as document or images files, or more elaborated like database queries using the object code. Object integration creates links between the objects being used simultaneously on the interactive surface. Contextual input adds environmental or situational information to the objects.

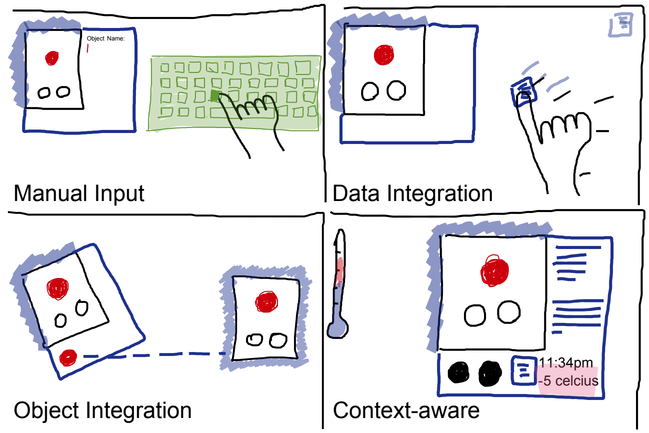

Figure 16. Information source dimension. The figure shows the different sources of digital information for a given physical object.

A biologist could use manual input to type the name and exact ingredients used for a given test tube. Manual input is not rare for biologists, as shown in figure 15A they keep notes on scrap paper and in their paper notebook. However, data integration could have a greater impact given that biologists increasingly use digital data; for example:

> *"It would also be cool if the kits [sets of tubes ordered from suppliers] had this RFID as an optional service. The suppliers generally give a [paper] spreadsheet with the tubes contents and their labels, and a excel file indexing the contents of each tube."*

A interactive surface application could leverage this information and extract the digital information using the RFID code on a given document.

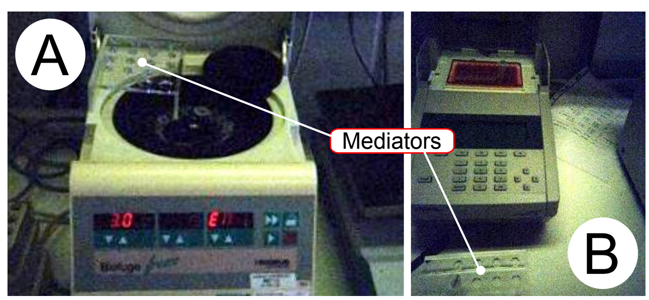

Figure 17. Molecular biologists use plenty of machines for executing their experiments. This machines normally sit on the same benches and most are electronic and programmable. A) shows a centrifuge, and B) shows an UV spectrometer, both are used in most of the experiments.

The picture taking activity documented several instances of object integration. For example figures 15A and 10 show how a tube is used in conjunction with other tubes, and even other racks. Moreover, object integration could also be implemented with other objects that also sit on the interactive surface. Figure 17A and B show different electronic instruments used by the biologists in their work. An interactive surface could integrate with such instruments and collect information from them like the parameters of their execution. Similarly to object integration, the interactive surface could collect contextual information relevant for an experiment like e.g. temperature by integrating to a thermometer.

Output Space

This dimension describes the amount of physical space that is expected to be normally available on the tabletop surface, i.e. space that is not covered by physical objects. Figure 18 shows the two possible values: *spacious* and *non-spacious*. We call it spacious when there are few objects and the designer can expect considerable UI space around them. Moreover, objects on the surface are part of the interaction, and are taken away at the end. In this situation the main purpose of the interactive surface is user interaction. Designers can expect users will reorganize the space so to make room for the UI. We call it non-spacious when there are many objects on the surface, little space between them, and objects remain on the surface for extended periods of time, or even permanently. In this situation the main purpose of the interactive surface is the interaction of the user with the objects; the objects take the central role on the surface. Designers can expect users will not be willing to change the organization of physical objects, and thus the UI has to adjust to the limited space available.

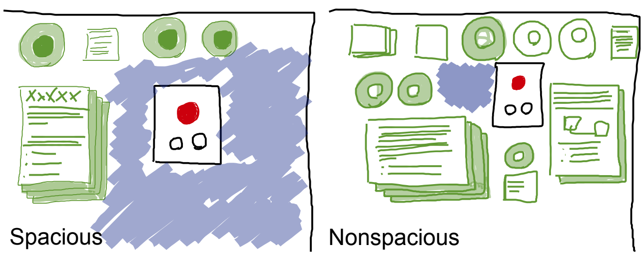

Figure 18. Output space dimension. This figure shows different space availabilities in actual workbenches, influencing the UI design.

The video material we produced for the focus group assumed the interactive surface to be spacious. However, analysis of the participants pictures showed us that laboratory benches are very crowded places. Figure 15A and 10 illustrate this situation. Besides containing tubes racks and bottles used for the current experiment, laboratory benches serve as temporary storage for bottles, new tubes, trashcans, etc. Moreover, often machines are permanently stationed on the benches.

Integration with Other Devices

These dimensions present the different ways in which mediators fit in a larger ecology of devices, covering the artefacts which a mediator can connect to, and also how one mediator can be used alongside others, or shared among many surfaces.

Ecology

This dimension considers the types of objects a mediator interacts with. Figure 19 shows the types we identified in our design space exploration, that, however tied to the domain we studied, we believe are valid for other domains. The types are: *interactive surfaces*, *storage*, *work-specific* machines, and *personal computers*. The general case is a workbench that is enhanced as an interactive surface. In this case the user will be able to access and interact with digital information related to an object. Storage relates to the object or place where the mediator rests while it is not being used on the interactive surface. Work machines relates to specialized machines with electronic properties to which a mediator could integrate to (as shown in *information source* → *object integration*). Finally, the user could also use his personal computer to access digital data related to an object. In this case the mediator allows the user to access content by connecting to his laptop via, for example, a USB connection.

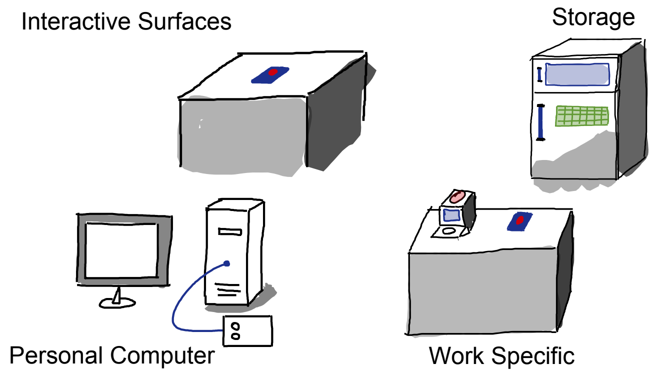

Figure 19. The ecology dimension. It refers to the types of objects which a mediator interacts with including interactive surfaces, storage places or machines, work specific machines, and personal computers.

Several cases of the ecology of devices where explicit in our exploration activities. Figure 20 shows some of the participants' pictures describing the ecology of devices. Picture 20A shows a mediator rack being stored inside a freezer. Storing test tubes racks in the freezer is a normal practice, and a mediator rack should support it. Picture 20B shows the integration with other machines in the bench. And picture 20C shows a participant pointing the mobile mediator against his laptop computer, as a way to tell us through the picture that the rabbit should integrate with it [3].

The use of a mediator in tandem with other devices opens up a new space for design. For example participants valued the possibility of querying a system to know the current storage location of test tubes that were produced in an experiment months before. One participant pointed out that a mobile mediator could help him managing the shared resources:

> *...one could integrate a machine as a resource into a project [experiment]. So you could say: ok, I use this type of scanner a lot in this project... and then you go to your computer or table and ask: when is this type of machine or scanner booked? And then the system [would] know exactly which one it is, because you scanned one but not the other one. Instead of having to remember a code like i7536VV.*

Surface Coupling

This dimension describes the degree in which a mediator is coupled to a particular interactive surface. Figure 21 shows the possible values: *single surface*, or *shared*. A single surface mediator is tightly coupled to the surface in which it is

[3] The picture is not intended to mean the laptop should read the code from the LED screen, but rather that the mobile mediator could serve as an information link between different devices.

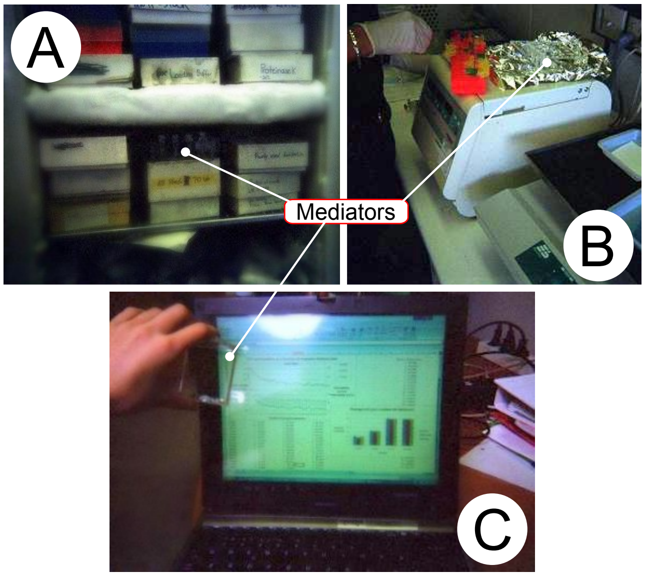

Figure 20. A test tubes rack mediator would have to interact with an ecology of devices. A) The mediator being put to store in a local freezer. B) The mediator on top of a centrifuge. C) A mobile mediator being used to access information from a laptop computer.

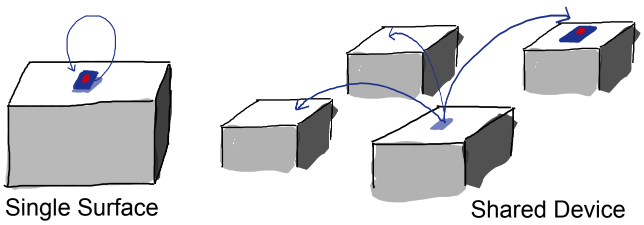

Figure 21. Surface coupling dimension. It describes whether a mediator is expected to be used on a single or multiple interactive surface.

normally used. Tight coupling can be given due to physical connections to the surface, or complicated pairing procedures (like required by BlueTooth). A shared mediator is loosely coupled to the surface in which it is normally used. Loose coupling allows for a mediator to quickly move from one surface to another without any set-up required.

Literature on interactive surfaces often focuses on single surface installations, where coupling is not an issue. However, our technology exploration showed that loose coupling might be necessary for some situations like a biology laboratory. A laboratory is made of multiple workbenches, with some assigned to particular researchers and some shared. Multiple resources including the racks are shared between all the researchers. Thus, a rack can be used by several different researchers during the course of a day. Moreover, a single scientist can move from his personal bench to the shared benches and back within the course of a single experiment. Thus, a mediator rack should support the seamless movement from one bench to the other.

DISCUSSION

Mediated tabletop interaction is our proposal to support tabletop interaction with objects not previously supported (small and big). This notion expands previous research on tangible interaction on tabletops, and opens up for new areas of exploration along the main themes of our design space definition: (i) mediator design, (ii) object+mediator+surface integration, (iii) and integration with other devices.

First, the mediator-related dimensions of *capacity*, *embeddedness* and *form factor* should lead the designer to consider different hardware technologies for building a mediator, and to balance the limitations of the chosen technologies. A highly embedded mediator (i.e. a faithful replacement of an existing holder object), requires the use of small electronics and unobtrusive tagging technologies to support multiple objects in a pre-defined form factor. While a less embedded mediator could let designers explore new form factors or other types of tagging and communication components that, while cheaper, could be bigger and obtrusive.

Second, the set of dimensions related to the object+mediator+surface integration, *reference*, *information source*, and *output space*, should lead the designer to consider the software aspects of the solution. All dimensions bring up interesting questions: does each physical object act as a bag of resources or rather like a resource attached to a digital object? how are the relationships between physical and digital objects created? by manual input? by database lookups? what happens with the digital records of discarded physical objects? how are UI elements organize around physical objects present on the surface? Answering these questions should lead to specific design choices that are reflected in the software, from foreign key relations in databases, to flexible/floating UI controllers.

And third, the dimensions related to the integration with other devices, *ecology* and *surface coupling*, bring to the arena of tabletop interaction traditional topics of distributed systems research. The issues of pairing of devices, standards for data exchange, support for multiple communication channels, and security provisions are all on the table. These topics gain relevancy when bringing mediated tabletop interaction out of the design lab into the everyday settings of users.

From our collaborative exploration in the context of the biology lab, introducing interactive surfaces to the lab requires a mediator implementation designed according to the colored values in figure 22. Rack mediators should support batches of tubes, have an appearance very similar to existing racks, and support tubes of different sizes. The application should index the physical tubes around a master digital object like a experimental protocol, support at least manual and data integration, and expect a rather nonspatious tabletop usage. And racks should initially support integration only with surfaces, but with many of them.

Finally, our explorations in the context of the biology lab could inspire researchers to look into other domains like for example the workbench work with electronic components, or to look into using mediators for purposes other than small objects' integration. In looking into different domains, a useful strategy is to look at instances where users interact with objects by means of an intermediate object like a place-

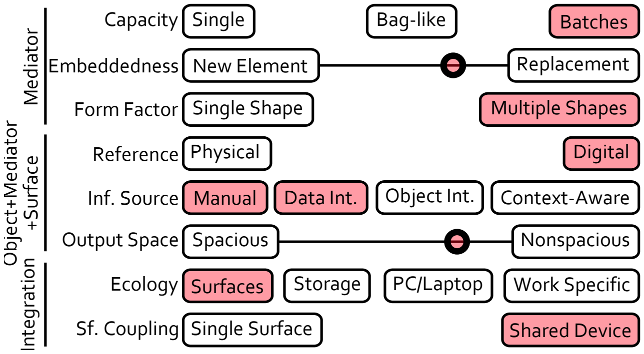

Figure 22. Summary of dimensions and dimension values for a test tubes rack implementation.

holder or an instrument. Like in the biology lab, the intermediate object can become the mediator and fit naturally within the existing working dynamics. As for purposes other than small objects' integration, researchers can look into objects that cannot be normally interacted with through the tabletop, like remote objects, big machines, wrapped objects, etc.

CONCLUSIONS AND FUTURE WORK

Current approaches to integrate objects to tabletops fail at handling small objects. In this paper we present the notion of *mediated tabletop interaction*: an approach to integrating small objects and tabletops, based on the fact that interaction with small objects often happens through a holder object. We explored mediated tabletop interaction by building an RFID+LED-based prototype, and collaboratively defining a design space for mediator solutions in the biology laboratory. Our design space definition introduces dimensions around to three areas: (i) mediator design, (ii) object+mediator+surface integration, (iii) and integration with other devices.

More than reporting final results of a research project, this paper starts the research into mediators and mediated tabletop interaction. Our most immediate path is the construction of multiple mediators with different hardware configurations in order to explore their performance in issues like cost, responsiveness, data transfer, battery consumption, etc. Moreover, we intent to carry out a longitudinal deployment of mediator devices supporting the lab work of molecular biologists. This deployment would shed light on how mediators and tabletop interaction in general can be better designed for everyday experiences. Particular focus would be on the UI layout when multiple physical objects limit the available space, and the UI options when the mediator contains multiple objects.

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