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Physically Flexible Control for Human-Computer Interaction

Céline Coutrix

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préparée au sein **du Laboratoire d'Informatique de Grenoble**
et de **l'École doctorale MSTII**

Physically Flexible Control for Human-Computer Interaction

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Contents

Research conducted prior to this thesis	5
1 Introduction	7
I Understanding reconfigurable interfaces	17
2 Benefits	19
2.1 Concept of Emergeables: Manipulation×Size of sensels	19
2.2 Experiment	20
2.2.1 Accuracy	21
2.2.2 Visual attention	23
3 Reconfiguration design space	25
3.1 Collection of everyday objects	26
3.2 Overlaps and improvements of taxonomies	26
3.3 New SIZE and MODULARITY features	31
3.3.1 Adding a feature: Size (1D, 2D and 3D)	31
3.3.2 Adding a feature: Modularity	32
Summary and discussion	33
II Exploring reconfigurable controls	41
4 Formative study:	
Balancing flexibility and physicality	43
4.1 Participants, apparatus and methods	43
4.2 Results	44
4.2.1 Interaction with a large number of parameters	44
4.2.2 Fast interaction	45
4.2.3 Accurate and precise interaction	45
4.2.4 Eyes-free interaction	46
4.2.5 Mobile interaction	46
4.2.6 Retro-compatibility	47
4.3 Concluding requirements	47

5 Exploring reconfigurable dials	49
5.1 ExpanDial: dial changing its height and circumference	49
5.1.1 Prototype	49
5.1.2 Focus group evaluation	50
5.2 KnobSlider: dial changing to a slider	55
5.2.1 Design	55
5.2.2 Qualitative study with end-users	57
5.2.3 Physical vs. on-screen preference for reconfiguration speed	62
6 Exploring reconfigurable sliders	67
6.1 Coupling the zooming in the motor and visual space	67
6.1.1 Design and prototype	68
6.1.2 Impact of the resizing on Performance	69
6.2 SplitSlider	73
6.2.1 Design	74
6.2.2 Experiment	75
7 Exploring reconfigurable mobile sliders	79
7.1 Impact of length and orientation	80
7.2 ClutchSlider: Extendable Tangible Slider	82
Summary and discussion	91
III Discussion and Research project	103
8 Summary and Discussion	105
9 Challenges	113
9.1 Design	115
9.1.1 Fundamentals	115
9.1.2 Interaction techniques	118
9.2 Engineering	119
9.2.1 Prototypes	119
9.2.2 Software	122
9.3 HCI theory	124
Publications	126
References	130

Research conducted prior to this thesis

Before working on reconfigurable tangible user interfaces, I worked on the link between the physical and digital worlds through mixed reality interfaces during my PhD, affective interfaces during my post-doc and gestural interaction with distant physical objects, mainly through advising the PhD thesis of William Delamare. This lead me to identify the flexibility of the physical part of the interfaces as a bottleneck in HCI. This thesis address this problem and focuses on physically reconfigurable interfaces. I will therefore focus in this thesis on this most recent work, started in 2014. Most of this recent work took place within the [ANR JCJC PhyFlex](#) (2015-2019) that explicitly tackled the flexibility of tangible interfaces through shape-change.

Chapter 1

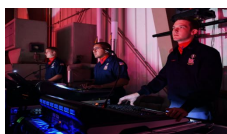
Introduction

Tangible User Interfaces

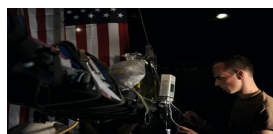
This thesis lies within the scientific domain of Human Computer-Interaction (HCI). This domain studies the design, prototyping, implementation and evaluation of interactive computing systems. In particular, this thesis studies physical user interfaces (PUIs), tangible user interfaces (TUIs) and embodied interaction. These interfaces use physical objects, e.g., physical cubes, buttons, sliders or dials, to interact with the computer.

Since their early, introducing works, TUIs have proved their performance. They provide directness [HHN85; FB97; IU97], passive haptic feedback [JDF12; JDF13], simultaneous access to physical devices arranged in the space around the user (space multiplexing) [FIB95], specialization of control [FIB95] and visual realism [JDF13]. For these reasons, they have been widely studied in research, but also used in real-world use cases for a long time. Their efficiency benefits to a variety of applications domains like interactive data visualization, sound or light mixing, cinema, construction, health, cockpit, power plant, etc. A few examples of such TUIs in real-world use cases are shown in Figure 1.1.

The benefits of TUIs are crucial in these application domains. For instance, users may need to focus on distant targets (Figure 1.1). As a result, they operate eyes-free and need haptic feedback. They cannot use a Graphical User Interface (GUI) without compromising performance or, more importantly, security. As a consequence, the success of TUIs has been limited to specific application domains such



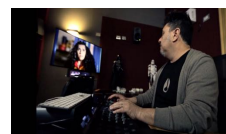
(a) Sound and light engineer looking at the stage while adjusting the sound and lights of a show (U.S. Air Force photo/Senior Airman Aaron J. Jenne)



(b) A nurse using an infusion pump, with physical buttons to specify a dosage and/or a flow. He concurrently focuses on the fluid and on the interface. (U.S. Air Force photo/Staff Sgt. Quinton Russ/released)



(c) Pilots in a cockpit, using tangible handles, joysticks, buttons, dials, etc. while focusing on the landing field.



(d) A color grading console includes tangible devices such as buttons, rotary knobs and trackballs. The operator of such consols focuses on the image he is processing.

Figure 1.1: Examples of applications domains where TUIs are routinely used.



Figure 1.2: Five shapes given to the mouse cursor through software in order to provide feedforward to the user and, e.g., more accurate control with the thin text cursor.

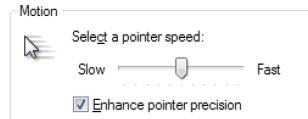


Figure 1.3: Panel for the user of the mouse on Windows OS: customization of the dynamic gain based on pointer acceleration

as the ones of Figure 1.1.

Graphical User Interfaces

Outside particular application domains like the ones of Figure 1.1, GUIs have taken over. Their success can be explained by both the directness of interaction [HHN85] and the flexibility [SB97] provided through software. As an example of GUI flexibility, direct touch, or the cursor of the mouse, can be associated to a different tool whether it activates a button, a scrollbar or it is used to edit a text. In some cases, even the shape of the mouse cursor changes in order to provide feedforward¹ to users and improve usability, as shown in Figure 1.2.

Another example is the control-display gain of the mouse cursor that is changed dynamically so that users' actions are more rapid or more precise. The user can even customize the gain transfer function, as shown in Figure 1.3. Users also zoom in a workspace when their target is too small, or resize their window to avoid scrolling or clutching. GUIs, including their control, are very flexible and can accommodate a large spectrum of users, tasks and situations of use.

A synergy between the flexibility of GUIs and the physicality of TUIs?

TUIs lack the flexibility necessary to scale to a large spectrum of users, tasks and situations of use. TUIs have been thus left apart to the benefit of the mouse and multitouch interfaces. **This thesis addresses the lack of flexibility in tangible controls.** We hypothesize that this lack of flexibility is preventing the wide adoption of TUIs for the benefit of the general public. All of our personal User Interfaces lack tangibility, which is critical for instance when one needs to focus on the road that is being crossed or for visually impaired users [Duc+16]. Providing flexibility to the already adopted TUIs (Figure 1.1) could even further improve the interaction: In these domains, current TUIs users compromise between performance and price or practicality. They usually use generic, abstract tangible controls that can be industrially produced in quantity and mapped to several functions, even though the specificity of the shape and its visual realism have been shown to significantly impact

¹Predictive information that tells users what the result of their action will be [Ver+13].

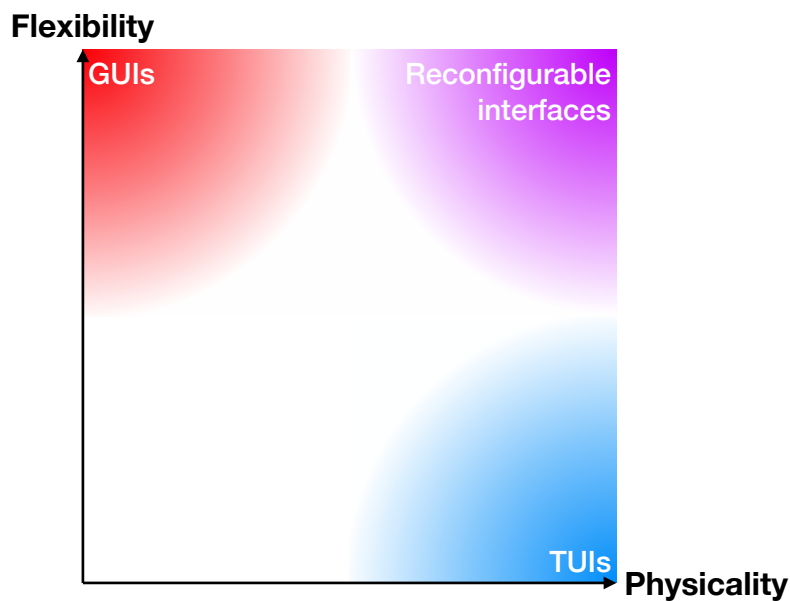


Figure 1.4: Reconfigurable interfaces described as the synergy between the physicality of TUIs and the flexibility of GUIs.

performance [FB97; JDF13]. Moreover, the requirements of current TUIs users change: e.g., sound or light engineers (Figure 1.1a) sometimes need to be mobile to adjust mixes from the performers' positions on stage or from a different location of a venue. In these domains, the lack of flexibility costs money, usability, mobility and, sometimes, even security. Our aim in this thesis is to explore ways to bring flexibility in the control of TUIs (Figure 1.4) and reinforces their operational performance.

To reach the synergy between flexibility and physicality, we set out in this thesis to advance both (1) the **understanding**, and (2) the **exploration** of *reconfigurable* tangible controls (Figure 1.5).

We define *reconfigurable* devices as devices with the ability to have multiple shapes and to be deformed manually (via user inputs) or automatically [KCR18b]. Other words such as “deformable” [BBV13; KW12; Rob+16; TPH14; TPH15; Van+13], “mutab[le]” [Sah+18], “malleable” [Koh+11; Fol+12; Wik+13; Mil+06; GK13], or “shape-changing” [CZ11; Fol+12; Nør+13; Ras+12; Rou+13; TTL16; Yao+13] have also been used to describe this concept. These words convey a change in shape, which means that there is an initial shape A and a final shape B. The transformation from A to B is called the deformation and can be initiated manually by the users (via molding [Fol+12], bending [GNV13; SJM13], twisting [Rou+14a], etc.) or automatically by the system as explained by [Ras+16b]. This last category is also sometimes called actuated [LI10; PNO07; Ras+13] or self-reconfigurable [SMS06; Yim+07] interfaces.

Understanding reconfigurable interfaces

Before spending decades researching reconfigurable interfaces, the thesis sets out to address two basic challenges. First, we studied if the benefits of TUIs, in particular in terms of performance, still holds with the change of shape of reconfigurable interfaces.

On the one hand, motor-spatial memory was considered as a key factor in the success of TUIs [Sha+04; FIB95]. While the benefit of tangibles has already been demonstrated, previous work is

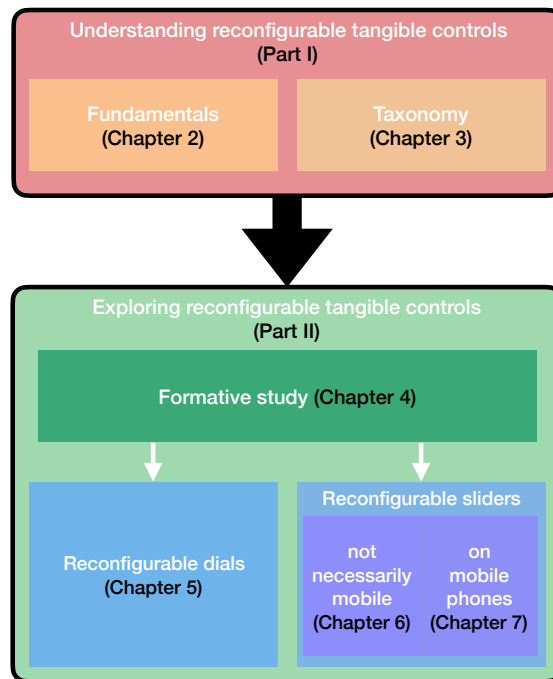


Figure 1.5: Structure of the contribution presented in this thesis.

limited to static or user-set shapes and locations. The users' awareness of physical configuration is a challenge. With dynamic and system-controlled [Ras+16b] change of shape, we deprive users from using motor-spatial memory. Like other intelligent user interfaces adapting at the initiative of the system, this deprives users from the benefits of direct manipulation [Hö00]. As a result, actuated interfaces challenge previous results on TUIs' performance. From prior work, it is not possible to tell how important motor-spatial memory is in relation to the other factors that contribute to TUIs' benefits.

On the other hand, current reconfigurable interfaces are of lesser resolution compared to current tangible ones [Ale+18]. It is also important to assess how the resolution impacts the experiments with reconfigurable interfaces. The work we did with Emergeables [Rob+16] (chapter 2) addresses these problems. This is joint work with Simon Robison, Jennifer Pearson, Matteus Torquato and Matt Jones from the University of Swansea in the UK, and Juan Rosso (then master student) and Laurence Nigay in Grenoble.

Second, we propose a unifying taxonomy of possible changes in shape in order to better define the design space of reconfigurable interfaces [KCR18b] (chapter 3). Taxonomies of reconfigurable interfaces [Ras+12; Rou+13; CZ11] have been defined to help design and communication among researchers. Despite their use, taxonomies are rarely evaluated. We analyze two established taxonomies –Rasmussen's and Roudaut's – using daily reconfigurable objects. We show relationships between the taxonomies and areas for improvements. We propose Morphees+, a refined taxonomy based on Roudaut's Shape Resolution Taxonomy. This is joint work with PhD student Hyunyoung Kim, and Anne Roudaut from the University of Bristol in the UK. The data set² is available on the Web, in order to be reused and extended in the future.

²<http://phyflex.imag.fr/EverydayObjects.html>

We detail these contributions in Part I and our contributions provide basic knowledge that lays the ground for the exploration of reconfigurable tangible controls as schematized in Figure 1.5.

Exploration of reconfigurable tangible controls

In order to ground the design of reconfigurable controls on users' needs, we conducted a formative study with professionals who routinely use tangible controls (chapter 4). The contextual interviews focus in particular on how users currently balance *physicality* and *flexibility* (Figure 1.4). Based on the results of this formative study, we propose design requirements for future interfaces for parameters control. In particular, we identified knobs and sliders as widely used tangible controls. For this reason, this thesis focuses on these widespread elements as a starting point for the exploration of reconfigurable controls. In particular, we investigate the design of reconfigurable dials in chapter 5.

Reconfigurable dials

We explored the design of a physical dial that can change its circumference and height to adapt to different contexts of interaction [Kim+19]. We design a prototype, ExpanDial, inspired from morphing origami. We use our prototype as a probe within design sessions and use the participants' feedback to devise a set of applications that can benefit from such reconfigurable devices. We also used the design sessions to better understand what kind of interaction and manipulation could be harnessed from such device.

We explored the design of a device that combines the advantages of a knob and a slider in one unique reconfigurable device. The resulted device is called KnobSlider [KCR18a]. A qualitative study with professionals shows how KnobSlider supports the design requirements, and inspired new interactions and applications. A quantitative experiment explored the impact of the speed of shape-change in users' perception [KCR19].

This work on reconfigurable dials is a joint work with PhD student Hyunyoung Kim, and Anne Roudaut from the University of Bristol in the UK. KnobSlider, in particular, offers a transition between reconfigurable dials (chapter 5) and sliders (chapter 6 and 7).

Reconfigurable sliders

Based on the Morphees+ taxonomy [KCR18b], we explored two dimensions of tangible sliders: their length to balance size and precision, and the modularity of their cursor to enable the input of the uncertainty.

With sliders, users need to balance between opposite concerns: the size and the precision of the slider. We propose a resizable tangible slider to balance between these concerns. Users can resize the on-screen representation of the slider by resizing the tangible slider. Our aim is to benefit from both tangibility and flexible control, and balance between precision and minimum size. We measured the pointing performance of our prototype. We also assess the potential drawback, i.e. the additional articulatory task for deformation, by evaluating the impact on pursuit precision of the additional articulatory task for deformation. This work [CM15] presented in Chapter 6 (section 6.1) is a collaboration with Cédric Masclat from G-SCOP laboratory in Grenoble.

We then explore the benefits of a modular cursor, in particular to enable users to express their uncertainty about a continuous parameter: experiencing uncertainty is common when, e.g., answering questionnaires. Enabling users to input their uncertainty is thus important to increase the data's reliability and to make better decision based on the data. However, few interfaces have been explored to support uncertain input, especially with TUIs. TUIs are more discoverable than GUIs [Hor+09] and better support simultaneous inputs of multiple parameters [KCR18a]. It motivates us to explore

different TUI designs to input users' best estimate answer (value) and uncertainty. We first generate 5 TUI designs that can input both value and uncertainty and build low-fidelity prototypes. We then conduct focus group interviews to evaluate the prototypes. We implement the best design, SplitSlider, as a working prototype. A lab study with SplitSlider explores if users are able to discover the interaction without any explanation, and if, once explained, users are able to input uncertainty. This work [Gre+19] presented in Chapter 6 (section 6.2) is a joint work with Miriam Greis, Andreas Korge and Albrecht Schmidt then at the University of Stuttgart in Germany, and PhD student Hyunyoung Kim.

Reconfigurable mobile sliders

We dig deeper into the exploration of reconfigurable sliders for the particular case of mobile interaction. Touch interaction is almost omnipresent on mobile devices and technological advances have made screens bigger. The users can then interact with more content displayed on screen but it is more difficult for the users to reach all the parts of the screen with one thumb. Deformable tangible interfaces offer promising opportunities to solve this problem. Bringing tangible objects to the flat screen [Rob+16] brings a new perspective on the reachability problem of the thumb.

We explore two ways to provide eyes-free interaction with sliders on mobile devices. First, we explore the impact on performance for thumb interaction within and outside the functional area of the thumb, while operating a tangible slider. Experimental results demonstrate that the size of the motor space has a significant impact on performance. Operations within and outside the easily reachable area of the thumb show marginal difference of performance. Second, we experimentally study a deformable tangible slider that facilitate thumb interaction on mobile devices through the expansion of its cursor. Doing so, we aim at avoiding hand-grip changes by maintaining the thumb within its comfortable area. Moreover, its tangible aspect allows eyes-free interaction. We first compared a low-fidelity prototype with a classic tangible slider. We then designed a actuated slider that we compared to a classic tangible slider and a graphical one.

This work [Ros+16; Ros+17; Ros+18], presented in chapter 7, is a joint work with PhD student Juan Rosso, Laurence Nigay from Université Grenoble Alpes and Matt Jones from the University of Swansea in the UK.

Assessment of the contributions

This manuscript is an opportunity to take a step back and reflect on our work in order to improve future research. We take this opportunity and assess the work presented in this manuscript through its ability to improve problem solving capacity of the HCI field [OH16]. This assessment is done at the end of each part of the manuscript and a synthesis of this assessment is presented in chapter 8.

The problem-solving view on the HCI field classifies contributions to the HCI field into three categories of problems they can address: empirical, conceptual and constructive problems. Each of these problems have three subtypes of problems (Figure 1.6) that build upon each other as the knowledge progresses.

For each of these types of problems, we use the five criteria proposed by the problem-solving view to assess HCI contributions: significance, effectiveness, efficiency, transfer and confidence. The criteria provide a tool for researcher to improve the capacity of their work to solve HCI problems.

Three types of contributions. HCI contributions solve one of the three types of problems: empirical, conceptual or constructive problems.

Empirical contributions describe of real-world phenomena. Empirical contributions can first, reveal a previously *unknown phenomena*, second, identify its *unknown factors*, and third, measure its *unknown effects*. In the first case, the work reveals that a phenomenon is happening. In the second case, the work reveals that a factor impacts this phenomenon, e.g., the work identifies a variable that can be used to model the phenomenon. In the third case, the work reveals how much the factor impacts the phenomenon, i.e. the work identifies the degree of impact of the variable on the phenomenon.

Conceptual contributions propose explanation for a phenomenon observed in HCI. Examples are theories, taxonomies or models. First, a conceptual contribution can make a phenomenon *plausible* by proposing a reason or an explanation for a phenomenon. Second, a conceptual contribution can make an existing conceptual contribution *consistent*, for instance with prior empirical results or with another conceptual contribution. Third, a conceptual contribution can make previous conceptual contributions *compatible*, i.e. reconcile opposing conceptual contributions.

Constructive contributions explain how to construct a particular interactive system. First, constructive contributions can present a *first prototype* (the first in terms of novelty). Second, constructive contributions can *extend, make effective or efficient* a previously existing constructive contribution. Third, constructive contributions can explain how to *implement or deploy* a previously existing constructive contribution.

Five criteria to assess the contributions. In the problem-solving view on HCI, each type of contribution can be assessed along the five following criteria that are orthogonal to the three types of contribution [OH16] (in other words the five criteria can be applied to the three types of contributions): Significance, effectiveness, efficiency, transfer and confidence.

Significance assesses the importance and relevance of the problems addressed. To analyze the significance of our work, we verified if the problems we addressed are in line with the grand challenges of shape-changing HCI research [Ale+18]. When possible, we also verified how many users are impacted by the solution, and the cost of an absence of a solution.

Effectiveness assesses the match between the solution and the essential aspects of the problem addressed. To analyze this, we first verified that our evaluation criteria matched the priorities of the target users. When relevant, we consider the end-users requirements presented in chapter 4 as the priorities of the target users. We also verified that we evaluated our solution with multiple, diverse criteria and in multiple contexts, and that we addressed the difficulties that emerge from the real world.

Efficiency assesses the cost in applying the solutions proposed, relatively to the gain achieved. To analyze this, we verified how much effort and/or resources are needed to produce our solution, the scalability of the solution, if we provided a tool for designers to leverage the solution, and if we shared datasets and code.

Transfer assesses how well does the solution transfer to other problems. To analyze this, we evaluated how many users, tasks and contexts can or could benefit from the solution.

Confidence assesses how well will the solution hold as time passes. To evaluate this, we verified empirical validity, reliability, replicability, reproducibility, robustness, if we allow re-analysis, and how many criteria were used to assess validity and reliability.

Confidence is more particularly assessed for empirical contributions through the following four criteria: internal validity³, reliability, reproducibility and replicability. Internal validity is the adequacy of the experimental procedure, the method for the recruitment of participants, and the method for analysis, in particular the statistical methods when applicable. Reliability assesses how consistent were the results across, e.g. participants, types of measure, or repetitions. Reproducibility is the ability for

³*External validity*, on the other hand, is assessed through the *transfer* criteria, i.e. how well does the experiment apply to other situations, tasks, users, etc. or in the field or in the long term.

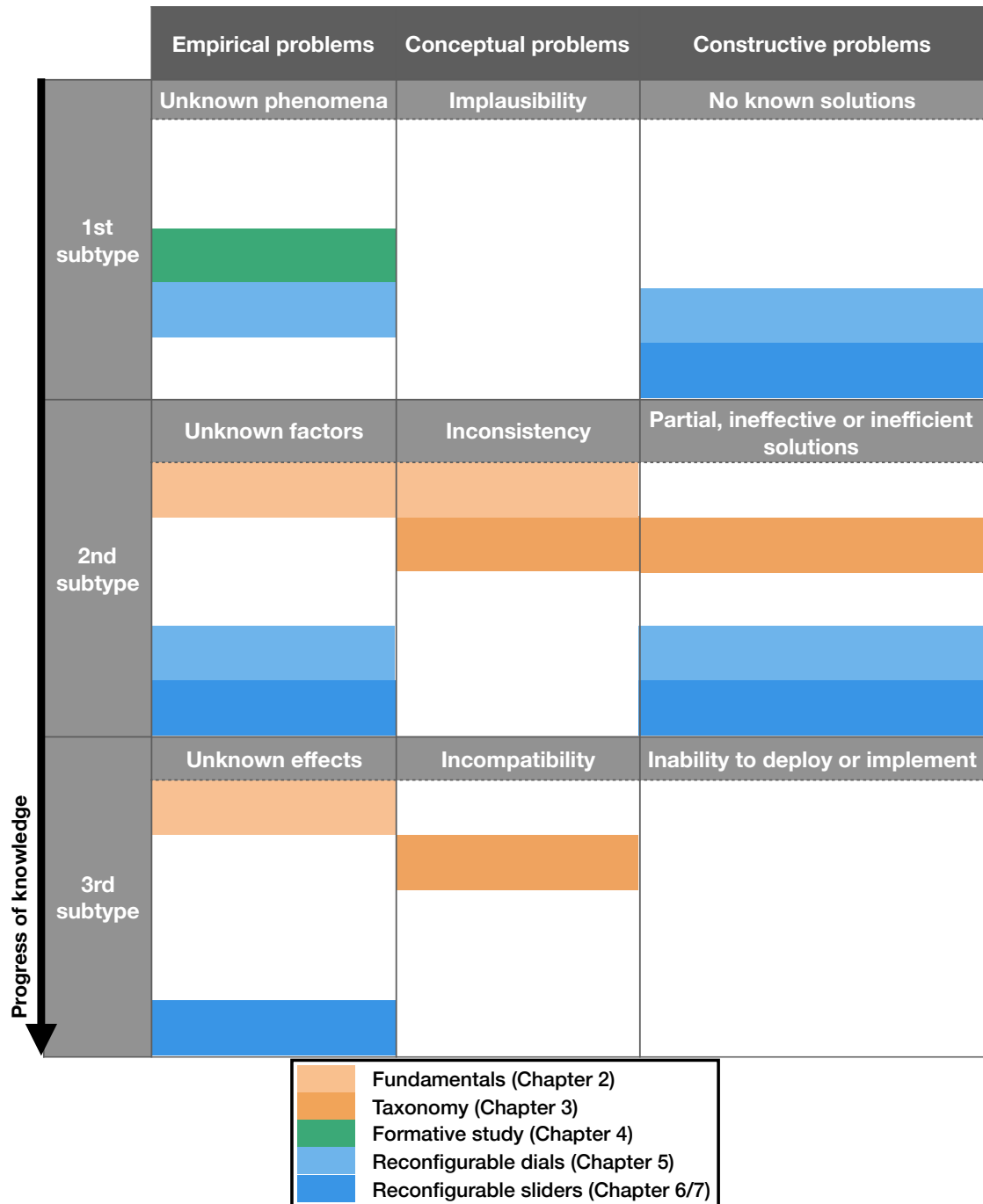


Figure 1.6: The problems addressed in the manuscript and their corresponding contributions. For each contribution we specify the chapter of the thesis.

others to recreate the same results by running again the same analysis from the collected data. Replicability assesses the ability of our empirical contributions to be repeated by running again the whole experiment and obtaining a consistent result.

We assess in particular our confidence in constructive contributions through their robustness and replicability.

Future work

In order to further bring the flexibility of control to TUIs through physical shape-change, we plan to work on the design of fundamental knowledge, tools and techniques for flexible tangible control. Flexible control of TUIs will bring together the best of TUIs and GUIs, going much beyond current respective benefits of TUIs or GUIs, in order to fully understand the synergy between TUIs and GUIs. To bring such interfaces to reality, we plan to explore the fundamentals of interaction with physically flexible controls, define an HCI theory and models accommodating physically flexible interaction, design physically flexible interaction techniques, research prototyping tools for physically flexible interfaces, and software development of physically flexible interfaces. This research project is detailed in Part III (chapter 9).

Organization of the document

To address the lack of flexibility in the control of TUIs, this thesis (Figure 1.5) first tries to understand reconfigurable interfaces in Part I, i.e. if the change of the devices' location lowers the benefits of TUI (chapter 2) and the design space for shape-change (chapter 3).

In Part II, the thesis explores reconfigurable controls. We first start by reporting formative contextual interviews studying current use of tangible controls in chapter 4. In chapter 5, we study the opportunities of reconfigurable dials, and in chapter 6, the opportunities that shape-change brings to sliders. In chapter 7, the thesis addresses the particular problem of reconfigurable *mobile* sliders.

In the concluding Part III, we first present a summary of our contributions and their assessment in lights of the problem-solving view on HCI [OH16] in chapter 8. We then present the future research that this exploration opens in chapter 9.

Part I

Understanding reconfigurable interfaces

Chapter 2

Benefits

Bringing shape-change to tangible user interfaces challenges one assumption. While the benefit of tangibles has already been demonstrated (e.g., [JDF12; FB97]), previous work is limited to static or user-set locations. Awareness of physical configuration is indeed a challenge when the system can relocate the objects to be manipulated by the users: Motor-spatial memory was considered a key factor in the success of TUIs [SH10; FIB95]. With dynamic and system-controlled [Ras+16b] change of shape, we deprive users from using motor-spatial memory. The system reconfiguration of the interface therefore challenges previous results.

From prior work, it is not possible to tell how important motor-spatial memory is in the combined factors that result in TUIs' benefits. We address this research question in the *Emergeables* paper [Rob+16]: **How efficient are system-reconfigured physical interfaces compared to tactile ones?**

In addition, current reconfigurable physical interfaces are of lesser resolution compared to current tangible ones [Ale+18]. We therefore go even further by studying the following research question: **What is the impact of the level of resolution of the reconfigurable physical interface?**

To study these questions, we introduce the concept of *Emergeables* in the context of mobile interaction. *Emergeables* are mobile surfaces that can deform or 'morph' to provide fully-actuated, tangible controls. Our goal is to provide the flexibility of graphical touchscreens, coupled with the affordance and tactile benefits offered by physical widgets. In contrast to previous research in the area of deformable displays, this work focuses on continuous controls (e.g., dials or sliders), and strives for fully-dynamic positioning, providing versatile widgets that can change shape and location depending on the user's needs. We built two prototype *Emergeables* to demonstrate the concept. We present an evaluation that compares both with a touchscreen alternative in order to assess our research question.

2.1 Concept of *Emergeables*: Manipulation \times Size of sensels

While display- and touch-screens are constructed of pixels, *emergeables*' elementary unit is a sensel [RP09], with two key properties (Figure 2.1):

Manipulation Sensels can be manipulated by the user. As a starting point to explore their potential, we consider two basic tangible manipulations from [Bux83]: translation and rotation, each in three dimensions.

Size The size of each sensel defines the resolution of the *emergeable* interface. Sensels' physical size is completely independent of the pixel resolution of the display surface.

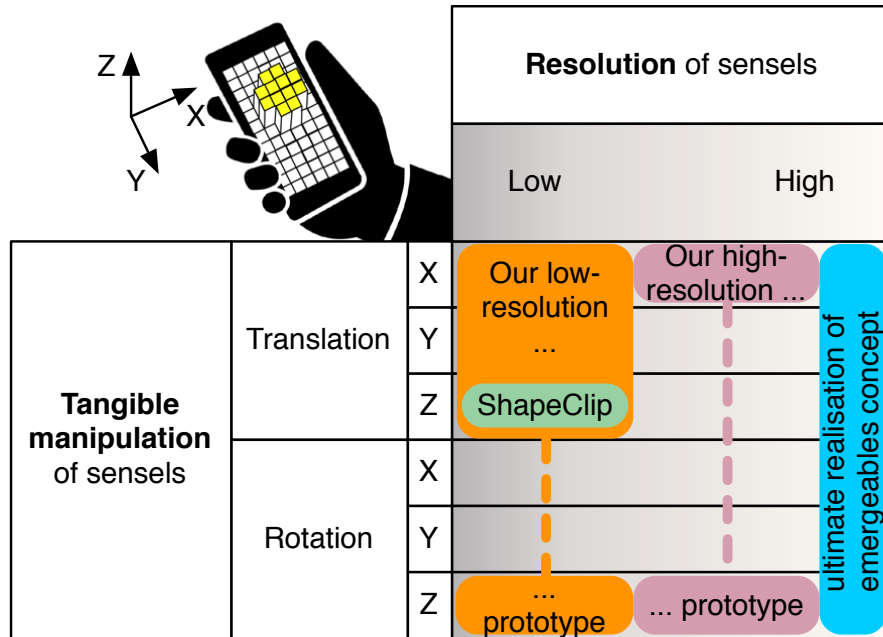


Figure 2.1: The Emergeables concept and design space.

Our ultimate aim is for emergeables to be created at very high resolutions, on the order of millions of sensels (just like today's visual displays have millions of pixels). Such a display would allow users to grab and manipulate groups of sensels to interact with as, for example:

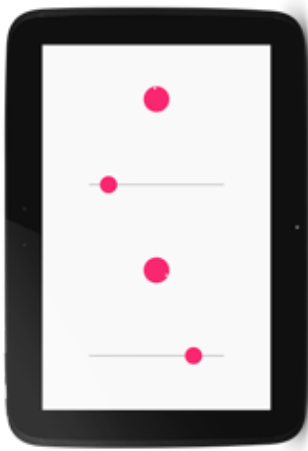
- A slider, by translating the sensels in the Y-axis only;
- A dial or handle, where the central sensel rotates around the Z-axis, while other sensels translate in the X- and Y-axes;
- A mouse wheel, where the central sensel rotates around the X-axis, while other sensels translate in the Y- and Z-axes.

2.2 Experiment

In this experiment, we evaluate the comparative performance of tangible interfaces, that the system reconfigures, and tactile interfaces, that have always been reconfigurable by the system. We also evaluate the impact of resolution on performance with mobile, reconfigurable dials and sliders. We compared three levels of RESOLUTION:

- A mock-up of a high-resolution emergeable prototype (Figure 2.2c),
- A low-resolution emergeable prototype (Figure 2.2b), and
- A non-emergeable touchscreen interface that displays standard dials and sliders in the same positions and at the same sizes as the two physical prototypes (see Figure 2.2a).

We additionally compared two level of task COMPLEXITY: 1 or 2 widgets (controlled simultaneously); and two types of WIDGET: Dial or slider.



(a) The graphical interface used in the study. A widget is shown in each of the four positions used (where the one at the bottom is a slider and the one at the top is a dial). Note that at most only two of these positions were used at any one time in the study.



(b) Low-resolution emergeable prototype, with projection to highlight a raised slider (top) and dial (bottom).



(c) Mock-up of High-resolution emergeable prototype.

Figure 2.2: The three prototypes used in the study: a tactile interface (a), a low-resolution emergeables (b) and the mock-up of a high resolution emergeables (c).

To simulate mobility and users switching between continuous control tasks, the main part of the study involved participants using the prototypes to control a graphical display projected on two separate screens either side of their location. The tasks required participants to follow a target cursor along either a linear or circular control (as, e.g., in [JDF12; FIB95]). Every 15 s, the projected control moved to the other screen, and participants were prompted by on-screen instructions to turn around, simulating a change in focus or application. When the task changed between screens, the location of the widget(s) used changed randomly (consistently on both the projected screen and the prototype). As a consequence, participants needed to reacquire the control(s), but could not use their spatial memory for this. This task design allowed us to take the change of focus or application into account in our evaluation (as happens in ecological, uncontrolled settings), and measure the impact of this change on the interaction.

All details about our experimental design and statistical analyses are reported in [Rob+16]. Figures 2.3 and 2.5 summarize our main results.

2.2.1 Accuracy

The results of our experiment show that when controlling eyes-free, continuous parameters, the high-resolution emergeable user interface was the most accurate (Figure 2.3A). Overall, this prototype was found to be almost twice as accurate as the GUI, and even higher when controlling two parameters simultaneously (Figure 2.3C). **This result illustrates the strong potential of high-resolution emergeable and reconfigurable controls, showing their improvement over GUI displays – even though their tangibility does not leverage spatial memory.**

Our next step, then, is to focus on the accuracy of the low-resolution emergeable design. The RESOLUTION did not impact much the design of the dials. As a consequence, the low-resolution prototype provides almost the same level of accuracy as the high-resolution prototype (Figure 2.3B–

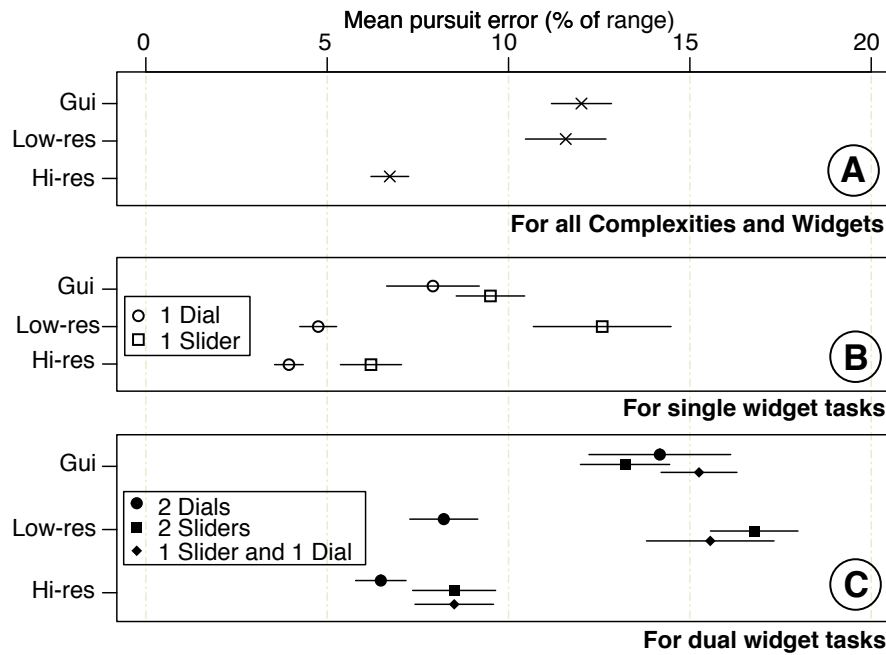


Figure 2.3: Mean pursuit error as a percentage of control range. Error bars show 95% confidence intervals.

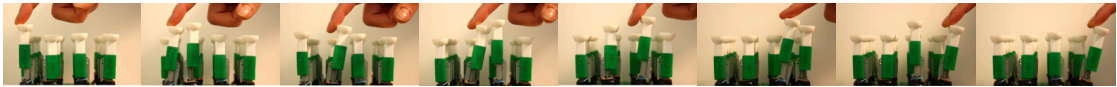


Figure 2.4: Slider interaction with the low-resolution prototype. First, a single sensel emerges at the slider thumb's current position (leftmost image). The user can then tilt this and each adjacent sensel in succession to simulate movement along the slider's path.

C). As expected based previous work (e.g., [TK13]), the GUI dial, however, is almost twice as inaccurate compared with our tangible prototypes.

In the case of the sliders, the RESOLUTION impacted the design (Figure 2.4). As a consequence, while the high resolution emergeable provided a gain in accuracy over the GUI, the low resolution slider performed worse (Figure 2.3B–C). The resolution provided in our prototype was created using four sensels, each of a size comparable to previous work (e.g., [Fol+13; Har+15]). **This experiment suggests that this resolution is not yet sufficient to provide a comparable accuracy to either high-resolution tangibles or GUI touchscreens.**

In the case of two sliders (Figure 2.3C), as with a single slider (Figure 2.3B), the low resolution prototype did not allow for better accuracy. This makes the need for future improvements in resolution even more important for complex tasks.

In a follow-up work [Pea+17], we used a 9-sensel deformable slider to further investigate the impact of resolution. Although the results of the two different experiments cannot be rigorously compared, it is interesting to see that a 9-sensel deformable slider resulted in 14.3% pursuit error, which is similar to the results of the 4-sensel slider. This result suggests that the higher resolution of sensel rods of this size does not seem to increase pursuit accuracy. **Future work should investigate the reduction of the sensel's size, or a new design for its manipulation** (Figure 2.4).

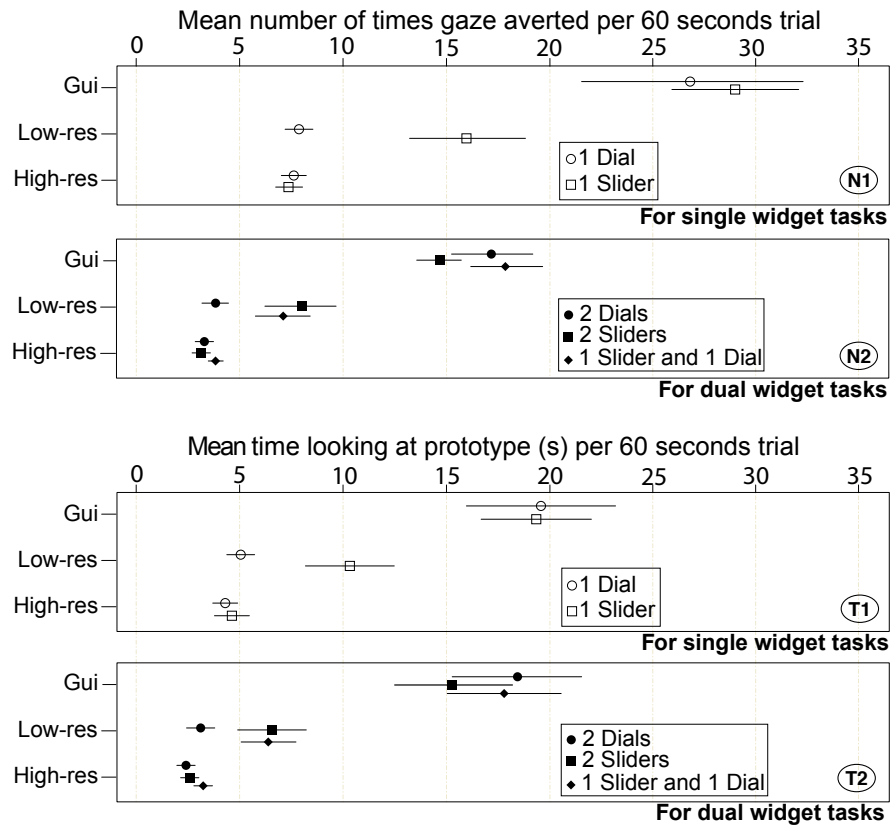


Figure 2.5: Glance rates. Top: mean number of times participants' gaze was averted from the projected screen. Bottom: the mean time participants spent looking at the prototype (rather than the display) per trial.

2.2.2 Visual attention

Beyond performance, users' safety can be at stake in situations where visual attention is critical – for example, controlling a car stereo while driving. The results of our video analysis show that **system-reconfigured emergeables require significantly less visual attention than the GUI approach** (Figure 2.5). Since the pursuit tasks in the study required as much of the users' focused attention as possible, we can deduce from this that the best interface for such activities is the high-resolution approach – requiring around 74% less visual attention than the GUI on the single widget task and 78% less on the dual widget task. **Even the low-resolution, sense-based emergeable prototype performed better than the touchscreen for the amount of visual attention required** – requiring around 57% less visual attention than the touchscreen on the single widget task, and 61% on the dual widget task. This tendency is true even in the case of the low-resolution slider. As a consequence, Emergeables are a promising direction for mobile user safety, and other scenarios where eyes-free interaction would be beneficial.

Conclusion

In this chapter we have presented emergeable surfaces for eyes-free control of continuous widgets. We have explored the design space by building two prototypes to test the viability of tangible, continuous controls that ‘morph’ out of a flat screen. Our first prototype—a high-resolution deformable UI—uses static dials and sliders that rotate on blocks to ‘change’ the device’s shape. This design gave us insight into the use of fully working widgets, but as a trade-off only allowed them to be placed in four specific locations on the display. Our second prototype—a lower-resolution sensel-based approach—is an initial demonstration providing dials and sliders that can be placed anywhere on its surface, and which could be refined over time to become smaller and of higher-resolution.

Our results show the value and benefits of system-reconfigurable tangible controls in terms of accuracy, visual attention and user preference [Rob+16]. While clearly still in its early stages, we have also shown the potential of our low-resolution sensel-based approach.

Our future work in this area will focus on decreasing the size of the sensel-based display. The current prototype uses stepper motors harvested from laptop DVD drives to facilitate the Z-axis motion of the sensels. The size of these motors, coupled with the additional wiring required for the joystick and rotation controllers, has resulted in the display being relatively large and adjacent sensels having small gaps between them. The next generation prototype could include smaller actuation motors such as small piezoelectric actuators [Jan+16] or even nano-level Janus particles [Sah+17] to create smaller sensels.

Based on the results of our experiment, further study into how best to improve the sensel-based slider interaction is needed. Also, future work should create dials made up of multiple sensels, allowing rotational controls of different sizes to be created anywhere on the display.

While this study shows the impact of reconfiguration on the benefits of tangibility over touchscreens, as well as the impact of resolution on the performance of a pursuit task, another very important aspect of the understanding of reconfigurable interfaces is the design space of their deformation. We address this problem in the following chapter.

Chapter 3

Reconfiguration design space

Shape-changing interface taxonomies [CZ11; Ras+12; Rou+13; BT19] help describe the reconfigurability of interfaces and can be used to design new interfaces [Kwa+14; Nør+13; Ras+16a; Stu+15]. Reconfigurable interfaces continuously evolve, and it was time to unify and strengthen these taxonomies. The descriptive power of the taxonomies was hardly tested, and it is uncertain if they are comprehensive and complete to describe all reconfigurations.

As a first step to sustain the taxonomies, we evaluate their descriptive power with end-users' daily reconfigurable objects. We choose reconfigurable daily objects, as users are used to manipulating reconfigurable objects in their daily life, e.g., a knife-changeable blender to prepare a smoothie, a height-adjustable chair at work, a foldable ladder to reach the attic or an orientation-changeable light to read a book in bed. Their continuously evolved manipulations are handy for users (e.g., being able to open and close a folding fan with only one hand [LHT08]). In addition, these objects have — explicitly or implicitly — inspired the design and taxonomy of reconfigurable devices (e.g., [Kha+12; Kha+11a; Le +16; LHT08; RSL14; Rou+14b; SJM13; Str+16]). Reconfigurable daily objects allow us to inform features of a taxonomy that are familiar to users, and can also inspire new reconfigurable interfaces.

We particularly focus on two taxonomies among previously suggested taxonomies. Roudaut et al. [Rou+13] proposed the term “shape resolution” which characterizes shapes as well as deformations in 10 geometrical features used to classify existing manual and automatic reconfigurable devices. Rasmussen et al. [Ras+12] presented a review of existing automatically reconfigurable devices and identified eight types of deformations to serve functional and hedonic design purposes. Both taxonomies are widely used within the HCI community (e.g., [Kwa+14; PSH14]). Our goal is to study their ability to describe everyday reconfigurable objects, as these continue to inspire new interfaces. In this chapter, we present our systematical analysis of 82 reconfigurable daily objects using two shape changing-interface taxonomies. We report our findings to improve the taxonomies. Our four steps approach provides the following contributions:

1. We collected 82 everyday reconfigurable objects¹ that are reusable by other researchers. The list includes pictures and descriptions.
2. Three authors classified the collected objects using two taxonomies (Rasmussen's and Roudaut's) describing topological changes. We reveal the relationship between the taxonomies and areas for improvement.
3. We add SIZE and MODULARITY features to the *shape resolution* taxonomy [Rou+13] which turned out to be the most complete and referenced taxonomy to describe shapes and deforma-

¹<http://phyflex.imag.fr/EverydayObjects.html>

tions altogether.

All details about our approach and procedure are reported in [KCR18b].

3.1 Collection of everyday objects

Of 149 everyday objects collected, 82 were currently available to end-users. We reserved the other 67 objects for future research, which are natural objects (e.g., armadillo) or not existing yet (e.g., deformable fridge). We obtained 82 single everyday reconfigurable objects. The full list with illustrations can be found on the Web². Figure 3.1 shows seven objects as presented in the Website, and Figure 3.2 shows on left hand side the list of the 82 objects.

The collection of objects itself can inspire the design of reconfigurable interfaces. For instance, in section 5.2, some of the KnobSlider prototyping ideas are inspired by everyday reconfigurable objects, such as a bike strap, an accordion, a party whistle, etc. Another example [PRT20] shows that the collection of everyday objects can be used as an inspiration tool to design the affordances of reconfigurable interfaces. Also, our original paper [KCR18b] reports how the collection can be used to inspire the fabrication of reconfigurable interfaces. An example is found in section 6.1.1, where the zoomable slider prototype was built on top of a retractable measuring tape, after exploring other solution inspired from other daily objects such as telescopic antennas.

3.2 Overlaps and improvements of taxonomies

We classified the 82 deformable objects with Rasmussen’s and Roudaut’s 18 total taxonomy features [Ras+12; Rou+13]. From the results, we gathered insights to improve each taxonomies. We draw insights on homogenization between the taxonomies, the completeness and level of granularity of the features, and discuss the level of precision in the definition of the features.

Homogenization between taxonomies

Some features from Rasmussen’s and Roudaut’s taxonomies overlap. For instance, 49 of the 50 objects in *M.Curvature* also have the *R.Orientation* feature, and all the 49 objects that change *R.Orientation* also change *M.Curvature*. *M.Porosity* and *R.Permeability* perfectly overlap with eight objects. Similarly, four out of the five objects that change in *M.Strength* also change *R.Viscosity*, and vice-versa. Even though more data should confirm the overlap between the features, homogenization of names would be beneficial for the research community.

The second interesting insight is related to the number of dimensions. Of the total 51 objects that have the 2D *M.Area* and of the 46 objects that have the 3D *R.Volume* feature, the vast majority (43) is shared between the two features. They tend to capture the same deformation while considering a different number of dimensions (surface vs. volume). E.g. a foldable chair (No. 117) increased its surface and volume when unfolded. One might ask then why the 1D extension transformation is not proposed in existing taxonomies.

The third interesting insight is the inclusion of some features in others. For instance, all 27 objects classified in *M.zero-crossing* also had *M.Curvature*. As a consequence, for all everyday deformable objects that we studied, it seems that a change in the number of zero-crossing points implies the ability to change the curvature too. Positioning taxonomies and their features relative to each other would help the understanding of the design space further.

²<http://phyflex.imag.fr/EverydayObjects.html>

OBJECT #26: FOLDABLE COMB

Reconfiguration and/or Purpose: Fold to carry and unfold to brush hair



Credits: the authors,

OBJECT #27: FOLDABLE DISPLAY

Reconfiguration and/or Purpose: Fold to fit in a bag or pocket and unfold to see information



Credits: Lordsaibaba,

Source: <https://youtu.be/bQXppSvtvtw>,

Last retrieved 17-Mar-17

OBJECT #28: FOLDING FAN

Reconfiguration and/or Purpose: Fold to carry or store and unfold to make wind



Credits: minshee93,

Source: <https://pixabay.com/en/fan-plum-bamboo-and-blooming-1571569/>,

Last retrieved 23-Mar-17

OBJECT #29: FOLDABLE KEYBOARD

Reconfiguration and/or Purpose: Fold to carry or store and unfold to type



Credits: Robert Whyte,

Source: <https://www.flickr.com/photos/robert-whyte/8386456509>,

Last retrieved 17-Mar-17

OBJECT #35: LUNCH BOX

Reconfiguration and/or Purpose: A lunch box consists of several containers for rice and side dishes. Combine to carry and uncombine and open to eat.



Credits: .

Source: <https://pixabay.com/en/lunch-box-lunch-camping-1141196/>,

Last retrieved 17-Mar-17

OBJECT #36: BLENDER

Reconfiguration and/or Purpose: The blade or container can be changed according to the purpose (mix; cut; different ingredient; etc.)



Credits: Paul Goyette,

Source: <https://www.flickr.com/photos/pgoyette/101146396/>,

Last retrieved 17-Mar-17

OBJECT #37: FOLDABLE LADDER

Reconfiguration and/or Purpose: Unfold to climb and fold to store



Credits: INCOSV,

Source: https://upload.wikimedia.org/wikipedia/commons/c/c2/Inco_Ladder.jpg,

Last retrieved 17-Mar-17

Figure 3.1: Seven everyday reconfigurable objects extracted from the Website: <http://phyflex.imag.fr/EverydayObjects.html>

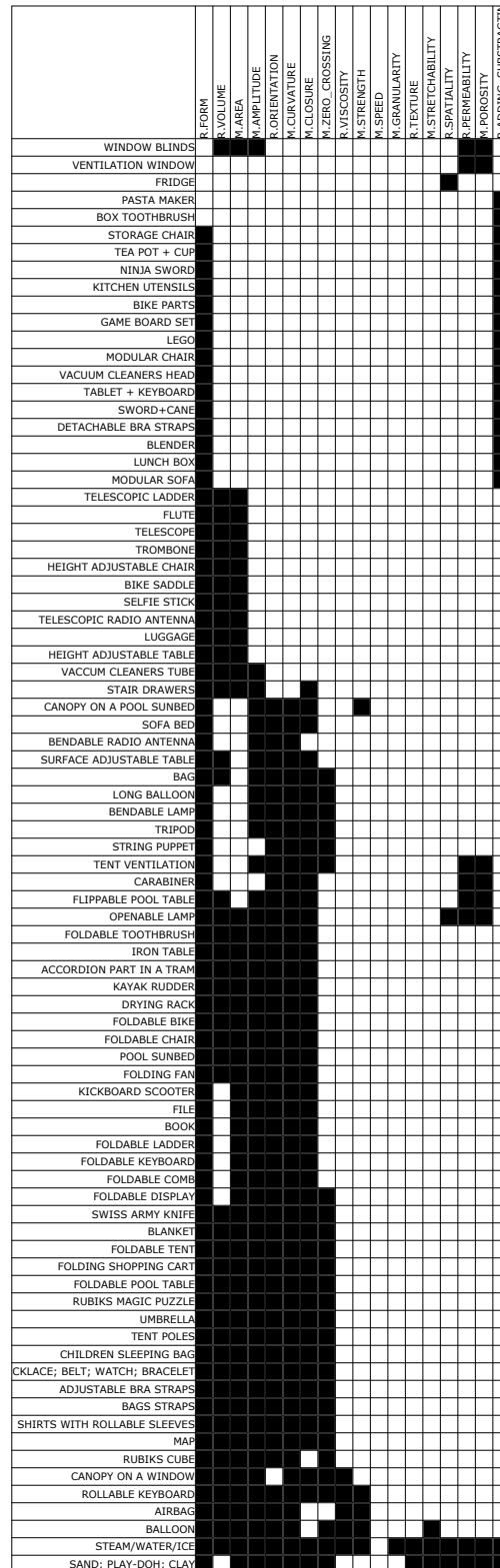


Figure 3.2: Everyday objects (lines) and the taxonomies' features (columns) they belong to (shown in black). The graph shows similar objects next to each other, and similar features next to each other. Visualization made with Bertifier.

The number of objects that have *M.speed*, *M.granularity*, *R.texture*, and *M.stretchability* was too small (0, 1, 2, and 3 respectively) to consider their similarities reliable. Hence, we did not consider their correlation.

Completeness of the taxonomies

Everyday reconfigurable objects are all classified in Rasmussen's taxonomy. However, Roudaut's taxonomy, which focuses on the model of Non-Uniform Rational B-splines, does not consider attaching and detaching parts of the object. As a consequence, corresponding objects are not classified in Roudaut's taxonomy, although they are considered reconfigurable by the Rasmussen's taxonomy.

Granularity of features

As shown in Figure 3.2, some features have many objects, while others few. Features with a large number of objects should be further detailed into sub-features in future work to precisely capture what is the deformation proposed to users. As an example, *R.Form* gathered almost all (i.e. 94% of) the everyday objects we collected.

Precision in the definition of features

When classifying, we found it difficult to attribute certain features to objects, due to ambiguous definitions, definitions that difficultly apply to human perception, vagueness, and shapes that have not been considered.

Ambiguous definitions

R.Orientation, *R.Form* and *R.Spatiality* leave room for subjective perception. It was difficult to classify an object objectively.

R.Orientation is defined as "distorting the original shape through rotations or changes in direction while preserving the recognisability of the original form". The three authors discussed whether we should agree to classify window blinds (No. 18) in *R.Orientation*. As they cannot bend, we chose not to classify them into it, even though users change the orientation of each layer.

R.Form is also lacking precision for us to easily classify many objects. *R.Form* is defined as "transformations that preserve the approximate volume of the shape while changing its overall form". We found that almost all reconfigurable objects (77 of 82, i.e. 94%) change in form (largest nodes in Figure 3.2).

R.Spatiality is also unclear for an object that can attach and detach, where spatial repositioning creates the illusion of shape-change if "individual elements being seen as part of a collective structure". During our discussion, it was difficult to objectively argue for detachable parts of the object being part of the whole.

How to compute *R.Volume* was unclear (defined as "changes in volume maintaining the approximate form"). To solve this, we took the inspiration from *M.Area*, area of the envelope of the object, to compute *R.Volume*. We considered the envelope of the objects to compute both *R.Volume* and *M.Area*. For instance, a Spanish folding fan (No. 28) and rollable sleeves (No. 48) can be compacted to a smaller area and volume of their envelope, when they are folded. It thus means that we do not consider hidden surface and space, like inside of the radio antenna where concentric cylinders can be stacked. As a consequence, many objects we gathered changed *M.Area* (51 of 82, i.e., 62%) and *R.Volume* (46 of 82, i.e., 56%). An interesting possible future improvement would be to characterize how much change in *M.Area* and/or *R.Volume* contributes to the overall deformation, i.e., if this is a major or insignificant change.

M.Zero-Crossing is about the change in the number of zero-crossing points. So if a foldable object goes flat, then it can change from 0 zero-crossing points to N (fixed number) zero-crossing points. A future improvement can be to further define if a change in the number of zero-crossing points has to be strictly greater than two (e.g., at least three with 0, N_1 , N_2), to better distinguish it from *M.Curvature*.

Definitions that do not apply human perception

M.Area feature is sometimes far away from the purpose of the object although it is easier to compute. For instance, a telescopic radio antenna (No. 23), by definition, changes its *M.Area* but not its *M.Amplitude*. However, it felt inappropriate to classify it this way as the purpose of the radio antenna is to change its height to better receive signals. After subsequent discussion, we decided that *M.Amplitude* was not considered when the extension of an object does not raise a single control point relatively to its neighbors on a surface. As a consequence, all telescopic objects (e.g., selfie stick No. 51 or extensible bike saddle No. 57) do not change in *M.Amplitude*.

Vagueness with modular objects

For *M.Area* and *R.Volume*, the difficulty comes from the object that is perceived as a single object and as several objects combined. For instance, the sword-cane (No. 52) was seen as two combined objects, and therefore did not have changing *M.Area* or *R.Volume*. On the contrary, the Spanish folding fan (No. 28) was seen as a standalone object, and therefore had changing *M.Area* and *R.Volume*. Similarly, *M.Closure* is difficult to assess with modular objects, like detachable bra straps (No. 49) or sword-cane (No. 52). We considered that they do not have *M.Closure* since the change does not happen on continuous surfaces. However, this needs further investigation since users may perceive the sheath as “closed” when the sword is in the cane, and “open” when the sword is out of the cane.

Shapes that have not been considered in previous literature

When objects show open parts, it is difficult to decide whether *M.Porosity* and *R.Permeability* are relevant or not. For instance, a carabiner (No. 38) already has porosity, and we were not sure if its porosity changes when the user opens it. During the discussion, we decided that its porosity changes because the central space becomes accessible from the side when it is open. We also considered they could show a change in *M.Closure*.

All raters agreed that objects that can flip parts (like No. 104 Flippable pool table) were not easy to classify because their deformation was not similar to the ones presented in previous papers. This shows the benefit of our approach, as it proposes a change of shape that can be considered in the future. We decided to classify them in a change of *M.Curvature* and *R.Orientation* because the exterior skeleton and the central rotating part make a curved shape when it is being flipped.

In the case of water that can change the state between gas (i.e., steam), liquid and solid (i.e., ice), it is difficult to assess the *M.granularity*. In other words, it was hard to define what is a control point. One could say it is a molecule but we were not convinced it really makes sense in terms of user deformation. Similarly, it was difficult to decide if a liquid is stretchable because we struggled to define what are the control points.

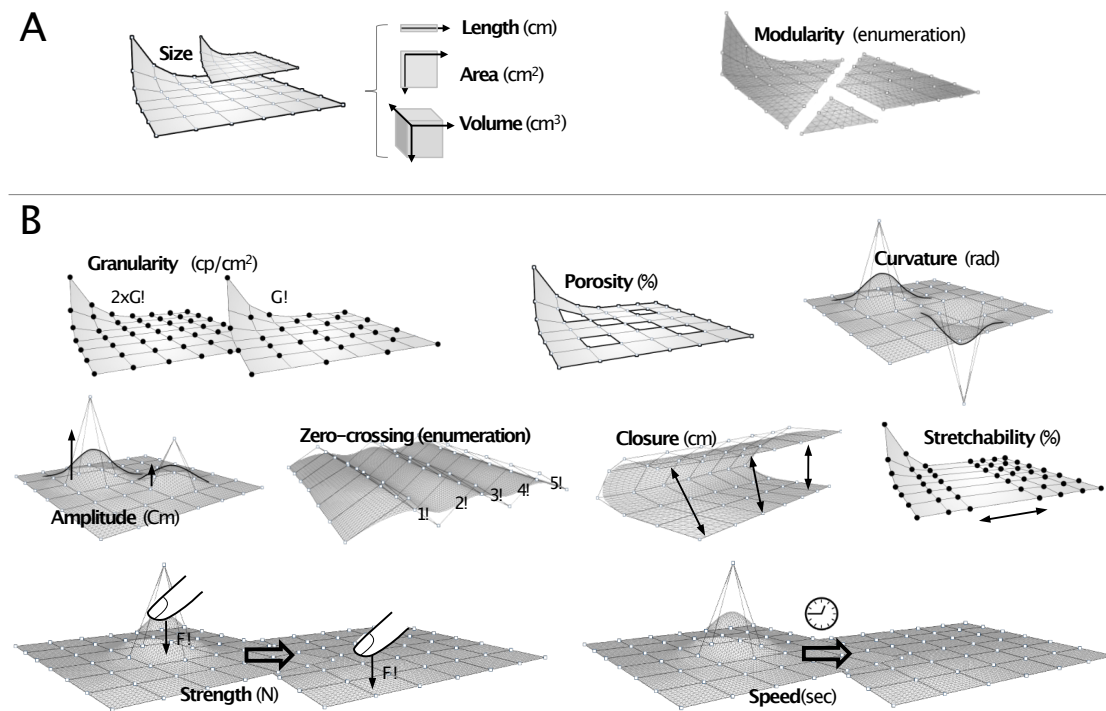


Figure 3.3: Morphees+ taxonomy. Among others, this improved taxonomy from the shape resolution taxonomy [Rou+13] extends the original Area feature into three Size subfeatures (A, left), including the original Area, and adds the new Modularity feature inspired from Rasmussen et al.'s taxonomy [Ras+12] (A, right)).

3.3 New Size and Modularity features

We choose to start from Roudaut's one because the features, being mathematically defined, are more straightforward to apply compared to Rasmussen's one. Although one critique of Roudaut's one is that the features are sometimes far away from the purpose of the object, Roudaut's taxonomy offers a mathematical framework with rigorous metric.

In the light of the issues revealed in our analysis, we propose to refine Roudaut's taxonomy by adding two new features (Size and Modularity, Figure 3.3) and refining one (Granularity). We also refine some of the metric definitions to accommodate our changes.

3.3.1 Adding a feature: Size (1D, 2D and 3D)

Size measures changes in the size of objects and can be split into 3 sub-categories that refine further the original definition of *M.Area*. We keep using imaginary envelopes of the objects (convex hull).

Length (1D) is the length of the object computed as the length of the mesh in one dimension (cm).

Area (2D) is the surface area of the object computed as the area of the mesh convex hull (cm²).

Volume (3D) is the volume of the object computed as the volume of the mesh convex hull (cm³).

The sub-categories help the explanation of deformations and give more descriptive power to the taxonomy. Changes in each category will probably affect the other categories.

For instance, *Length* is good to describe actuated pin displays. For example in inFORM [Fol+13], each pin can extend 100 mm. When all pins are fully extended, the interface volume increases approximately 14,516 cm³. Examples for *Area* are foldable and rollable displays such as FoldMe [Kha+12] and Xpaaand [Kha+11b]. Xpaaand reduces its *Volume* when reducing its *Area*, as the display is hidden in the boxes. When FoldMe has a folded shape, the *Volume* changes depending on the angles, but the summation of exposed surface area does not.

Some interfaces are better described in *Volume*, like pneumatic interfaces. For instance, the transformable tablet case [Yao+13], Inflatable Mouse [Kim+08a] and morphing cube [Hor06] change their volume to notify the user of the device status. Choosing a right sub-category would help designers precisely describe their complex reconfigurable devices.

3.3.2 Adding a feature: Modularity

Modularity is the ability of an object to be split into n several parts that can be combined while maintaining its original functionality. This feature essentially derives from the adding/subtracting feature of Rasmussen's taxonomy, which did not exist in Roudaut's original taxonomy. It is computed as the number of functionally possible combinations (C_{possible}) of k parts among n available parts in total (see Formula 3.1 below). Modularity is defined for objects that can be split into at least two parts ($n > 1$).

$$\text{Modularity} = \sum_{k=1}^{k=n} C_{\text{possible}}(n, k), n \in N, n > 1 \quad (3.1)$$

For instance, the *Modularity* of the vacuum cleaner (no. 74) that can change between 3 suction heads H1, H2 and H3 is 4. The vacuum cleaner can combine its body B with all three heads (B, BH1, BH2, BH3 are possible) where as H1H2, H2H3, H1H3, BH1H2, BH2H3, BH1H3, H1H2H3 and BH1H2H3 are not possible. Note that we also count B itself alone as it can serve the cleaning function. Objects that do not have pre-defined modules such as the steam/water/ice (No. 84), or Sand, Play-doh, or Clay (no. 149) have infinite modularity ∞ .

As with Rasmussen's taxonomy of reconfigurable devices, considering this type of reconfiguration of devices is inclusive and does not exclude many types of devices.

Conclusion

In this chapter, we propose a unifying taxonomy of possible changes in shape in order to better define the design space of reconfigurable interfaces [KCR18b]. We analyze two established taxonomies –Rasmussen's [Ras+12] and Roudaut's [Rou+13] – using daily reconfigurable objects. We show relationships between the taxonomies and area for improvements. We propose Morphees+, a refined taxonomy based on Roudaut's Shape Resolution Taxonomy. We wish for the data set³ – freely available on the Web – to be reused and further extended in the future by the research community.

³<http://phyflex.imag.fr/EverydayObjects.html>

Summary and discussion

In this chapter concluding the first part, we summarize our contributions and assess them through their abilities to improve problem solving capacity of the HCI field [OH16]. We first identify the categories of problems we addressed: empirical, conceptual or constructive problems, as Figure 3.4 shows. We then assess our contributions through the five complementary criteria, from the problem-solving framework [OH16]: significance, effectiveness, efficiency, transfer, and confidence. By doing so we highlight the strengths and limitations of our contributions. Some of the listed limitations are well identified described in the chapters of this first part and the corresponding publications as future work. We found that it is relevant to gather all the strengths and limitations of our conducted work to take a step back on the conducted research path.

Contributions

The Emergeables experiment (chapter 2, section 2.2) is an **empirical contribution** that reveals **unknown factors** and measures the corresponding **unknown effects**. The experiment shows that tangible user interfaces offer better performance even though the computer changes the shape of the tangible widgets, and that resolution of the widgets impacts performance. While we knew that tangible user interfaces show better performance for pursuit tasks compared to tactile user interfaces (e.g., [JDF12]), we did not know if this would hold when the shape of the widgets are controlled by the computer. This reveals that the actuation of the shape of the widget by the system does not impact the performance of reconfigurable TUI in this situation. We also did not know that the resolution of the widgets was a factor for performance. The experiment thus reveals a new factor impacting the performance of reconfigurable TUI and measures the corresponding effect.

The concept of Emergeables in chapter 2 (section 2.1) is a **conceptual contribution** that makes existing conceptual contributions **consistent** with each other and with future, envisioned interactive systems. The concept builds on top of several existing conceptual contributions, such as the definition of the input and output channels from Norman's theory of action [ND86], Buxton's early taxonomy of input devices [Bux83], the definition of sensels [RP09], and the definition of display resolution.

The Morphees+ taxonomy is a **conceptual contribution** that addresses the limitations and reconciles two existing taxonomies in chapter 3 (sections 3.2 and 3.3). This provides a solution to a problem of **inconsistency** in these existing taxonomies, and provides a solution to a problem of **incompatibilities** between both existing taxonomies (see chapter 3).

The collection of 82 reconfigurable everyday objects (chapter 3, section 3.1) is a **constructive contribution** that helps the design of reconfigurable interactive systems by **extending** a previously existing constructive contribution. The collection of 82 reconfigurable everyday objects can inspire the design of reconfigurable interfaces. This was the first time, to the extent of our knowledge, that such a collection was proposed. We believe that this collection is an important addition to the tools a designer can use to inspire the design of reconfigurable interfaces, as shown in [PRT20]. As a

	Empirical problems	Conceptual problems	Constructive problems	
Progress of knowledge ↓	1st subtype	Unknown phenomena	Implausibility	No known solutions
	2nd subtype	Unknown factors	Inconsistency	Partial, ineffective or inefficient solutions
	3rd subtype	Unknown effects	Incompatibility	Inability to deploy or implement
	▷ Emergeables experiment 2.2	▷ Emergeables concept Morphees+ 2.1 3	▷ Collection of everyday objects 3.1	
	▷ Emergeables experiment 2.2	▷ Morphees+ 3		

Figure 3.4: The problems addressed in this first part, the corresponding contributions and the chapter and section of the manuscript where the contribution is presented.

consequence, we think the collection *extends* previous work that helps the design of reconfigurable interfaces.

We now further assess our contributions through the five associated criteria [OH16]: significance, effectiveness, efficiency, transfer, and confidence. Figure 3.5 shows a synthetic summary of this assessment.

Significance

Significance assesses the importance and relevance of the problems addressed. To analyze the significance of our work, we verified if the problems we addressed are in line with the grand challenges of shape-changing HCI research [Ale+18]. When possible, we also verified how many users are impacted by the solution, and the cost of an absence of a solution.

We rate the significance of the **Emergeables experiment** as very high. The experiment contributes to understand the user experience of shape-change, which is a grand challenge of the field [Ale+18]. We found very important to know if the dynamicity of a tangible interface was putting in danger the expected performance of reconfigurable interfaces. The cost of the absence of this knowledge could have been high for the HCI community: some of the benefits of shape-changing interfaces were taken for granted from previous work on physical user interfaces, in the very dynamic field of shape-changing interfaces, when proposing constructive work (prototypes, interaction techniques, etc.) in the last decade. As an example, [GC19] builds on top of this experiment to build a shape-changing tactile screen for eyes-free interaction in cockpit.

The **Emergeables concept** and the **Morphees+ taxonomy** address the challenge of theory building, identified as one of the grand challenges of shape-changing HCI research [Ale+18], and HCI in general [OH16]. The **Emergeables concept** allows to structure the exploration of empirical and constructive problems together, such as the Emergeables prototypes ([Rob+16; Pea+17]) or later constructive papers (e.g., [Sah+17]) citing the Emergeables paper for their exploration of higher RESOLUTION values. The **Morphees+ taxonomy** provides a conceptual tool to explore the design space, as explained below in section 3.3.2. Both contributions currently only impact HCI researchers, which are few compared to the general public. However, the design exploration these tools will lead to, will eventually impact the general public in the future. Without such contributions in the field of

Empirical contributions

	Significance	Effectiveness	Efficiency	Transfer	Confidence			
					Internal validity	Reliability	Reproducibility	Replicability
Emergeables experiment	High	Medium	High	High	High	Medium	Low	Medium

Conceptual contributions

	Significance	Effectiveness	Efficiency	Transfer	Confidence
Emergeables concept	High	Medium	High	Medium	Medium
Morpheus+	High	Medium	High	Medium	Medium

Constructive contributions

	Significance	Effectiveness	Efficiency	Transfer	Confidence	
					Robustness	Replicability
Collection of objects	Medium	Medium	High	Medium	High	High

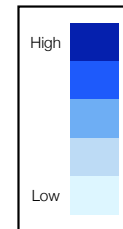


Figure 3.5: Our synthetic assessment of the contributions presented in this first part of the manuscript. Light colors show low significance, effectiveness, efficiency, transfer or confidence, while dark colors show a high significance, effectiveness, efficiency, transfer or confidence.

reconfigurable UIs in general, the exploration of the design space is often driven by technology, and research on reconfigurable UIs would probably miss important design alternatives.

The **collection of everyday objects** addresses the grand challenge of developing more tools that support the design process to integrate artifact and interaction [Ale+18]. While only HCI researchers or makers can benefit from the collection of everyday objects, we believe design explorations of reconfigurable physical interfaces would be solely driven by the technology without such design tools, as said above.

Effectiveness

Effectiveness assesses the match between the solution and the essential aspects of the problem addressed. To analyze this, we first verified that our evaluation criteria matched the priorities of the target users. We verified that we evaluated our solution with multiple, diverse criteria and in multiple contexts, and that we addressed the difficulties that emerge from real world scenarios.

The **Emergeables experiment** is an empirical contribution, and effectiveness is difficult to assess in empirical contributions [OH16]. In this case, it is therefore difficult to demonstrate that the essential aspects of the phenomenon have been identified or addressed. Toward this aim, we identify areas to improve effectiveness by finding relevant factors that could be evaluated in the future.

The experiment compared the **Emergeables** concept with basic tactile sliders and knobs. On the one hand, we believe, as we will show in our formative study (chapter 4), that evaluating widespread knobs and sliders, and considering widespread tactile interfaces as a baseline, is capturing the most essential aspects of the problem. On the other hand, we think the results would benefit in the future from a more diverse and advanced evaluation baseline. For example, it would be interesting to consider more advanced tactile interaction technique for instance using cutaneous or kinesthetic feedback. Comparing shape-changing and haptic interaction techniques is seldom, although it would help the HCI field to better explain the performance of physical user interfaces. Another way of increasing the effectiveness of our results is to experiment with other relevant tasks, such as target acquisition.

Another issue that needs to be addressed in future work is that the **RESOLUTION** did not impact the design of the dials. Future work should create dials made of multiple sensels, allowing rotational controls of different sizes to be created anywhere on the display. Therefore, we think this experiment shows medium effectiveness.

The **Emergeables concept** was used to explore the design space for our **Emergeables** experiment. It matches our own needs and expectations, but we cannot be sure how well it serves other researchers' needs. While the **Emergeables** paper received an *Honorable mention award* at the conference CHI 2016, we cannot be sure about the reasons for this award. We did not evaluate yet the **Emergeables** concept on design problems coming from researchers that were not co-authors of the concept. We are also aware that there is a richer design space to be explored that goes beyond manipulation and resolution (Figure 2.1). The basic tangible manipulations from [Bux83] originally includes pressure in addition to translation and rotation. As we could not include it in the **Emergeables** experiment, we chose not to add it to the design space, but this can be easily added. Moreover, controls could be provided with a range of textures and vary in response, some gliding smoothly, others providing more resistance. Adding such features to a prototype will certainly create a broad range of interaction experiences, including a method to address the eyes-free recognition of controls as they emerge. For these reasons, we rate the effectiveness of the **Emergeables** concept rather low.

We have taught the **Morphees+ taxonomy** at Masters level in Grenoble and Stuttgart, in order for students to explore interaction ideas without considering technology. The taxonomy was subsequently used for our own work presented in part II (**SplitSlider**, **Expandial**, etc.) However, formally evaluating conceptual contributions is a difficult, ill-defined problem. For these reasons, we rate the effectiveness of the **Morphees+ taxonomy** rather low.

Our **collection of objects** showed its effectiveness to identify issues with current taxonomies. However, the collection was not evaluated with designers. For these reasons, we think the collection of objects has a medium effectiveness.

Efficiency

Efficiency assesses the cost in applying the solutions proposed, relatively to the gain achieved. To analyze this, we verified how much effort and/or resources are needed to produce the solution, the scalability of the solution, if we provide a tool for designers to leverage the solution and if we share datasets and code.

We rate the **Emergeables experiment** as efficient. We fabricated prototypes with the fidelity necessary to address our research questions. However, our work did not plan for the experimental code, the collected data and the analysis code to be shared.

The **Emergeables concept** enables an easy and systematic exploration of the design space. However, as stated above for its effectiveness, we are aware that there is a richer design space to be explored that goes beyond the presented contribution. In this work, though, we focused on *manipulation* and *size* that are key to describe the fundamental operation of the controls, and left other dimensions (e.g., stiffness) for future work.

The **Morphees+ taxonomy** is more difficult to use as it relies on precise definitions. Measurable definitions of features are also a strength of **Morphees+** that allows precise comparison between design alternatives. We provided with a summary illustration in order to lower the floor for designers to start working with the taxonomy. We had bachelor and masters students use it during courses and internships in order to verify that the cost of using it was lower than its benefits.

The **collection of everyday objects** is very easy to use and browse for inspiration. We provide a webpage and slides for designers to browse the collection. The collection can easily scale, as we welcome suggestions from others and the webpage is automatically created from a .csv file containing

the collection. We could improve the efficiency by allowing the classification of the daily objects through keywords and tags.

Transfer

Transfer assesses how well does the solution transfers to other problems. To analyze this, we evaluated how many users, tasks and contexts can or could benefit from the solution.

We assess the transfer of the **Emergeables experiment** in a speculative way, as it is difficult to assess without performing additional experiments [OH16]. In general, we cannot be sure that such a contribution could be applied to further users, contexts, such as new tasks and new widgets, in the field or in the long term. However, we easily transferred our own Emergeables experiment to a follow-up experiment [Pea+17].

To assess how well the **Emergeables concept** transfers to other problems, we looked for papers citing the Emergeables paper. At the time of the writing of this manuscript, we found 27 papers, using the ACM digital library and Google Scholar as sources. In our and/or our co-authors' papers, Programmable Liquid Matter [Tok+17], JDLED [Sah+17] and Tangible Drops [Sah+18] do not explicitly refer to the Emergeables concept, although the contributions fit the Emergeables concept. E.g., authors explicitly aim at higher RESOLUTION compared to previous work [Sah+17]. ExpanDial [Kim+19] did not explicitly use the Emergeables concept, although the contribution partially fits in the Emergeables concept. Exhi-bit [OMN17] and KnobSlider [KCR18a; KCR16] (chapter 5.2) explore a space outside of the Emergeables concept. E.g., KnobSlider aims at reaching high resolution at the cost of less flexibility, hence stand outside the Emergeables concept. Other papers, such as the deformable Pain Palette [Ste+17] refers to the experiment rather than the conceptual contribution. In others' papers, PneuModule [Han+20] does not explicitly refer to the Emergeables concept, although it clearly extends the exploration of the Emergeables design space to *force* that was in the Buxton's original design space [Bux83], in addition to translation and rotation, however with a low resolution of sensels. Tacsels [GC19] and shiftIO [Str+17] do not explicitly refer to the Emergeables concept, although they fit the Emergeables concept. Other papers, e.g., GazeForm [Pau+18] and DynaKnob [Oos+19] explore a space outside of the Emergeables concept. E.g. GazeForm explores the activation of shape-change rather than the design space of Emergeables. Other papers, such as UnCovers [Hog+17], do not refer to the Emergeables concept, but rather to the experiment. As we were able to find a few papers for which the concept applied well, we evaluate the transfer of the Emergeables concept to rather high.

The **Morphees+ taxonomy** is an improvement of the Morphees taxonomy [Rou+13] for shape-changing surfaces, which itself was transferred from the features of B-splines of computer graphics [Rou+13]. Morphees+ paper [KCR18b] is cited 8 times when writing this manuscript. Some of these citations do use Morphees+ as a design space (e.g., our own SplitSlider [Gre+19]) or as a tool to compare design alternatives (e.g., HapTwist [Zhu+19]). Others do not use it explicitly (e.g., transTexture Lamp [Zho+20]) or rather cite its definition of reconfigurable interfaces (e.g., Multi-plié [Pau+19]). Therefore, we evaluate the transfer of the Morphees+ taxonomy to rather medium.

Few papers refer to the **collection of everyday objects** (e.g., [Zhu+19]). The best documented use of the collection by others is found in a work using the collection of everyday objects as an inspiration tool to design the affordances of shape-changing interfaces [PRT20]⁴. In other papers, it is difficult to know if the collection helped to generate design alternatives or worked as an inspiration,

⁴While Petersen, Rasmussen, and Trettvik [PRT20] clearly refer to the collection of everyday objects as an inspiration tool to design the affordance of shape-changing interfaces, the authors –probably mistakenly– cite the original *Morphees* taxonomy instead of the improved *Morphees+* taxonomy.

as there is often a gap between the design process as presented in a paper and as it really happens. Without such information, we rate the transfer of the collection of everyday objects to medium.

Confidence

Confidence assesses how well will the solution hold as time passes. To evaluate this, we verified empirical validity, reliability, replicability, reproducibility, robustness, if we allow re-analysis, and how many metrics were used to assess validity and reliability.

Our **Emergeables experiment** is an empirical contribution. We therefore more particularly assess our confidence in this contribution through the following four criteria from the problem-solving view on HCI [OH16]: internal validity⁵, reliability, reproducibility and replicability.

Internal validity is the adequacy of the experimental procedure, the method for the recruitment of participants, and the methods for analysis, in particular the statistical methods when applicable. For our Emergeables experiment, we tried to reach high confidence through the recruitment of 18 participants, with a rather large range of age (18 – 66). Half were female and half male. While the prototypes were targeting mobile interaction, the participants did not walk and were in a lab rather than in the wild. This was necessary as the prototype was tethered to a laptop. Reviewers of our corresponding publications [Rob+16; Pea+17] mostly found our methods for analysis relevant.

Reliability assesses how consistent were the results across, e.g. participants, types of measure, or repetitions. We did not explicitly evaluate the reliability of the Emergeables experiment. The consistence between participants and repetitions together is implicitly evaluated through, e.g., the confidence intervals. As a consequence, it is taken into account in the reporting of the results. We systematically explored the data after its collection, for instance by drawing graphs of raw data, overall boxplots and boxplots per participants, checking the learning or fatigue, etc. However, these results are not reported in the papers [Rob+16; Pea+17].

Reproducibility is the ability for others to recreate the same results by running the same analysis again from the collected data. For the Emergeables experiment, we did not plan to share the collected data at the time of the writing of the consent form. This makes it difficult to have the participants' consent to share the anonymous data afterwards.

Replicability assesses the ability of our empirical contributions to be repeated by running the whole experiment again and obtain a consistent result. The experimental codes and fabrication materials of the Emergeables experiment are not distributed. As a consequence, a replication would need to build the prototype and code the tasks again. In this case, it is difficult to evaluate the impact on the results of a difference between two different implementations of a prototype and of an experimental software.

It is currently early to assess our confidence for the **Emergeables concept** and the **Morphees+ taxonomy**, as it was little applied (as seen on p.37). For such conceptual contributions, confidence can be assessed by checking that we did not forget to consider any important elements [OH16]. This is also our assessment of effectiveness on p.36.

The **collection of everyday objects** is a constructive contribution. We assess in particular our confidence in this type of contributions through its robustness and replicability.

Robustness assesses how the collection of everyday objects addresses any elements that could work against it. The collection is a simple .csv file with scripts that can convert it to a Webpage or a deck of slides. We believe its simplicity makes it very robust.

Replicability assesses the ability of the collection of everyday objects to be exactly copied or reproduced. Although this is of little interest, copying the collection is very easy from the Webpage.

⁵External validity, on the other hand, is assessed through the *transfer* criteria, i.e. how well does the experiment apply to other situations, tasks, users, etc. or in the field or in the long term.

In this Part I, we aimed at providing basic knowledge to lay the ground for the exploration of shape-changing tangible controls, that we present in the next part.

Part II

Exploring reconfigurable controls

Chapter 4

Formative study: Balancing flexibility and physicality

While the HCI research on reconfigurable interfaces tries to focus on the users' needs, most of this research does not *start* from the users' needs. The main reason is that reconfigurable interfaces now mostly face technological challenges [Ale+18]. It is therefore hard to conduct evaluations with end-users manipulating fragile prototypes (e.g., [PSH14]). Little research therefore studied end-users needs before designing an interface, as the resulting prototypes are not robust enough to then validate the ability of the interaction techniques to answers end-users' needs.

We wanted to ground our research on real-world needs, as we did not know how end users currently balance between flexibility and physicality. To learn this, we conducted in summer 2015 the study presented in this chapter.

4.1 Participants, apparatus and methods

To gather requirements as general as possible, we decided to target various professions requiring physical interfaces. We first identified the most widespread professions extensively using physical input control, thanks to the US Bureau of Labor Statistics¹. We therefore decided to recruit graphic designers (261,600 in 2014 in the US), pilots (119,200 in 2014 in the US), sound engineers (117,200 in 2014 in the US), camera operators (20,060 in 2014 in the US), and light engineers (included in the 11,930 exhibit designers in 2014 in the US). This approach allowed us to seek significance through a large population of users (e.g., graphic designers) and whose performance is critical to others (e.g., pilots); as well as to seek generality through diverse professions. Through our extended social network and contacting local professionals, we recruited 8 participants² (ages 25–63, 2 females, Figure 4.1) using control interfaces in their professional activities: 1 movie operator (P1), 1 graphic designer (P2), 2 light engineers (P3, P4), 2 sound engineers (P5, P6), and 2 pilots (P7, P8).

We used a notebook and a camera during the study. All participants were voluntary and consented to photo and video recording. The interfaces participants were using were mainly physical, although a few recently started using touchscreens.

¹<https://www.bls.gov>

²Eight participants is said to be enough to obtain robust results using the contextual interview method [HWW05].

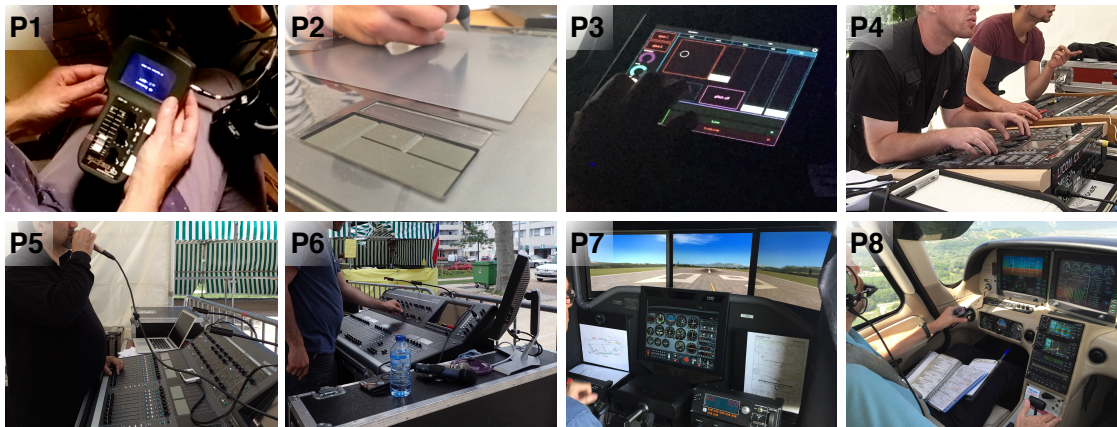


Figure 4.1: Participants using physical interfaces in their professional activities: (P1) a camerawoman; (P2) a graphic designer; (P3) a light artist using a custom UI in a dark environment; (P4) a light engineer using the UI while observing a stage; (P5) a sound engineer communicating with musicians on the far stage while using the UI; (P6) a sound engineer controlling the UI while watching a screen; (P7) a pilot using a flight simulator for his training; (P8) a pilot using physical controls during a flight.

We conducted a contextual inquiry with the participants [HWW05]. The method is based on semi-structured interviews where researchers observe users performing tasks in their real work environments and note –or ask about, when not clear– everything happening around a particular topic. Our inquiry specifically targeted the balance between *physicality* and *flexibility* during the use of their system. The details of the method and analysis can be found in the corresponding papers [KCR16; KCR18a; KCR19].

4.2 Results

While we observed push buttons for the control of modes, discrete parameters or commands, we will particularly focus here on the interaction with continuous parameters, as discrete physical and flexible UIs were researched before (e.g., [HH09]).

We identified six users' needs regarding a *physical and flexible control of continuous parameters*. We mostly observed knobs and sliders allowing the control of continuous parameters. For this reason, the remaining of the thesis explores in particular these two types of interfaces. Most knobs were potentiometers with no bounds or detents, of around 1cm diameter with small lobes on their sides. We observed a few varied knobs: e.g., with position mark (P1), concentric ones (P8), discrete arrow-shaped ones (P8) or large knob with a concave notch for rotation with a single finger (P4). Most participants used large sliders (between 8 and 10 cm).

In the following, we present the users requirements, and illustrate them with examples of actions we observed, or comments made by the participants.

4.2.1 Interaction with a large number of parameters

All participants interacted with a large number of parameters. The number varied depending on their professions. For instance, the fewest number of parameters were ten, which P1 (cinema operator) used

to control the stereoscopic cameras: 3D position and 3D orientation, focal length, 1D focus distance, interaxial distance, and convergence. P2 (graphic designer) used as many of the ~60 Photoshop tools and their parameters (e.g., brush size, tip, roundness, hardness, etc.). During the show, P3 adjusted around 50 parameters in total. P4-8 (sound engineers, light engineers, and pilots) had more than 100 parameters to deal with.

4.2.2 Fast interaction

We observed that participants needed fast access to, fast manipulation of, and fast observation of the parameters.

Fast access to parameters. In many situations, the users needed to quickly acquire the devices. For example, to quickly access the parameters of a fan and a fog machine during the show, P3 (light artist) chose to permanently display two dedicated knobs on the left-hand side of his interface (Figure 4.1). P2 explained that her desk is always tidy: the participant needed a clear space to go from one device to another without losing time. P5 told that he never used the sliders that are too far away, and preferred pressing a button to quickly switch the parameters associated with the sliders that are close to him.

Fast manipulation of parameters. For instance, P7 related that the throttle was used by default for quick, coarse adjustments. P1 and P3-P6 worked “live”, i.e., during the shooting or the show, so they must manipulate the parameters promptly. When working for music concerts, they needed to be very reactive as musicians never play the same way. The need for fast manipulation required some participants (P3-P6) to use several fingers on sliders or each hand on different devices. P2 explained that she started using the computer to work faster: her work requires several back and forth exchanges with the client who asks for modifications. She uses the computer to do quick corrections (undo) that physical brushes and pens could not do.

Fast observations of parameters. For example, P1 was manipulating interaxial distance between stereoscopic cameras and the bounds of the slider were clearly showing her the physical constraints of cameras. She also used red tape to mark a particular value of the interaxial distance during the shooting (see Figure 4.1 (P1), the left side of the slider). P5 and P6 sometimes quickly glanced at their interfaces to observe a parameter value during the show. During manipulation, the knobs of the cockpits (P7-P8) provided haptic feedback through haptic detents. For quick observations of parameters, P7-P8 looked or touched the corresponding devices. P7 explained that in emergency situations, quick observation of parameters is critical. Overall, sliders were preferred for rapid observation of parameters.

4.2.3 Accurate and precise interaction

For precise interaction, most participants used large sliders (between 8 and 10 cm), with very little friction to allow tiny movements. The only small slider we observed was a tactile one with a placeholder (Figure 4.1, P2), to zoom on the screen.

Knobs, even when small, also offered high precision as most of them were multiturn. Using the knob for precise control was done by P2 who used her tactile dial with a placeholder to scroll webpages. We observed P4 (light engineer) using a knob before the show to very precisely set the angle of a projector (Figure 4.1, P4). For this, P4 performed many rotations on a knob with low control-display (CD) gain. Similarly, P7 and P8 (pilots) used knobs to accurately input decimal values of radio frequencies. P7 related that the extremity of the throttle of his aircraft could be rotated

for precise adjustments. P6 needed to adjust the curve of the sound level for each frequency of each instrument and microphone on stage. The participant preferred using the physical knobs for this rather than the touchscreen. P1 (movie operator) used a knob to adjust, at pixel precision, the horizontal shift between stereoscopic images, by performing multiple rotations. Overall, knobs were preferred for precise interaction.

4.2.4 Eyes-free interaction

P1 needed eyes-free interaction because her screens were not collocated with her knobs and sliders. Similarly, P2 focused on her canvas on the screen. She looked away from the canvas to modify her tool, and lost time finding her object on the canvas again. P3-P6 watched the stage while interacting (Figure 4.1). P5 explained that he preferred physical controllers, and never used the touchscreen of the console, which our observations corroborated. P5 and P6 said that interacting with bounded parameters on multiturn – i.e. unbounded – knobs was not comfortable, as they have to look away from the stage to watch the LEDs around the knob. Bounded knobs were not available on the mixing console we observed, and the two sound engineers participating in the study said that they also seldom find them on other mixing consoles.

P3's problem with touchscreens was that he felt "blind" as there was no haptic feedback. We observed P3 missing an intended trajectory of a knob on the screen: the participant started to follow the knob on the tablet. While looking at the stage, P3's finger drifted from the knob, losing control of it. When the participant realized it, he looked down to reacquire the knob. We observed the participant trying to acquire two touchscreen sliders eyes-free: one with the index finger and the second with the middle finger, both unsuccessfully. P3 then looked down to re-acquire the sliders. This participant recouped the lack of tangibility with extra-large widgets, but it was not satisfactory for him: he lost space, and still lacked tangibility, which caused critical errors.

P7 and P8 (pilots) used push/pull handle for power and mixture (of air and fuel) and often placed their hand on the handles to know their status without looking (Figure 4.1, P8). P7 said, "If you put your hand on [the control device], you know in which mode you are". They commented that physical devices were particularly useful when visibility in the cockpit was altered by smoke. P7 and P8 both explained that aircraft manufacturers were introducing touch screen interfaces. Both agreed that the idea was dangerous. Their comments strengthened the cockpit design requirements in previous work [CC16; Vin+16].

4.2.5 Mobile interaction

All users needed mobility. P1 used her cameras and control devices at different shooting locations. P2 sometimes worked away from her desk, e.g., in a van during a vacation. P3 explained that moving around the stage was crucial for him: when not possible, he communicated with someone in front of the stage as a proxy. Unfortunately, this person might not understand what he wanted, or this person did not have the same demand on the final quality. To avoid losing time or quality, P3 used a tablet, but sub-optimally moved back and forth between his desk and the stage. P4 went on the stage to better see the projectors, and then came back to the console. We observed P5 going on the stage to ease the communication with musicians. P5 said this was the only reason he used the tablet, as he did not like using the sliders/knobs on touch screens. To avoid using the tablet, the participant communicated with musicians via a microphone (Figure 4.1, P5), or even shouted or signed. Sometimes a third person was necessary to help communication with drummers who did not have a microphone. Thus, all solutions were suboptimal. Mobility was also necessary during the show: P6 walked around the venue to hear the sound from other locations. P6 then had to come

back to the mixing desk to adjust the parameters. P7 and P8 (pilots) had a compact interface that fits in the flying cockpit.

4.2.6 Retro-compatibility

The professional users needed to leverage their existing expertise with current interfaces. For example, P2 explicitly commented that she was not keen to change her interface to another, because her workflow was efficient and she was not ready to lose income for a short term. Similarly, P5 did not use his tablet as much as he used his mixing console, as the tablet lacked retro-compatibility, such as tangibility. The only participant that explicitly showed no interest in retro-compatibility was P3. P3 built a new interface dedicated for each show and improved it with practice. He used the touchscreen interface and laptop, and tried to use new technologies such as Leap motion although he did not use it during our observation. Yet, his touchscreen controllers were mimicking physical ones (knobs, sliders, buttons, etc.).

4.3 Concluding requirements

We derived the following six requirements directly from the themes of our formative study.

- R1 **Interaction with a large number of parameters.** All participants needed to control a large number of parameters through their workflows. The cameraman had the least (10). The sound and light engineers can deal with more than 100. Types of parameters were diverse: some were discrete (e.g., tool in Palette) or continuous (e.g., sound volume). Some were bounded (e.g., flaps' angle) or not (e.g., shift between cameras). Some were cyclic (e.g., projector's angle).
- R2 **Fast interaction.** Participants needed to control parameters quickly. To do so, they needed quick access to, rapid manipulation of, and fast observation of parameters. Quick access to parameters can be supported by placing devices within users' reach. Rapid manipulation of parameters can be supported through smooth trajectories. Fast observation of parameter value can be supported by visual and/or haptic display, including min/max value or value of interest.
- R3 **Precise and accurate interaction.** The participants also needed accurate and precise control of parameters. Precision can be supported through a large interaction area (multiturn knob or large slider) and little friction. Enough space between devices prevents errors. A stable grip on the device also allows its operation without slipping and therefore increase accuracy.
- R4 **Eyes-free interaction.** The participants needed to observe how the controlled parameters affect the stage, video, graphic, sound, etc. while interacting with the interfaces. Eyes-free access to parameters can be supported by spatial stability of the device to leverage motor-spatial memory (chapter 2). Eyes-free manipulation of parameters can be supported through physical trajectory guide (e.g., the rail of a slider, the rotational axis of a knob), and cutaneous or kinaesthetic feedback. Eyes-free observation of the value of a parameter can be supported through a physical cursor or kinaesthetic feedback such as provided by detents.
- R5 **Mobile interaction.** Some of the participants such as the light engineers needed to move around the workplace to check the audiences view. Mobile interaction can be supported by small devices, such as when the light engineer used his tablet to control some parameters in front of the stage.
- R6 **Retro-compatibility.** The participants are professional, and new interfaces need to provide a very smooth transition from current interaction: it is arduous for users to give up current UIs

– even though new ones can be beneficial in the long term [Sca+11]. This can be supported by standard operations of standard devices and customizability.

Some of these requirements call for physicality, such as R4 (eyes-free interaction). Some of these requirements are incompatible with each other. For instance, a slider should be large for precision and small for mobility. This is where flexibility could solve current usability problems. As a consequence, this thesis will explore UIs that are both physical and flexible, in order to maximize users' satisfaction. These requirements served as a basis for the exploration of reconfigurable control widgets, presented in the following chapters.

Chapter 5

Exploring reconfigurable dials

A dial is a control device for “analogue (infinitely variable) adjustment of a one-dimensional variable” [BT02]. It is controlled through its rotation around the axis perpendicular to its support surface. Dials have been here for decades, and are widespread as seen in our formative study (chapter 4). Dials allow precise and rapid control that is not achievable with other tangible devices [BT02]. However, our formative study (chapter 4) showed that dials lack physical flexibility. In particular, users would benefit from dials that can change from low to high (e.g., [JH16]) and small to large (e.g., between 7mm and 80mm [AFN08]) (section 5.1) and dials that can change to a slider (section 5.2). In this chapter, we present two studies introducing physical flexibility into dials.

5.1 ExpanDial: dial changing its height and circumference

Design handbooks and previous research explore different ranges of width and height: e.g., between 10 and 30 mm (height and width) [BT02], 7mm and 80mm (height and width) [AFN08], 25 and 75 mm (width) [KKK01], or 10 mm and 82.5 mm (width) [Bra69]. Despite being widespread, there have been few researches on opportunities and challenges of dials that can change their size dynamically.

While previous work explored dials changing a single shape parameter (e.g., height [SKB17] or diameter [OBJ18]) and focused on particular applications (e.g., music [SKB17] or temperature control [OBJ18]), on the contrary we would like to explore reconfigurable dials *in a general perspective* with a design changing both height and diameter.

5.1.1 Prototype

Based on our formative study (chapter 4) where we observed many shapes of dials, and on our grasp study [Kim+19] where we observed how users grasps each shape, we prototyped the reconfigurable dial presented in Figure 5.1. We used NASA’s Star Shade pattern [Noj02; Sal15] (Figure 5.1) as a round resizing mechanism. The pattern allows the folded piece of paper to change width while keeping its round circumference. The ratio between the minimum and the maximum width varies depending on the design and the paper material [Noj02]. We tried various patterns and chose the one working well with simple paper. We grooved the pattern on paper by using a vinyl cutter. We then stacked five pieces of the folded paper to make a cylinder and connected the edges of the sheets using 3D printed connectors (Figure 5.1b). We then fixed the stack on a Palette¹ sensor that senses rotational movement and click.

¹<https://monogramcc.com/#palette>

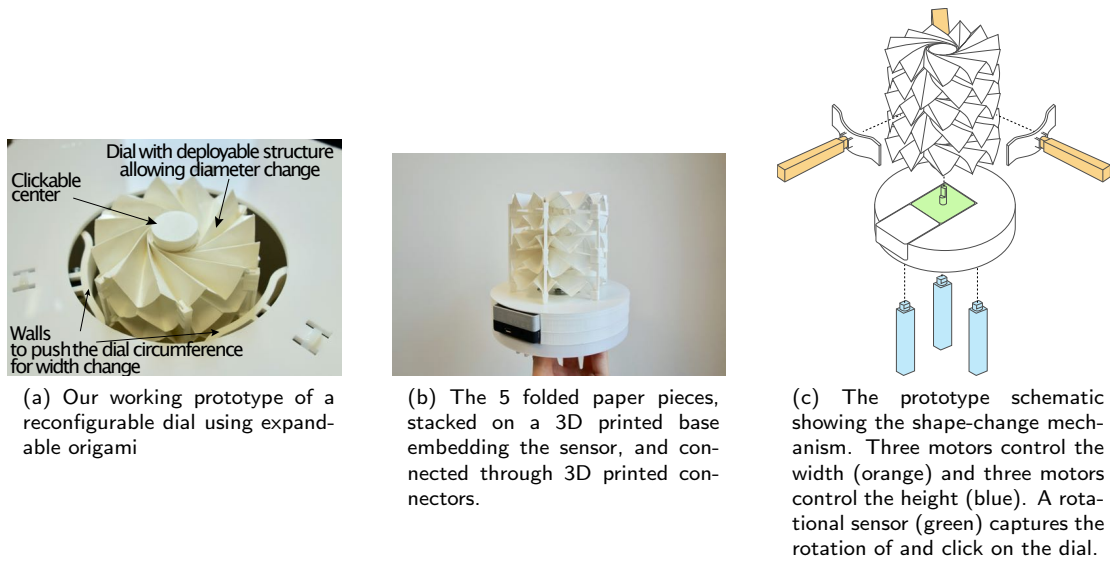


Figure 5.1: ExpanDial prototype: a reconfigurable dial using expandable origami.

Below the sensor, we placed three linear actuators that enable height changes (Firgelli L12-50-100-6-R, blue in Figure 5.1c). To change the width, we placed the three identical linear actuators around the circumference (orange in blue in Figure 5.1c), with walls at their extremities. The walls evenly push and release the circumference of the dial. When the walls push the stack, its width is reduced. When released, the stack goes back to its maximum width thanks to the paper tension.

The size of the case below the dial was around $W360 \times L305 \times H230$ mm. For clarity, we call the stack of folded sheets of paper the *dial*, and the box that accommodates the shape-changing mechanism the *case*. The prototype can change its width from 3.6cm to 9cm and its height from 2.3cm to 6.3cm.

This prototype aims at addressing the requirements of end-users (chapter 4). In particular, it allows to control 2 parameters (angle, height) in addition to the angle controlled by existing dials. Its 3.6+cm diameter and 2.3+cm height, allow for its fast acquisition. Its change in diameter could allow for a change in control-display gain in order to allow for both fast and precise manipulation of parameters. Fast observations of parameters could be improved, e.g., by adding a marker indicating the current value of the parameter. The prototype allows for eyes-free manipulation. The prototype is however large and tethered, preventing mobility. The prototype allows for retro-compatibility with existing dials.

5.1.2 Focus group evaluation

We collected opinions on dials that change height and width through 2 sessions of focus group interviews, each gathering 5 participants. We provided ExpanDial (Figure 5.1) as a probe. We aimed to gather feedback and suggestions on our ExpanDial prototype, its potential applications, and the possible users' gestures to change its height and width. The detailed procedure can be found in [Kim+19]. We asked all participants to try the prototype (Figure 5.1) such as rotating, clicking, and squeezing. Participants wrote down their answers to the following questions on sticky notes:

1. *What do you like/don't like about the dial?* We aimed here at collecting user generated ideas

for the improvement of the prototype.

2. *What would be the dial's applications?* We asked the participants to think in the frame of application areas (work, home, entertainment, others) and modalities (control and/or display), where ExpanDial may be able to support current applications and replace current interfaces. By doing this, we expected the participants to generate application ideas that can reveal potential advantages and challenges of reconfigurable dials.
3. *Let's say you know that you can change the dial's width and height, but you don't know how. What kind of actions or gestures would you perform?* We asked participants to think about at least one gesture for each of the following control methods of the dial: increasing width, decreasing width, increasing height, and decreasing height.

Participants were asked to consider only the dial and not the case. They were asked to think that the device works perfectly and sense the changes in width and height done by the user. After each question, the participants shared their ideas while putting their notes on a board in order to trigger group discussions.

Prototype improvement and implications for reconfigurable interfaces

We report here the participants' comments about ExpanDial that concerned the design of a shape-change device. Detailed results are presented in [Kim+19].

Affordance. Five participants liked how the origami pattern afforded pressing to reduce the diameter. Affordance and feedforward allow users to perceive that, and how, a device can change its shape. It is knowingly difficult to inform users of the transformational capabilities of the system [Ish+12; HV08; TH16]. However, this is an important ergonomic property, known as the *Prompting* ergonomic criterion [BS93]. Using a reconfigurable material that explicitly shows how it works, such as origami or kirigami as we did with the ExpanDial prototype, can improve the *prompting*. The design of interfaces that explicitly show how they can change shape is an interesting future work [PRT20].

Control over shape-change. Two participants complained that they could not "squeeze" the device vertically. This shows that direct control [Ras+16b] is important for users, known as *explicit user action* criterion in ergonomics [BS93].

Integrity vs. separability. Three participants said that the dial was too easily squeezable so that it could cause unwanted squeezing while grasping or rotating. While shape-change is an opportunity to increase the bandwidth between users and the system, it is important to know the integrity/separability of these novel modalities, including the change of shape, for the future reconfigurable devices to be usable [Jac+94].

ExpanDial application ideas

Our participants suggested 41 application ideas that were relevant to height- or diameter- changing dials.

Work, home, entertainment. We categorized 23 ideas as work-related, 11 as home-related, 13 related to entertainment, while four did not belong to any of the three categories.

Around half (11/23) of the **work** ideas were using ExpanDial to interact with desktop computers. It was not surprising as our participants' background was Computer Science. Seven of them were using ExpanDial for 3D interaction or graphical tools, e.g., changing camera-view in a 3D modeling software and changing airbrush size in Photoshop by rotating or squeezing the device. The rest of the desktop computer interaction ideas were OS level interactions, e.g., users squeezing the dial to

minimize all windows, or the dial changing its width to notify new emails. Only three of the work ideas were not related to desktop computers: using the dial as a controller of a surgery robot or a construction machine. E.g. the width would change when patients' heart rate dropped around a limit.

Many of the **home** ideas (7/11) were about controlling remote home appliances and displaying information about them, as in smart home scenarios. Three other ideas were changing the width and rotating the dial to set the temperature or the timer of an oven. The system changed the dial height and/or width to show remaining time. The last idea was using the dial as a morning alarm clock. E.g., users set the time by rotating the dial, and the dial would become larger and larger until that users cannot ignore it anymore. The participant said that the dial would have light inside, and it would get brighter as the set time comes as well.

Among the 13 ideas in the **entertainment** category, five were related to gaming. The system gives feedback on the game status (e.g., the character in a danger) with shape-changes, or users squeeze the dial to activate certain functions. Two ideas were using the dial to control multiple audio parameters (e.g., volume, distortion, tone) at the same time. Another two were to use the dial as stress release by squeezing it.

Other ideas were general interaction methods and could be applied to any applications or systems. Two of them were using the particular design of ExpanDial (i.e. origami), e.g. using each paper layer for discrete control or display. For instance, each layer could set or display the temperature of each room in a house. Another idea was to change the dial size for better ergonomics, e.g., smaller sizes for small children or bigger sizes for elderly who lack fine motor skills [Hoo+14]. The last idea was to give force feedback when the system cannot perform a desired function. E.g., users try to squeeze the dial to reduce a Photoshop brush size while the size is minimum. The dial gets stiffer and prevents any further squeezing.

Control and/or display. We categorized twenty ideas into control, fifteen into both control and display, four into display, and the last two into others. For these categories, we did not allow multi-selection as they were mutually exclusive.

Half of the **control** ideas (10/20) were controlling multiple parameters by using the shape-changing ability of ExpanDial. For example, users can explore a color space, or change transparency and size of a brush by rotating, squeezing, and change height of the device simultaneously. There was no idea of controlling different parameters by changing the force or speed of interaction, which was suggested in Dynamic Knobs [Hem+08]. Two control ideas were combining the dial to existing devices, such as a joystick or Wii remote.

Fifteen ideas were in the **control and display** category. Among them, ten were to give haptic or force feedback with the width/height change of ExpanDial. These included leading users to use different forearm muscles (e.g., rehabilitation game), giving an immersive experience (e.g., force feedback for an airbrush interaction in VR), and notifying users when they are holding the dial (e.g., expanding the width when there is an urgent task while scrolling through a to-do list with rotation). Another control and display idea was using the dial combined with a mouse, to scroll by rotating or to notify users of desktop events by expanding the width, similarly to the Inflatable Mouse [Kim+08b].

One **display** idea was to use the device as a shape-changing ambient or peripheral display as in previous work [Hem+10; Yu+16]. The participant said that ExpanDial could animate an air quality display in a room with a breathing rhythm (i.e., slow breathing when the air quality is good and fast breathing in the other case). The other two ideas were changing the width or height to notify the user about a new email or that a cooking timer finished.

Overall, these ideas shows that the participants found the ExpanDial prototype possibly useful. The results from this part of the focus group aim at identifying an application as context for a future

evaluation of a more advanced prototype.

Gestures for controlling the change of shape

We collected 48 gesture ideas to increase or decrease the diameter or height of ExpanDial (see Figure 5.2). After merging duplicated ideas, we got on average six types of gestures per interaction: increasing the diameter, decreasing the diameter, increasing the height, and decreasing the height.

Changing the diameter. Participants' ideas for changing the diameter of the dial are shown on the first two lines of Figure 5.2.

Participants proposed nine rotation gestures with the dial to increase or decrease its diameter. Two participants explained that this interaction was similar to screwing, while one participant mentioned an analogy with the centrifugal force. One problem with these propositions of rotational gestures, is that it conflicts with the primary interaction with the dial, also through rotation. To distinguish the rotation for changing the diameter from the one for rotational input, the participants suggested ideas such as having modes (e.g., pulling up the dial for diameter change) or using different speeds (e.g., slower rotation for width change).

Six ideas were inspired by touchscreen gestures: sliding outward or inward on the top of the dial, tapping or double-tapping side of the dial, and pinch-out or pinch-in on the dial. One participant said that she prefers touch gestures as they are simple, and she would feel lazy to do other gestures (e.g., rotating).

Participants proposed four direct interaction ideas to decrease the diameter, i.e. squeezing the dial. The corresponding gestures to increase the width varied. The four corresponding gestures are shown at the top row on the right of Figure 5.2. First, participants proposed to quickly squeeze the circumference to activate the expansion of the dial, and to grasp it again to stop the expansion when they reach the desired diameter. Second, participants proposed to grasp the dial with two hands and pull the circumference outward to reach the desired diameter. Third, participants proposed to click the top of the dial to reset it to the largest diameter and then squeezing to reduce the diameter. Fourth, participants proposed to use all five fingers around the circumference of the dial and to stretch out the fingers to expand the diameter.

Changing the height. Only two of the height-changing gestures were rotating the dial. Although two participants said that the rationale of rotating gestures was from rotating screws, surprisingly fewer rotating ideas were suggested for height change than for diameter change.

Similar to the diameter-changing gestures, touch gestures (slide and tap) were also suggested for height change. The touch gestures were similar to gestures for changing the diameter, but the locations of the gestures changed: sliding on the side of the dial and tapping on the top of the dial. The directions of the touch gesture is parallel to the direction of the change.

Participants proposed direct interaction. Five ideas revolved around pulling up or pushing down the dial, although two participants mentioned that they would feel lazy to move their arm upward. To cope with this problem, an idea was clicking the dial to make it go back to the maximum height then decrease the height by any other gestures. The last idea was manually adding more layers of segments (e.g., layers of folded paper), which was probably inspired by the layered design of ExpanDial.

Interestingly, many of the suggested gestures were from touchscreen interactions. On the one hand, one of the aims of reconfigurable interfaces is to fully use human's dexterity [Ish+12], and thus mapping touchscreen-based gestures to them might not fully exploit human capabilities. On the other hand, it could improve users' learnability and transition from touch interfaces to reconfigurable ones (R6 Retro-compatibility in section 4.2.6). The challenge lies in finding a trade-off between gestures

Targeted shape-change	Rotate	Slide	Tap	Pinch	Decrease Cir./Height & Let Go	Direct Deformation	Click & Action	Use All Fingers	Use Segments
Increasing Circumference	Rotate (5)	Slide Outward (1)	Tap (1)	Pinch Out (1)	Squeeze & Let Go (1)	Grab & Pull (2)	Click & Squeeze (1)	Use All Fingers	Use Segments
Decreasing Circumference	Rotate (4)	Slide Inward (1)	Double Tap (1)	Pinch In (1)	Squeeze (4)				
Increasing Height	Rotate (1)	Slider Up (1)	Double Tap (2)/Tap (1)		Click & Let Go (2)		Click & Push (1)		Add Segments (1)
Decreasing Height	Rotate (1)	Slide Down (1)	Tap (2)/Double Tap (1)						

Figure 5.2: Suggested gestures to increase/decrease the diameter and height of dials. Gestures are vertically aligned by their similarity with other shape-change gestures (e.g., “Squeeze & Let Go” to increase and “Squeeze” to decrease the diameter were suggested together). The numbers in the parenthesis show how many of our 10 total participants suggested the gesture.

that are general and easy to be applied to all kinds of interfaces and gestures that leverage the input capabilities for each particular interface.

Many of the non-rotating gestures (e.g., slide, pinch, click and action) were using the top of the dial. This is compatible with another study of ours [Kim+19] where we found that users grasp dials mostly from the top. Squeezing, pushing and pulling also require grasping the device, but they are new interaction with dials and users may grasp the dial differently for these manipulation than for rotating. Future work should study users' grasp for these particular interactions.

Conclusion

Motor and perceptual abilities. The participants were concerned about their own capability to control the width and height. This raises the question of the human resolution [BR12; BWC11] for these deformation gestures. The participants were also concerned about their ability to properly perceive a change in width and height. The height of bars similar to dials can be recognized [JH16] but we are not sure this result would hold for widths.

The participants were concerned about the undesired width change when grasping or rotating the prototype. Future work should study how much pressure users may apply to rest their hands, to rotate the device, and to change the width or height of the device.

Some application ideas were using the height for display. These ideas take for granted that users would feel the height when manipulating *Expandial*. However we are not sure that users would be able to always feel the height change, especially when they are manipulating the device.

Interaction techniques. Future work should address the design of the gestures allowing the manipulation of the angle, the diameter and the height, without affecting the users' grasp-s. Some of the open research questions are: Is the simultaneous change of height, width and angle possible? Can the sequential manipulation of these physical parameters efficiently support the user's tasks? Is one- and/or two-handed interaction desirable? Can we find a set of gestures that allows simultaneous change of angle, width and height while avoiding undesired input? A first intuition resulting from our evaluation is that different kind of pressures might be applied for turning vs. deforming the dial.

Future applications and studies should explore a wide range of expected benefits, from emotional and hedonic user experience to task performance. A grand challenge for such novel devices is to support simultaneously an easy transition from known interaction (e.g., touchscreen) to the new interaction techniques, while at the same time exploiting all its capabilities to augment the input bandwidth.

5.2 KnobSlider: dial changing to a slider

The work on KnobSlider that we present in this section, is grounded in our observations from the formative study (chapter 4), where we observed users interacting with either sliders and/or dials, sometimes for a same task. To support a flexible use of dials and sliders, we present the design approach of the KnobSlider reconfigurable device, before we present the qualitative users' feedback we gathered. We finally present a study on how users' perception of shape-change varies depending on the speed and presentation of the prototype (tangible vs. video).

5.2.1 Design

Our approach consists in the three following steps: First, we explored the design space of existing control interfaces in terms of space- and time-multiplexing (Table 5.1). Second, we created low-fidelity prototypes (Table 5.2) by using ideas inspired from deformable artifacts found in daily objects

	No time-multiplexing: Device(s) available all the time	Time-multiplexing: Devices available in sequence
No space- multiplexing: One device available on the workspace	(1) A dial or a slider [CM15; Mic+04; SKB17; Váz+15]	(2) A dial and a slider in sequence [Fol+13; Nak+16; RSL14; Rob+16; Tsi13]
Space-multiplexing: Multiple devices available on the workspace	(3) Adjacent dials and sliders, and stacked dials and sliders [BE09; Cha+12; DMS07] and current, observed systems	(4) Dials and sliders anywhere, anytime: [Fol+13; Rob+16; Tsi13; JDF12; Wei+09] and current, observed systems

Table 5.1: Design space of control interfaces, in the perspectives of time- and space-multiplexing.

or on fabrication and DIY websites. Third, we analyzed them using the design requirements from the formative study (Table 5.3).

The result of this approach is the working prototype of KnobSlider that we present at the end of this section.

Exploration of the design space

We focus on the physical interfaces that have some retro-compatibility (R6, section 4.2.6) with physical knobs and sliders. These interfaces can have different spatial and temporal combinations as shown in Table 5.1. The current solutions largely cover the design space but lack some of the requirements from chapter 4:

1. A single knob would hinder the fast and eyes-free operation of a parameter (R2, section 4.2.2 and R4, section 4.2.4). A small single slider would either hinder precision (R3, section 4.2.3) and a large single slider would take too much space (R5, section 4.2.5) on a surface.
2. A knob or slider sequentially morphing out of a surface currently lacks continuity (R1, section 4.2.1) or physical cursors (R4). Manually placing a knob or a slider on a surface is time-consuming (R2).
3. Adjacent knob and slider are space-consuming (R5). A knob on top of a slider (and vice-versa) would cause unwanted movement thus lack precision (R3).
4. Physical knobs and sliders anywhere, anytime are not fully supported yet. As in B, manually placing knobs and sliders on a surface is time-consuming (R2) and knobs and sliders morphing out currently lacks continuity (R1) or physical cursors (R4).

Current systems partially support time-multiplexing through banks of sliders only. We aim at a novel solution improving the trade-off between users' requirements: a device that takes the shape of either a knob or a slider in sequence, improving time-multiplexed solutions (item 2 in Table 5.1).

Several of such devices combined will improve time- and space-multiplexed solutions (item 4 in Table 5.1).

Low-fidelity prototypes

To systematically generate low-fidelity prototype ideas (Table 5.2), we used Morphees+ features and the collection of everyday objects. We additionally used origami books (e.g., [Jac13]) and fabrication websites² to accelerate the prototyping process. The detailed presentation and envisioned implementation of each prototype can be found in corresponding publications [KCR16; KCR19].

Prototypes analysis

We analyzed how low-fidelity prototypes satisfy or do not satisfy the design requirements from chapter 4, based on the current designs of the prototype and their envisioned implementations.

To enable the interaction with a large number of parameters (R1), we count how many parameters the prototype can support without banks. To enable fast interaction (R2), we consider how fast the shape-change between the knob and slider states would be. This depends on the actuation methods. To enable precise interaction (R3), we consider both the knob and slider states of the device. First, it is desired to have multi-turn knob to allow low CD gain. We evaluate if the designs can allow multiple rotation of the knob. Second, it is desired to have a long slider. We evaluate the ratio between the slider length and the knob circumference. We decide that the minimum desired ratio is 1:1, and that the bigger the ratio, the better the system can support precise interaction. When evaluating if the prototype can support eyes-free interaction (R4), we look at the cursor of the slider. With a physical cursor, users can continue controlling the slider without looking at it once they grab it. To enable mobile interaction (R5), we verify if the prototype could be used in mobile context, e.g., while users are moving around a stage. To ensure retro-compatibility (R6), we verify if users can interact with the prototypes in the same way they interact with currently available commercial interfaces.

The detail of the analysis can be found in corresponding publication [KCR19]. We chose to implement the working prototype of the best evaluated low-fidelity prototype (Table 5.3).

Working prototype

Through the evaluation of the low-fidelity prototypes, we converged on a particular design that better supports the requirements. The design has six triangular prism blocks connected to each other (Figure 5.3 A-C). When folded (C), the prisms form a hexagonal prism (dial). When unfolded (A), the prisms are aligned, thus create a connected surface, along which a cursor moves.

5.2.2 Qualitative study with end-users

Our aim was to evaluate the working KnobSlider design and prototype from the users' perspectives. To do so, we gathered feedback from professional users in ecological setups. We also gather possible applications and future developments of KnobSlider. For this, we used technological probing [Hut+03]. The details of the study, such as participants, tasks and procedure, can be found in the corresponding publications [KCR18a; KCR19]. While the publications focus on the ways KnobSlider supports each requirement, and on areas for improvement for the design and the prototype, we take a step back in this thesis and particularly focus on the transverse issues of the **speed of shape-change** and the **approach for the design of reconfigurable devices**.

²e.g., <https://www.thingiverse.com>







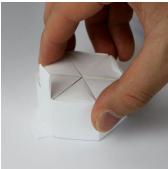
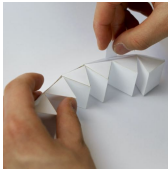
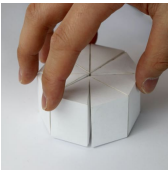
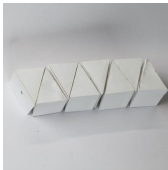
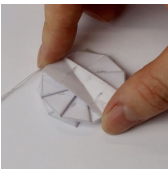


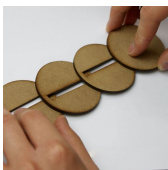

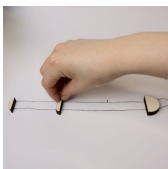
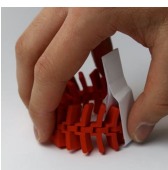
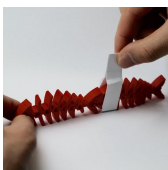


Index	Inspiration	Dial shape	Slider shape
(1)	Slap bracelet		
(2)	Party whistle		
(3)	Accordion		
(4)	Roly-poly		
(5)	Twisty toy		
(6)	Origami		
(7)	Stackable disks		
(8)	Zip line		
(9)	Fish bone		
(10)	Dukta pattern		

Table 5.2: Low-fidelity prototypes

Design requirements	Low-fidelity prototype ideas									
	1	2	3	4	5	6	7	8	9	10
R1. Interaction with a large number of parameters	•	•	•	•	•	•	•	•	•	•
R2. Fast interaction	•	•	•	•	•		•	•		•
R3. Precise interaction	•			•		•	•	•	•	
R4. Eyes-free interaction	•	•	•	•		•		•	•	•
R5. Mobile interaction		•	•	•	•				•	•
R6. Retro-compatibility	•	•	•	•	•	•	•	•	•	•
Total score	5	5	5	6	4	4	4	5	5	5

Table 5.3: Summary of the low-fidelity prototype analysis based on the design requirements from the formative study in chapter 4.

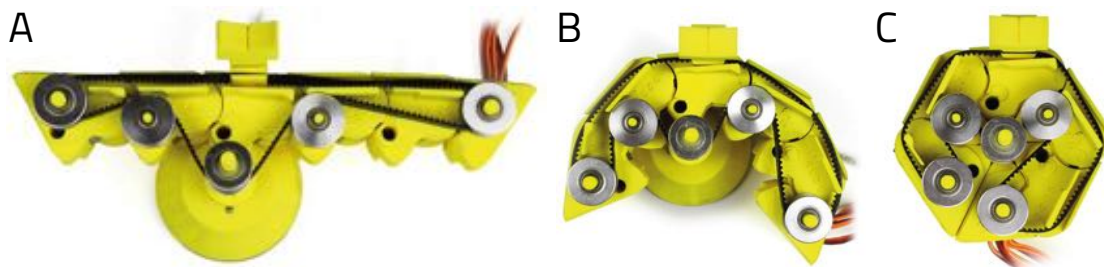


Figure 5.3: (A-C) KnobSlider working prototype without the top cover to expose the slider's timing belt and the slider mechanism. (A) In slider shape, the movement of timing belt is conveyed through the gears, (B) during transformation, the edges of blocks start to lock the bottom central gear, (C) the edges completely lock the bottom central gear, the rotation of the knob does not affect the timing belt.

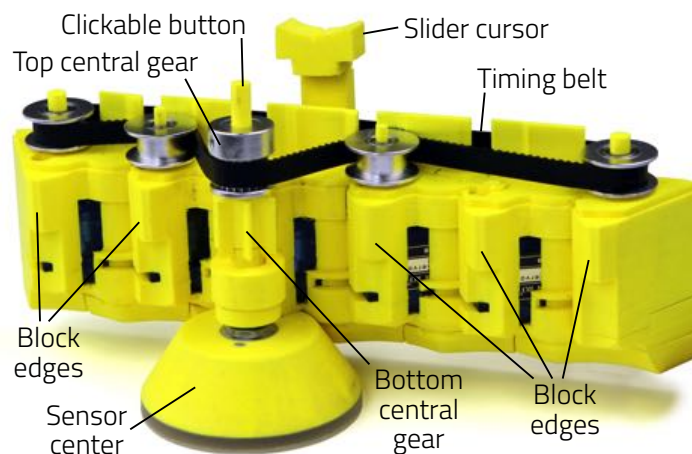


Figure 5.4: Elements of KnobSlider, here without the top cover to expose the slider's timing belt.

Speed of shape-change

We noticed that for some participants, the change of shape was scary at first: “it seems that it is going to explode” (P11), “it scares me [...] because it moves” (P5). However, after a few trials they liked it and appreciated its speed: “it needs to be fast” (P11), “it is not disturbing” (P11), “it is fun, like an animal” (P11). We observed participants clearly playing with the shape-change capability and getting used to its speed. P7 even said that it might take too much time to change the shape: “There is a time between both [shapes], so it has to be two different steps of my work. [...] It is for two distinct tasks, two ways to work on the same data”. This suggests that the change of shape can be even faster for an expert user.

This raises the question of the perception of the speed of shape-change, explored in the experiment presented in the next section (5.2.3). This also shows the necessary trade-off between fast speed for immediate feedback and low speed for safety. Both immediate feedback and safety are ergonomic criteria [BS93] that are contrasting here. This is a research challenge for the future design of reconfigurable devices.

Trade-off between learnability and enlargement of the interaction bandwidth

In the users requirements we derived from our formative study (chapter 4), retro-compatibility (R6, section 4.2.6) express the need for the end users not to loose any, or little and temporarily, of their work efficiency. Although this problem is well-known in graphical user interfaces [Sca+11], this has not been extensively discussed for Tangible User Interfaces. Reviews and discussions with the audience at conferences show that there is a strong culture for radical novelty in TUI research. We believe this is beneficial and should be further fostered. We also believe that paying attention to learnability in TUI is also important and should also be further fostered in order to avoid the repetition of GUI’s drawbacks and lack of transfer to industry. In particular, we think there is a middle line between radical novelty and a retro-compatibility. This is what devices such as KnobSlider try to achieve.

Envisioned interactions. The participants themselves were inspired by the working prototype to imagine the following novel interaction techniques.

Novel manipulation of the same prototype. Eight participants suggested novel interactions. E.g. P3 was holding the knob shape in one hand while turning with the other, and deforming the flexible slider. The additional rotational axis of the slider gave P8 (pilot) the idea to explore the surroundings’ visualization with polar coordinates, by orienting the slider (angle) and sliding the cursor (distance or scale). Two participants asked the interviewer if it was possible to use the slider’s cursor when in knob shape.

Beyond knobs and sliders. P3 suggested adding accelerometers, gyroscopes and compass for KnobSlider tracked when moved in hand. P3 suggested bending KnobSlider as a way to interact. P6 mentioned that the slider could be bent to mark values of interest.

Beyond mixing tables. P1 and P3 also thought about using KnobSlider on a flat table and tracking its displacement on the table (P1 mentioned the ReacTable [Jor+07]). P3 also mention holding KnobSlider in its knob shape in a hand, without any support.

We also envisioned interaction techniques based on the KnobSlider design and inspired on highly flexible graphical user interfaces such as *SketchSliders* [TBJ15]. Figure 5.5 shows three examples of interaction techniques (Figures 5.5b, 5.5c and 5.5d) that lie in between a rotary knob (Figure 5.5a) and a slider (Figure 5.5e). The slider could fold into a rotary knob from anywhere along its travel. This would allow users to quickly reach a value with the slider, and fold a bit of the slider into a knob around the value, in order to make more precise adjustment of the parameter. The user or the system can also fold the slider with an angle (or several angles such as Multi-plié [Pau+19]) to mark a value of interest. For instance, the camera operator in our formative study marked her values of

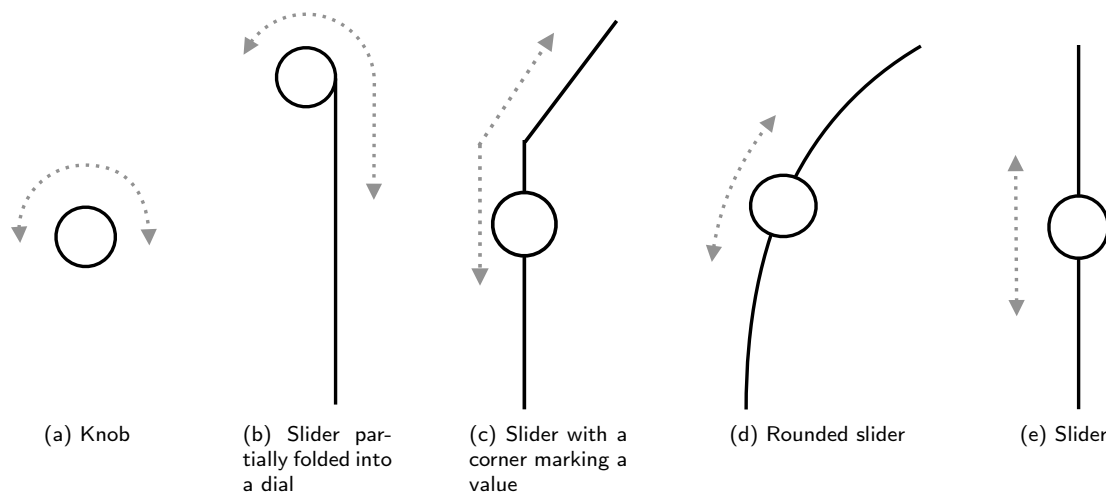


Figure 5.5: Example of envisioned interaction techniques.

interest with red tape (chapter 4). The user or the system could also deform the slider into a rounded slider, to notify, e.g. a change in CD gain, for example for logarithmic scales. This approach lies in the middle, ensuring basic retro-compatibility with existing interaction techniques, and allowing users to freely explore new techniques to better support their tasks.

Envisioned applications

Participants gave feedback on the applications we prototyped and proposed new ones. Graphic designers agreed that the prototype allowed them to balance their need for a tidy desk with few devices and dedicated devices, either for fast navigation in Photoshop's tools or precise adjustment of a parameter like the size. They expected to gain time by avoiding mouse movements and clicks. They further envisioned easier access to parameters through a physical shape analog to the GUI widget: e.g., slider shape for red levels, displayed as sliders on the screen, and knob shape for rotating the canvas.

Sound and light engineers agreed that the prototype allowed gaining space when parameter adjustment happens in sequence: e.g., the slider to control the gain, and the knob the frequency, or the slider for the volume of an effect, (e.g., a reverb), and then the knob to send this effect to the master channel. They also agreed that the device allowed adapting to users' preferences: some prefer to control volume or pan with a fader, while others prefer to do it with a knob. They further envisioned the flexible footprint of the device. If physical sliders do not fit any more on P5's mobile surface, he would switch to physical knobs rather than graphical sliders or constantly switch between banks of sliders.

Pilots agreed that the prototype allowed adaption to the preferred control because they control flaps only twice (takeoff/landing). However, changing the shape of other controls might lead to errors, as the logic of each aircraft is different. Pilots further proposed to leverage the different precision of both shapes: When taking off, P7 wanted to coarsely slide from 0 to maximum power, and while cruising, he wanted the knob to precisely adjust the power. P7 proposed to have KnobSlider in flight simulators so that trainees can train on different controls while reducing costs. Pilots imagined prototype improvements to perform tasks that are currently not supported, like seeing backwards before performing a U-turn.

Our participants also proposed new application domains based on their experience. For example, P6 proposed to use the change of shape in the manufacturing industry. It could indicate that a security requirement is met after a first adjustment—e.g. the pressure is low enough after rotating the knob—and that the worker can proceed to adjust the porosity with the slider if its shape is unlocked.

5.2.3 Physical vs. on-screen preference for reconfiguration speed

In the previous qualitative study, we observed that end-users perceived differently the change of the shape. Some people wanted it to be faster, while others were surprised and thought they could get hurt by the device. Following this observation, our goal in this subsequent experiment is to investigate user preferences on different speed conditions, and the difference in user preference depending on the physicality of the device –i.e if the device is in the real world or on a video.

We explore the physicality (vs. video display) of the device as users might perceived differently the speed of the device is real and close to them –they might feel unsecure– compared to a video. Video has been used to evaluate reconfigurable interfaces (e.g., [PSH14; Str+16]) as working prototype are still difficult to implement. However, we do not know if they are equivalent and mutually substitutable. It is therefore important to evaluate the offset between physical and on-screen perceptions.

We conduct a controlled study where we compared two conditions: in the first we used KnobSlider to show different speed properties to the participants; in the second condition, the participants only saw videos of the reconfigurable KnobSlider on a screen, with the same speed properties from the first condition.

The goal of our study is subjective in nature, and we choose to conduct a paired comparison experiment [Dav63]. It is a typical method used to gather Quality of Experience (QoE) feedback in HCI, marketing, environmental sciences, and health economics [Che+09; AR17; SRI17; Jen86; Win80]. The study is conducted by asking participants to choose between two conditions, mostly to choose the most preferable condition out of two. The experiment is designed to show all possible combinations of two conditions to the participants. Performing pairwise comparison ratings has been proven to produce more realistic results than asking for individual rankings (e.g., using a Likert scale) [BT52].

In this experiment, we try to answer to the following questions.

1. Is the preference with the physical device equivalent to a video on a screen?

The observation of the change of shape is limited to visual feedback and does not include manipulation of the prototype, or any other types of feedback. Hence, we believe that the preference of the physical prototype is transferable to screen medium. However, users may prefer a little faster speed on the screen, because they know that the device cannot harm them.

2. Do users prefer a certain range of speed?

We expect that users would prefer a certain range of speed, not randomly any sort of speed. The preference will have a pattern such as a normal distribution.

3. Which speed profile users prefer?

We expect that users would prefer a speed profile that gradually changes the speed than one that instantly changes the speed. We assume so because gradual speed profiles give time to users to prepare themselves for the change of shape.

Experimental Design

The study had three independent variables: PHYSICALITY, MAX SPEED, and SPEED PROFILE (see Table 5.4). PHYSICALITY refers to the fact that the shape-changes occur on the physical KnobSlider

Variables	Conditions	Experiment design
PHYSICALITY	<i>device (physical), video (virtual)</i>	between subject
MAX SPEED	<i>50, 200, 400°/s</i>	within subject
SPEED PROFILE	<i>square, mountain</i>	within subject

Table 5.4: The variable and conditions of the controlled study. For the PHYSICALITY variable, we use a between subject design to remove the learning effect. For the MAX SPEED and SPEED PROFILE variables, we use a within subjects design to eliminate individual differences between participants.

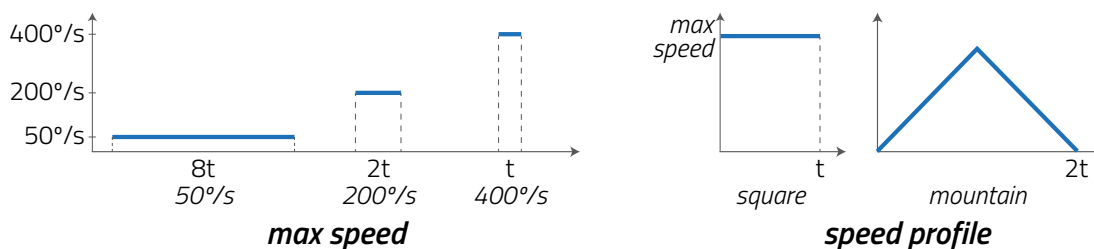


Figure 5.6: The speed variables explored in the experiment. MAX SPEED is the maximum speed that the motors will have over the change of shape. We use three amounts of MAX SPEED: 50 , 200 , and $400^\circ/s$. SPEED PROFILE is the change in the speed during the change of shape. *Square*: the speed of shape-change is constant over time. *Mountain*: the speed increases with a constant amount of acceleration until it reaches the maximum speed and then decreases with the same absolute amount of the acceleration.

device or on a video. MAX SPEED variable correspond to the maximum speed the shape-change of KnobSlider. We want to figure out which of the MAX SPEED and SPEED PROFILE has the most impact on preference. The third variable, SPEED PROFILE, was the dynamic of the shape-change: *square* and *mountain* (Figure 5.6 right). With the *square* profile, the motors changed their speed over the shape-change from $0^\circ/s$ to MAX SPEED, and then back to $0^\circ/s$. With the *mountain* profile, the motors linearly accelerated until reaching the MAX SPEED and then linearly decelerated until reaching $0^\circ/s$, resulting the speed making the mountain-like shape on the graph. This variable was to know if there is distinguishable preference on *speed profile* when the MAX SPEED is the same.

The details about the experiment such as participants, experimental design and procedure, can be found in the corresponding publications [KCR19].

Results

We used Bradley-Terry-Luce model [BT52] to compute the “ability” (i.e. preference) of the conditions that have been compared in the study. Figure 5.7 shows the ability of MAX SPEED conditions and Figure 5.8 shows the ability of SPEED PROFILE conditions. The complete analysis and results, including individual and overall consistency, can be found in the paper [KCR19].

Is a preference with a physical device equivalent to a video on a screen? The participants preferred different MAX SPEED depending on the PHYSICALITY variable (Figure 5.7). With the device, the participants most preferred the lowest speed ($50^\circ/s$), and with the videos, the participants most preferred the medium speed ($200^\circ/s$). This means that using videos for perceptual study on reconfigurable interfaces can result in different conclusions than using physical devices.

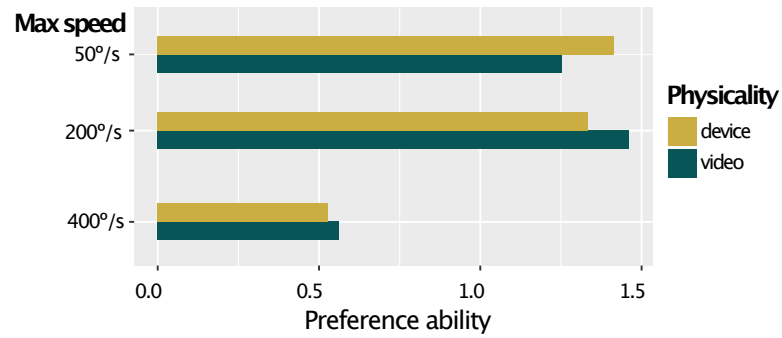


Figure 5.7: The Bradley-Terry-Luce model output of different MAX SPEED and PHYSICALITY variables. The yellow bars show the preference ability of physical *device* (*physical*) condition with different conditions of max speed, and the dark green bars show the preference ability of *video* (*virtual*) condition of the same device with different conditions of MAX SPEED.

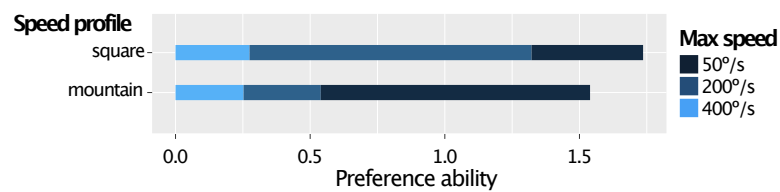


Figure 5.8: The Bradley-Terry-Luce model output of SPEED PROFILE variable. The participants preferred the *square* profile over the *mountain* profile, when the MAX SPEED conditions were aggregated.

Do users prefer a certain range of speed? Users preferred a certain range of speed, as their preference is not equal for all ranges of speed (Figure 5.7). We observed the very least preference on the highest speed ($400^\circ/s$). This reassures the result from our previous qualitative study that some users got surprised by the shape-changes of KnobSlider. Users do not like surprising feelings caused by the fast movements of the device.

Which speed profile do users prefer? Figure 5.8 shows the users preferences on the *speed profile* conditions, square and mountain. Surprisingly, they preferred the mountain profile over the square profile, regardless of the MAX SPEED. This is not consistent with the fact that the mountain profile reduced the average speed of the change of shape with the highest *max speed* (e.g., $400^\circ/s$) to the half ($200^\circ/s$), and that the participants preferred the medium *max speed* ($200^\circ/s$) than the highest *max speed* ($400^\circ/s$). This might be related to the fact that some participants mentioned too slow changes of shape were “boring”. They explained that they could know the device would change its shape once it started moving. In the same way, we can hypothesize that the first acceleration part of the mountain profile made the participants prepared for shape-changes with any maximum speed, and they felt bored over shape-changes with the mountain profile. It would be interesting to investigate if it is more acceptable to have gradual speed change only at the beginning of the change of shape.

Conclusion on reconfigurable dials

In this chapter, we presented our explorations of reconfigurable dials. We first presented a study around a dial changing its diameter and its height. We then presented our studies around a dial that can change into a slider.

Both these prototypes allowed us to explore how to meet end-users requirements (chapter 4), that are sometimes contradictory, through dynamic reconfiguration of the shape of the tangible control widget. We show that the speed of shape-change can be fast ($200^\circ/s$), as long as it start slowly not to surprise users.

Both design explorations open many research questions for the future. The affordance of reconfigurable dials needs to be carefully studied and designed [PRT20]. The integrality or separability of the control over the parameter and the shape should be carefully studied. The shapes in-between two shapes that are familiar to users can serve as a design space for novel interaction techniques fully leveraging the reconfiguration while supporting the retro-compatibility requirement. The many applications possibilities and possible benefits of reconfigurable dials should be further studied.

Chapter 6

Exploring reconfigurable sliders

A slider is a control device allowing the control of continuous one-dimensional parameters, like dials [BT02]. It is controlled through the translation of its cursor along its axis, parallel to its support surface. The support surface is often horizontal, or slightly inclined [BT02]. Sliders are often oriented vertically and grouped, in order to allow for user's finger to accurately and simultaneously interact with adjacent sliders [BT02]. Sliders allows for the accurate observation of the parameter's value [BT02]. Sliders have been here for decades, and allow for simultaneous control and observation that is not achievable with other tangible devices [BT02].

Our formative study (see chapter 4) showed that sliders lack physical flexibility. In particular, users would benefit from sliders that can change length (section 6.1) to balance between accuracy (R3, section 4.2.3) and mobility (R5, section 4.2.5), and sliders that can change their number of cursors (section 6.2) in order to balance between fast (R2, 4.2.2) and accurate interaction (R3, section 4.2.3). In this chapter, we present two studies introducing such physical flexibility to sliders.

6.1 Coupling the zooming in the motor and visual space

As shown in previous work [FIB95; JDF12] and in our formative study (chapter 4), the physicality of TUIs benefit users when the visual attention is not on the input interface but rather on a distant target. As a consequence, TUIs have been extensively used in professions requiring eyes-free interaction, such as the ones studied in chapter 4.

When interacting with a distant target, users sometimes need to balance between opposite requirements: minimal footprint of the device for, e.g., mobility (R3 from chapter 4, section 4.2.3), vs. precise and accurate interaction (R5 from chapter 4, section 4.2.5). Existing fixed-shaped TUIs are limited to a fixed and single compromise between these opposite requirements. To overcome this particular limitation, we explore a resizable slider. For instance, to browse an on-screen timeline, a small tangible slider allows coarse browsing of the whole period, a medium tangible slider allows to browse days, and a long tangible slider allows to precisely browse minutes.

The respective importance of both motor and visual scale for the selection of small targets was demonstrated *for a mouse* [CD11]. Several graphical interaction techniques leverages the idea of visual scale for improving performance [BH94; Ram+07; RHL08; ACP10]. However, these GUI techniques lack the benefit of physicality.

Resizable displays have been proposed through folding/rolling/coupling displays [Kha+12; Kha+11b; LHT08; SHD10; SO12; OMN17]. The authors explored resizing in two ways: first, to increase the display real estate; second, as an input technique itself. They do not leverage the change of

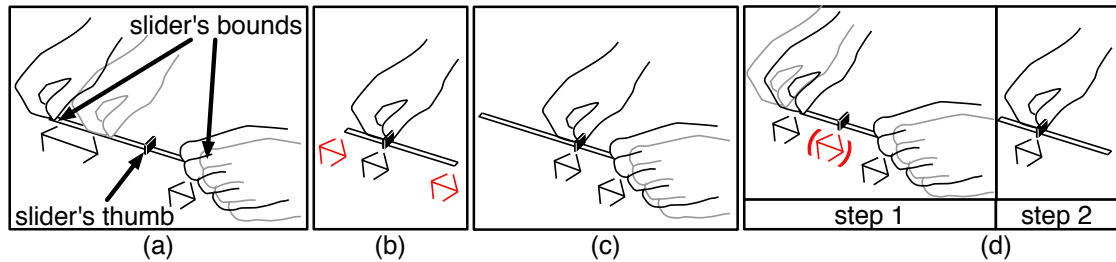


Figure 6.1: Design alternatives for our resizable slider (a-b-c) and the one we study in this paper (d). Black (resp. red) arrows show elements that can be moved by the user (resp. the system).

shape for modifying control properties. No zoomable tangible slider was proposed before, as it is not straightforward to design a reconfigurable slider to be scaled in motor space.

An alternative solution would be to provide users with multiple sliders of different sizes. Sliders in the industry come in a large range of sizes. For instance, few millimeters long slider switches for mobile devices to 10cm long sliders on mixing consoles.

However, when size is critical, for instance when walking or craving for space on a table, multiplying the number of sliders is not an optimal solution. On the contrary, a resizable slider can give the user the opportunity to compromise on the precision in order to lessen the size. In this section we investigate the concept of resizable tangible sliders. We allow zooming up in motor and visual space when precision is critical, and zooming down when space is restricted. Users can enlarge the slider to get more definition and be more precise. Users can also shrink the slider to gain space and still interact, e.g. while seating at an encumbered desk. Doing so, users can benefit from both the physicality of tangible sliders and flexible control of digital sliders.

We build proof-of-concept prototypes of such a resizable slider and integrated them in two example applications among our three envisioned scenarios of use (section 6.1.1). Beyond proposing a new tangible interaction technique, we measure its pointing performance [CM15] and relate it to a second experiment assessing its possible flaw (section 6.1.2): the additional articulatory task and time needed for resizing. We show that the drawback of the resizable slider does not compromise its benefit: in our experiment, if the user does not need to resize more often than around every 9 seconds, our resizable tangible slider allows better precision compared to a small fixed-shaped tangible slider.

6.1.1 Design and prototype

Figure 6.1 shows the design alternatives that we considered. In Figure 6.1(a), the slider's thumb is fixed and the user simultaneously resizes to zoom and moves the slider's bounds to acquire a target. A drawback is that the space necessary to interact is large.

In Figure 6.1(b), the user only manipulates the thumb and the slider is resized by the system. A drawback is that it only suits a target-aware system.

In Figure 6.1(c), one bound is fixed and the user simultaneously zooms with the other bound and points with the slider's thumb. A drawback is that the user cannot freely place the slider.

Figure 6.1(d) shows the design that we study in this paper: zooming is performed with two hands, one on each bound of the slider. We chose to study the efficiency of this design first, as it did not have the drawbacks of the others.

Before addressing the technological challenges for making such resizable sliders, we aim at studying the relevance of the concept. As resistive, capacitive, optical or magnetic embedded technologies currently used for tangible sliders are difficult to adapt for physical extension, we used external tracking to prototype a high-resolution proof-of-concept resizable tangible slider (Figure 6.2). We

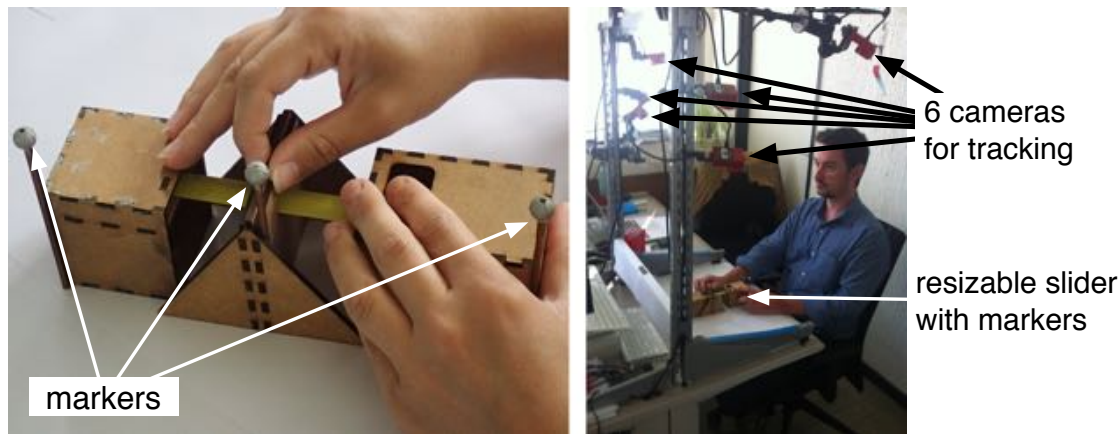


Figure 6.2: (Left) Prototype of a resizable tangible slider. A rigid retractable measuring tape allows for the laser-cut thumb to slide on the slider's range. Three reflective markers are tracked by an infra-red tracking system with 6 cameras (right), detecting relative positions of the reflective markers placed on the bounds and the thumb (left).

used a retractable and rigid measuring tape as a smooth slide rail for the slider's thumb. For the bounds, we laser-cut two boxes. One of them hides the body of the measuring tape. The button to retract the measuring tape was made accessible to the user through a hole in the corresponding box. For resizing the slider, the user brings the bounds closer/further while pressing the button. For the slider's thumb, we laser-cut a piece to slide on the measuring tape. For better yaw stability, we (1) made the thumb 9 mm large and (2) made it to measure so that it perfectly fits the tape's shape and dimension. For better pitch stability, we added buttresses to the slider's thumb so that it stays horizontal when it slides. Buttresses were positioned far enough from the tape in order for them not to prevent the slider's thumb to reach the bounds. This physical prototype ensures that the tangible interaction takes place smoothly and efficiently as expected by the users.

We track the position of the upper and lower bounds and of the thumb through three reflective infra-red markers and six cameras (OptiTrack Flex V100R2 infrared cameras from NaturalPoint). The tracking system is placed on a table to allow users to comfortably manipulate the slider with their elbows resting on the table. Cameras were placed as close as possible to the slider in order to maximize its resolution. Indeed, the resolution is a variable of the cameras, their number and their position. We measured the resolution of the slider [BWC11] by four standard deviation of the sensed position of the static device. Throughout 500 measurements of the position of the static thumb (in fixed bounds), we found a resolution of 0.009 mm, i.e. 2822 dpi. The resolution was constant over all sizes of the slider. High-resolution mice are about 2000 dpi. As a consequence, we do not expect the resolution to limit the interaction, even in the smallest sizes like 2cm long slider for instance.

6.1.2 Impact of the resizing on Performance

The aim of the experiment that we present now, is to answer the following question: *how is the additional resizing task affecting the performance of the resizable slider compared to small and large sliders?*

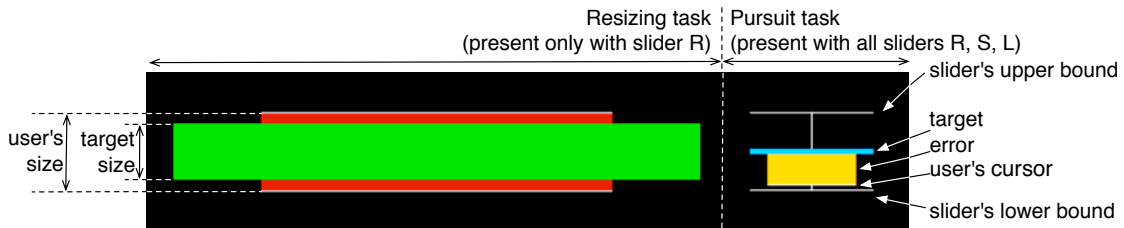


Figure 6.3: Close-up screenshot of the experimental tasks during the resizing condition (R). On the left, the primary resizing task: the green rectangle shows the slider's size to reach. The size error is shown in red. On the right, the pursuit task: the thin white slider and the blue moving target to pursue. The pursuit error is shown in orange.

Procedure

We used a within subjects design with the following independent variables:

SLIDERS: Large (8cm) fixed-size tangible slider (L), Resizable tangible slider (R), and Small (2cm) fixed-size tangible slider (S).

INTERVALS of difficulty change: every 3/9/18/30 seconds, the difficulty randomly changed between 3 levels of difficulty. The three levels of difficulty were 1, 2 and 4px of target's widths when the slider was small (2cm). When the slider was large (8cm) then the three corresponding target's widths were 4, 8 and 16px. In the case of the resizable slider, the user was asked to resize the slider when the difficulty changed so that the target's width reached 4px.

Participants were asked to follow a target cursor as many higher-level tasks depend on it [JDF12] like smooth adjustments of parameters in time. In Figure 6.3, this task is presented on the right hand-side of the screen. Participants controlled the white cursor to follow the blue, moving cursor (target), i.e. to move the slider's thumb so that the white cursor coincides in the blue target cursor at all times. This allowed us to evaluate the impact of the additional articulatory task for resizing on this continuous pursuit task. The cost of resizing was then measured as the impact of the primary, resizing task on the performance of this secondary, pursuit task.

The error was highlighted in orange (Figure 6.3). The participants were instructed to keep this error as small as possible at all times. The pursuit task was conducted with their right hand operating the tangible slider's thumb. The target followed a pseudo-random path among three paths whose order was randomized between each block. The target moved at constant speed and darted off at pseudo random intervals (between 2 and 4 seconds). The slider's speed was $0.15 \times$ the slider's size (in px per second). The dart-off distance was $0.3 \times$ the slider's size.

With resizable slider (R) only, participants were asked to first reach the target size when the difficulty (i.e. the size of the target) changed, before pursuing the target cursor. Resizing the slider was conducted with both hands operating the bounds of the tangible slider. In Figure 6.3, this task is presented on the left hand-side of the screen. The target size is green, the user's slider's size is white and the error is red. The aim of this resizing task is to reproduce in a controlled setting the fact that users will adapt the size of their interface to the space available and accordingly degrade their performance in order to keep interacting. As we aim at evaluating the consequence of this resizing on the secondary task, we controlled how participants performed the resizing task as accurately as possible: they could not perform the pursuit task, i.e. their white pursuit cursor was not displayed, as long as they did not reach the target size (± 50 px). In the case of fixed-size sliders (S and L), the left part of the screen (Figure 6.3) was empty.

The detailed description of the experiment can be found in the corresponding publication [CM15].

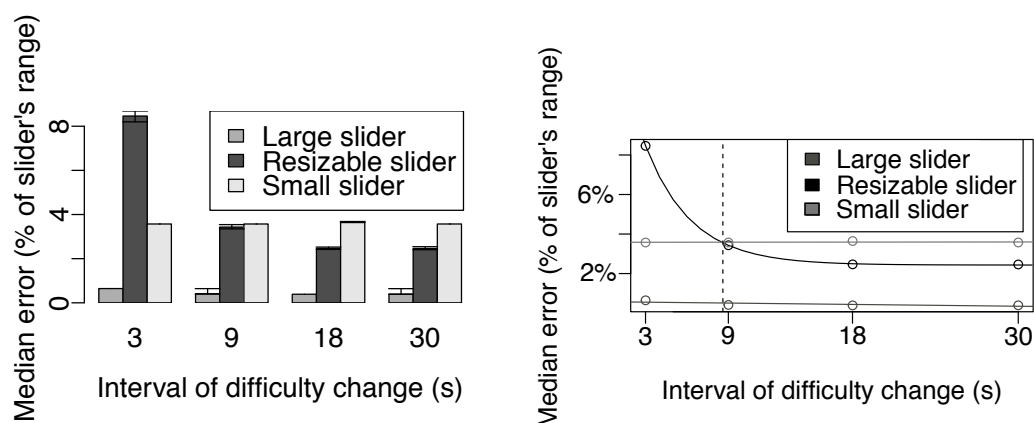


Figure 6.4: Left: impact of Slider and Interval of difficulty change on the median error. Right: limit of difficulty change (around 9s) for preferring R over S if space is an issue.

Results

We present in this thesis the results for the *size error* (the distance between the size and target size, in cm) and the *pursuit error* (the distance between the cursor and the target, as a percentage of the slider size).

We confirm through this experiment that subjects were able to resize the slider as asked: size error was very close to zero for the resizable slider. As a consequence, the small and resizable sliders are the only sliders that could adapt to constrained space.

As the distribution of the pursuit error is skewed, we considered the median pursuit error as it gives in this case a good measure of location. Figure 6.4(left) shows the impact of the interval of difficulty change on this median pursuit error.

When the difficulty changes every 3 seconds, the pursuit error with the small slider is 5.53 times the pursuit error with the large slider (i.e. a loss in precision of 2.93% of the slider's range). The pursuit error with the resizable slider is far more important when the difficulty changes every 3 seconds: 13.10 times the pursuit error with the large slider (i.e. a loss in precision of 7.82% of the slider's range).

However, while the pursuit error of the small slider does not improve when the difficulty changes less often, the resizable slider gains in precision: from 2.37 times the pursuit error of the small slider at every 3 seconds (i.e. a loss of precision of 4.89% of the slider's range), the resizable slider becomes more precise than the small slider: its pursuit error is 0.68 times the pursuit error of the small slider at every 18 seconds (i.e. a gain in precision of 1.18% of the slider's range).

To make the best of this result, users with space constraints can keep their slider small at fixed size if the difficulty is changing too often, and start resizing only if the difficulty does not change too often.

We performed the modeling of the medians of the pursuit error for each slider (Figure 6.4, right) to find the limit of performance: if the difficulty changes less often than around every 9 seconds and space is an issue, then the resizable slider has to be preferred over the small slider. If space is not an issue, a large slider has to be preferred. If the difficulty changes more often than around every 9 seconds and space is an issue, then it is better to leave the resizable slider at a fixed, small size.

This conclusion was confirmed by participants during interviews, as all agreed that 3 seconds was too fast for the resizable slider to be usable, whereas 18 and 30 seconds was slow enough for the resizable slider to be usable. For 9 seconds, 3 participants could not decide if it was too fast or slow

enough, while 2 found it too fast and 3 found it slow enough.

Very high errors occur when the difficulty changes. As the video analysis showed, the participants sometimes could not control the location of the thumb when they needed two hands to resize the slider. Future improvement of the prototype should investigate ways for the system to control the location of the thumb while resizing the slider (Figure 6.1(a, c, d)).

Pursuit errors occurred around 2s more in the 90s trial with the resizable slider than with the small slider when the difficulty changes every 3 seconds. As the resizing occurred less frequently, the pursuit error occurred less often with the resizable slider than with the small slider: as soon as the difficulty changes every 9 seconds, there is also a significant difference between S and R. When resizing occurs every 9 seconds, users gain 3s of precision with the resizable slider compared to the small slider during the 90s trial and, when resizing occurs every 18s, they gain 6s in a 90s trial. The large slider performs best, at the cost of its larger size.

Discussion and conclusion

Through this experiment, we measured the impact of the additional articulator task for resizing.

Overall, participants reported that the manipulation of the prototype was easy. This is confirmed by comparison to previous work: our experiment is not a replication of previous work [15], but the task was identical, and, interestingly, our 8cm slider lead to 6% of mean pursuit error, achieving similar performance as previous 8cm prototype [15].

Depending on the precision demand of the pursuit task, fixed-size or resizable sliders should be considered. If space is not an issue, then a large slider is better as it is more efficient. If space is limited or changing, then designers have to consider two cases: First, if the task demands to be as efficient as possible most of the time, then a resizable slider is better. Second, if the task demands not to exceed a threshold of error, then the small slider, kept at fixed size, is better. For example, for a mobile mixing console allowing to mix a performance from several viewpoint of the venue (e.g., performer, front row, back row, edges, etc.) as seen in our formative study (chapter 4), engineers can face two different requirements: if the show is live, the engineer will prefer to avoid outliers, e.g., uncontrolled high levels. In this case, when the outliers have to be avoided, fixed-sized small sliders would prevent them to occur. On the contrary, if the show is recorded, the engineer would rather control the sliders as precisely as possible for best quality. In this case, when outliers will be cut during editing, a resizable slider is a better option to make the best out of each mixing location.

We also conducted a target acquisition experiment with the same prototype in order to relate its results to this one. The target acquisition experiment can be found in the related publication [CM15]. In the experiment presented here, we found that the time needed to resize was 0.7s ($\pm 0.5s$). As a consequence, in the worst-case scenario, resizing takes 1.2s. In the experiment presented in the paper [CM15], we measured the mean pointing MT when $ID=5(4)$, at 2.8s(2.1s) for the small slider. The corresponding MT for the large slider is 1.8s(1.5s). If the user has to perform at least two of such pointing tasks consecutively and space is not an issue during these interactions, it is better to first resize the slider. This would allow for a gain of 0.8s(0.1s) in this worst-case scenario – 1.8s(1.1s) in the best-case scenario. When a user, like the illustrator from our formative study (chapter 4), performs such pointing tasks for parameters adjustments hundreds of times a day, a resizable tangible slider can save a lot of her time over a small tangible slider, and save space over large tangible slider.

The benefits of our prototype for parameters adjustments (pointing and pursuit tasks) are promising. This work validates the relevance of the concept and shows that further improvements are worth addressing in future work. In particular, several major challenges have to be addressed to improve the design and the prototype:

1. **Improving the pointing performance:** as reported, we felt that very small corrections performed with the thumb of our prototype were slightly more difficult than with a mouse due to static friction. One participant corroborated this hypothesis. In order to bring the pointing performance of our resizable slider to the one of a mouse [CD11], future improvement of the prototype will investigate ways of decreasing the force needed to start moving the thumb, e.g., decreasing its contact area on the support surface or decreasing its weight.
2. **Decreasing the pursuit error during resizing:** we have two avenues to enable the control of the thumb while resizing. Pausing interaction during resizing is not considered for real-time interaction. First we plan to evaluate a resizable slider with a fixed bound in order for the user to resize with the left hand only and keep controlling the thumb with the right hand (Figure 6.1c). We can limit the negative impact of this design on the mobility of the slider with an unobtrusive blocking mechanism between the slider's bound and the support surface (e.g., watch, smartphone, tablet, table, etc.). Second, if two hands are used for resizing, two stepper motors could actuate the thumb for the system to maintain its relative position during resizing.
3. **Improving both pointing and pursuit performance through reducing the size of the prototype:** Future miniaturization needs to address two issues: slide rail and tracking. Current rigid, retractable tape can be shortened to fit in a smaller volume. Tracking can be done from the support surface (e.g., [JDF12; TK13]) or magnetic sensors at both ends, computing position and size. In longer term, our vision is addressed by nanotechnologies, which work towards reconfigurable and controllable material that could be used for implementing such resizable sliders.

The zoomable slider we presented in this section allows users to balance between performance and footprint. In the next section, we will present another flexibility of physical sliders: the number of their thumbs (also named cursors).

6.2 SplitSlider

SplitSlider [Gre+19] (Figure 6.8 (left)) is the prototype of a reconfigurable slider, resulting from the design of a device to input uncertain data in a survey.

Inputting data into a system while being uncertain about this data is a common task. For instance, in a usage survey at the train station, we might get asked about how often we take the train. If we do not take the train regularly, it is difficult to answer a precise value between like “daily” and “never”. Our answer might rather be “between every 6 months and weekly, and most often every 2 months”. Other examples range from satisfaction surveys in airports to availability inquiry or medical questionnaires, where we might hesitate between 54kg and 56kg to input our weight. Currently, respondents are forced to answer a single, precise value even when they are uncertain. However, allowing respondents to express their uncertainty about their answer enables the people who requested the questionnaire to have precise and reliable data. For example, intra-participant uncertainty can increase transparency and reliability of the data [MDL08; Rou+06], produce relevant results [BD09; Gre+17] and help to make better decisions [JL12; Rou+06].

Therefore, input mechanisms should allow expressing uncertainty together with the most probable input value. For instance, previous work proposed GUIs for users to express their uncertainty [Gre+17]. Among others, they compared 1-thumb, 2-thumb and 3-thumb sliders to input uncertain data:

- The 1-thumb slider allows users to input a probability distribution by moving the single thumb: users move the peak of the distribution, while the standard deviation, skew and kurtosis are fixed.

- The 2-thumb slider allows users to input a probability distribution by independently moving two thumbs: users move the minimum and maximum values, while the peak of the distribution stays in the middle of these two values.
- The 3-thumb slider allows users to input a probability distribution by independently moving three thumbs: users move the minimum, the maximum and the peak values of the distribution.

However, there is a tradeoff between the usage simplicity and the ability to express the uncertainty. Interactions with questionnaires are recommended to be easy to use and discoverable while providing sufficient information [Fin15]. Respondents often stay novices when responding to a survey, as they rarely answer to the exact same questionnaires twice. Hence survey companies either choose to offer a simple interface to encourage as many respondents as possible, or a more complex interface able to gather richer data from fewer participants but with the help of surveyors. Corresponding examples can be found in public transportation surveys, where clients are offered either happy or angry faces buttons in airports, or a surveyor approaching respondents with tablets and multiple questions. Allowing respondents to input uncertainty can increase data reliability, but it can also increase the survey's interface complexity and cost.

This motivates us to balance the simplicity and the ability to express the uncertainty. To achieve this goal, we explore TUIs as a way to offer users with a flexible compromise between simplicity and the ability to express the uncertainty. TUIs are a good candidate to offer a flexible compromise between simplicity and expressiveness, as they were found more discoverable than GUIs [Hor+09] and better foster the simultaneous adjustments of parameters than GUIs, even more than multitouch GUIs [Ma+15].

TUIs are already used to answer questionnaires, e.g., VoxBox [Gol+15], and happy or angry faces on buttons in satisfaction surveys in airports¹. However, these TUIs do not yet allow users to express their uncertainty about their answer.

To balance the simplicity and the ability to express the uncertainty, we explore the design of physical dials and sliders in order to meet the end-user requirement of retro-compatibility (R6 from section 4.2.6). We explore designs of physical dials and sliders that can especially capture users' value and uncertainty with a single device.

6.2.1 Design

In a previous study [Gre+17], a graphical 3-thumb slider was experimentally found the best compromise between easiness and the ability to express uncertainty. However, it offers a fixed compromise between the ease of use and the ability to express uncertainty. Moving the three thumbs in sequence was found cumbersome by the participants, compared to the 1-thumb slider. In addition, the 1-thumb slider was better suited for users with little knowledge in statistics, while the 3-thumb slider was better suited for users with more expertise in statistics. We aim at supporting all levels of expertise in statistics.

To support all levels of expertise in statistics, we explore deformable TUIs that allow both certain and uncertain inputs. Instead of using the one-, two-, three- thumb sliders, we suggest different deformation of both dials and sliders to learn about their pros and cons to input uncertain data.

Although previous work could be extended to input uncertain data, such as the zoomable slider (section 6.1 and [CM15]) or the inflatable mouse [Kim+08b], we chose to systematically explore the design space of uncertain input TUIs from scratch, in order to consider more interactions than extending or squeezing only.

¹E.g., the system "Smiley terminal" from the company *Happy or Not*, <https://www.happy-or-not.com/en/smiley-terminal/>

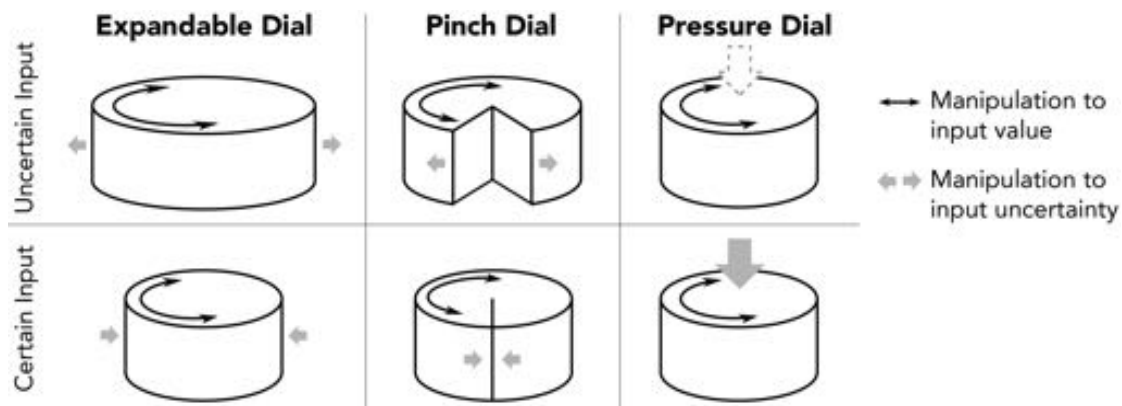


Figure 6.5: The dial-based interfaces, enabling both value and uncertainty input. The usual rotation interactions are to input value and the extended inputs (grey arrows) are to input uncertainty. Expandable Dial: users increase the diameter to express more uncertainty. Pinch Dial: users increase the open space – between the center and one side of the circumference – for more uncertainty. Pressure Dial: users enter their uncertainty by adjusting the pressure at the top of the dial (less pressure = more uncertainty).

We first use Morphees+ [KCR18b] features to design five controls based on standard tangible dials (Figure 6.5) and sliders (Figure 6.6) and that can input both value and uncertainty. The details of the design can be found in the corresponding publication [Gre+19].

We then built low-fidelity prototypes (Figure 6.7) and conduct a focus group study to find design requirements for uncertain, tangible input. The study is reported in the corresponding publication [Gre+19].

Following the design study, we selected the SplitSlider as the most promising design. The SplitSlider’s thumb supports entering one value (1-thumb slider) and can be split to additionally enter a probability distribution (2- and 3-thumb slider).

6.2.2 Experiment

We implemented and evaluated the functional tangible prototype as shown in Figure 6.8. The SplitSlider aims at balancing simplicity and ability to express the uncertainty. In order to measure how discoverable it is, we first asked participants to use it without being provided any explanation. Then, in a second phase, after having explained SplitSlider to participants, we measured its perceived ease of use and its ability to express the participants’ uncertainty. Note that we decided to focus on the 1-thumb and 3-thumb modes only in this study to keep the study simple.

We asked participants to use the working SplitSlider to answer public transportation survey questions (see [Gre+19]). The questions were selected to have continuous and quantitative answers, which our interface accommodates.

As an independent variable, we had the two phases of the study: the phase before and the phase after the explanation of the prototype, to see if the use of the slider is discoverable and participants can use the uncertain input function without explanation. At the end of each phase, the participants filled in a feedback questionnaire, including a “Usability Metric for User Experience” (UMUX) questionnaire [Fin10]. We used the same Likert scale for all these feedback questions, ranging from 1 (Strongly Disagree) to 7 (Strongly Agree). The participants then answered the Berlin Numeracy Test [Cok+12], at the end of the experiment not to bias the participants.

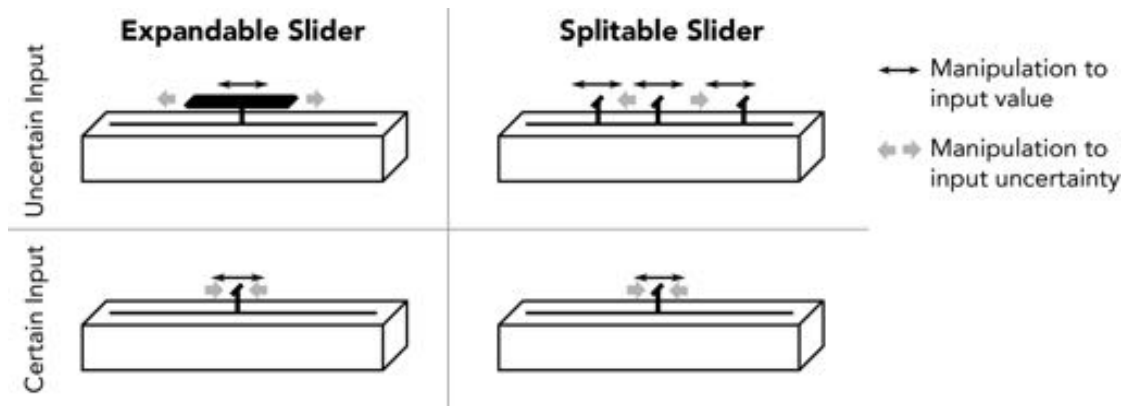


Figure 6.6: The slider-based interfaces, enabling both value and uncertainty input. The usual interaction of sliding thumbs is to input value, and the additional interactions (grey arrows) are to input uncertainty. Expandable Slider: users increase the width of slider thumb to increase uncertainty. Split Slider: users split the thumbs into two or three, to input the range of uncertainty.

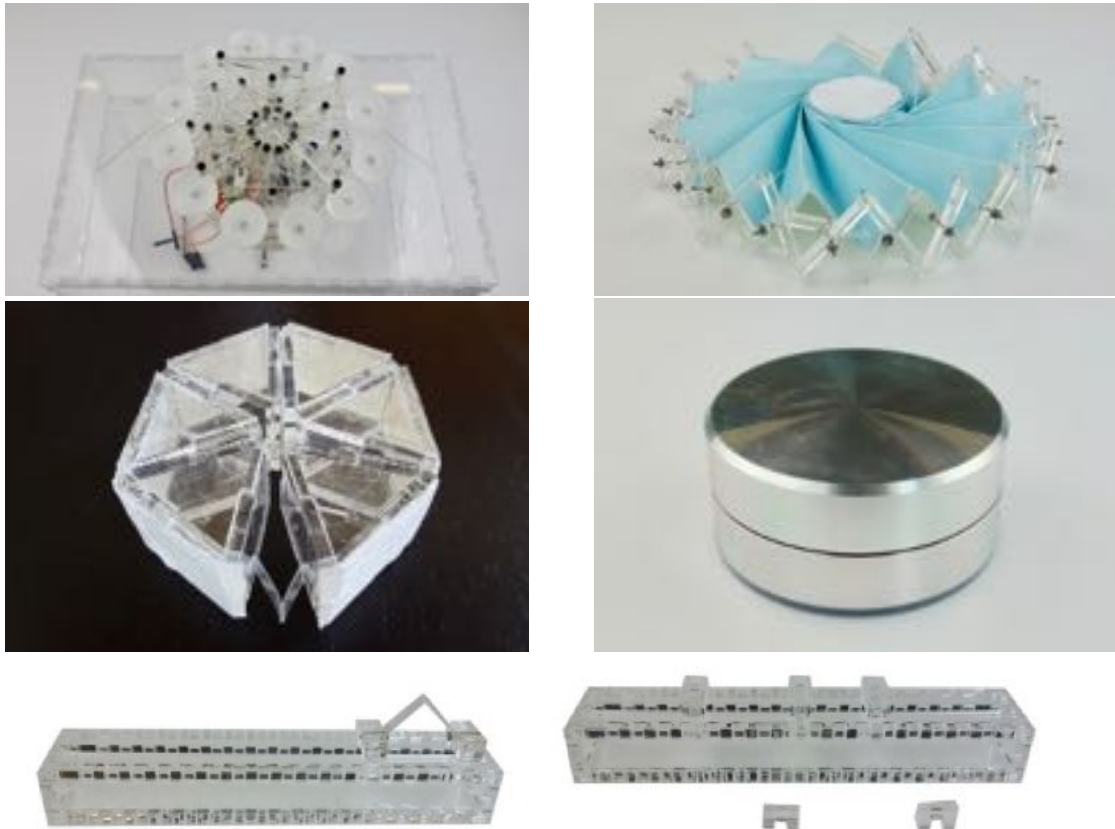


Figure 6.7: Low-fidelity prototypes of the explored uncertain input dials/sliders designs. (Top left) Expandable Dial – Stretching Design, (top right) Expandable Dial – Squeezing Design, (middle left) Pinch Dial, (middle right) Pressure Dial, (bottom left) Expandable Slider, (bottom right) Split Slider.



Figure 6.8: (Left) Experimental setup with the functional prototype used by the participants. (Right) Close-up of the distant visual feedback.

For most users, the SplitSlider as a 3-thumb slider is not discoverable without explanation.

Only one third of the participants were able to discover the splitting function and used it to input uncertainty in Phase 1 (before explanation) (4/12, 33.3%). Among the other eight participants, only one managed to split the thumb into three at the last question of Phase 1, but he tried this for around 8 seconds and then put them back together to answer the question. In Phase 2 (after explanation), all participants used three thumbs to answer questions.

Although the questions were calling for similar amount of uncertainty in Phase 1 and in Phase 2, the participants expressed different amount of uncertainty in both phases. In Phase 1 the participants used the 3-thumb mode less than in Phase 2. A chi-square test of independence showed that participants used the 3-thumb mode significantly more often after the explanation ($p < 0.001$), showing that the prototype is not self-explanatory.

The SplitSlider is easy to use, both in 1-thumb and 3-thumb modes. The median UMUX score was 87.5 (Q0=33.3, Q1=75, Q3=92.7, Q4=95.83, mean=82.29) in the first phase, with a minor increase to 89.58 in the second phase (Q0=29.17, Q1=83.33, Q3=96.88, Q4=100, mean=85.75). Both scores are interpreted as excellent [BKM09], and there was no significant difference between the scores ($p = 0.366$). This shows that the SplitSlider was found easy to use, whether expressing uncertainty or not.

The major criticisms in the qualitative feedback were the lack of smoothness of the thumb movement and the too large minimum interval between the thumbs. Removing the magnets that we embedded in the three cursors to ensure they stick together, could solve the problem.

Conclusion

In the example of SplitSlider, our design, like the others designs explored in this thesis, was based on the end-users' requirements (chapter 4), in particular on retro-compatibility with existing devices such as knobs and sliders (R6, section 4.2.6). Despite this, the ability of the prototype to support the input of uncertain value was not easily discovered. Future work should explore how to improve the discoverability, learning and adoption of interaction techniques based on physical shape-change, in order for users to benefit from the expected gain. Further design cues such as feedforward and affordances should be explored to better invite the user to explore the possibilities of such reconfigurable sliders, and interfaces in general.

Chapter 7

Exploring reconfigurable mobile sliders

The interaction on mobile devices is currently mainly supported through touchscreens. Tactile interaction allows both the discrete control of parameters, such as tapping or pressing a button, and the continuous control of parameters, such as moving a tactile slider. In particular, tactile, graphical sliders are proposed for a large range of tasks, such as controlling the brightness of the screen or the volume of the sound, controlling a distant mixing console (as observed in chapter 4), filtering data displayed on a wall-sized screen [JDF12], or adjusting the TV sound volume while walking toward the door. Graphical sliders lack tactile feedback, forcing the user to visually focus on the input device to operate it. This visual dependency deprives users from their required eyes-free interaction (as shown in chapter 4).

A problem specific to interaction with mobile devices is the unreachability of some areas of the touchscreen by the thumb when using only one hand. Users prefer to interact with their smartphone with a single hand [KBC08]. One-handed interaction can even be unavoidable when the other hand is carrying other objects [NBW13]. When both holding and operating the device with a single hand, the most popular grasping position is to hold the device vertically with the four fingers and the palm on its back, and to interact with the thumb on the screen [Lee+16]. This is particularly problematic for large mobile devices, which are difficult to use with this grasping position [Cha+15]. When reaching outside the functional area of the thumb, users perform different types of hand movements in order to change their handgrip [Hoo13; Cha+15; Ear+16]. These hand movements can lead to uncomfortable handgrips for the user. This problem has motivated several studies on the functional area of the thumb (e.g., [BO14; Hoo13; KBC08]).

The flexible reconfiguration of tangible widgets on the mobile device, such as proposed by Emergables (chapter 2) could solve both these problems: eyes-free and comfortable interaction. In this chapter, we explore two ways to leverage reconfigurable tangible sliders at the surface of mobile devices: First, mobile tangible sliders could adapt their length and orientation to the grasping position of the hand in order to keep the tangible slider inside the comfortable area of the thumb. Second, to reach targets that are past the comfortable area of the thumb, the reconfigurable tangible mobile sliders could extend the length of its thumb (also called cursor) to allow the user to clutch to reach the target while keeping a comfortable handgrip. We present both studies in the next two sections.

7.1 Impact of length and orientation

Several models for computing the functional area of the thumb have been proposed (e.g., [BO14]). Based on these models, the difficulty of reaching outside this area can be solved by a flexible arrangement of the graphical widgets on the touchscreen [Che+13].

However, while graphical widgets offer the flexibility of dynamic on-screen arrangement, they do not allow to interact without looking at the mobile device. On the contrary, tangible widgets, such as sliders, allows interacting without looking at the device [JDF12]. This is important when the user is mobile, in order to, e.g., safely cross a street while interacting.

The contribution of reconfigurable tangible widgets (sliders or dials) for mobile interaction has been demonstrated in chapter 2. In the two experimental studies described in [JDF12] and chapter 2, participants were able to continuously control a remote object without looking at the screen thanks to the tangibility of the widget, by interacting with one hand while the other hand carried the mobile device.

When tangible widgets are manipulated by the thumb of the hand holding the device, two questions arise:

1. Is the easy manipulation of *tangible* widgets defined by the same functional area of the thumb as the area for *graphical* widgets?
2. In order to interact beyond the functional area of the thumb, do tangible widgets, thanks to the haptic feedback they provide, allow an easier change of grip of the device than with graphical widgets?

In this section, we aim to explore which phenomenon - 1 or 2 - has the strongest impact on performance. To do so, we study the impact on performance of the design of a tangible slider and its ease of use.

For the design of the tangible slider, we study two design parameters: the size and orientation of the slider along which the cursor moves. These two parameters have indeed an impact on the ease of manipulation with respect to the functional area of the thumb. We therefore built four prototypes by considering combinations of the two design parameters: large vertical slider, large tilted slider, small vertical slider, and small tilted slider (Figure 7.1). Only the large vertical slider involves actions outside the area easily reached with the thumb.

Experiment

Our study explores the following independent variables:

- **ORIENTATION:** vertical (90 degrees) or tilted (68 degrees) slider. We chose the vertical orientation because it is the most common on our devices (for example mixing consoles or smart home control panels). Hirotaka [Hir03] measured an average rotation angle of 68.1 degrees with the thumb. We therefore chose an angle of 68 degrees to correspond to the functional area of the thumb.
- **LENGTH:** small (20mm) or large (70mm) slider. This variable is the distance that the cursor can travel. To define the longest length (70mm), we computed the length of the chord D between the two points on either side of the angle of rotation of the thumb. The value of D is given by the following equation: $D = 2 \times r \times \sin(\theta)$, where r is the radius, i.e. the length of the thumb and θ is the angle defining the chord, i.e. the angle of rotation of the thumb. Hirotaka [Hir03] measured the average length of a thumb (r) of 60.4 mm and an average rotation angle (θ) of 68.1 degrees. This gives us a maximum average chord (D) that the thumb can perform of 70.16 mm.

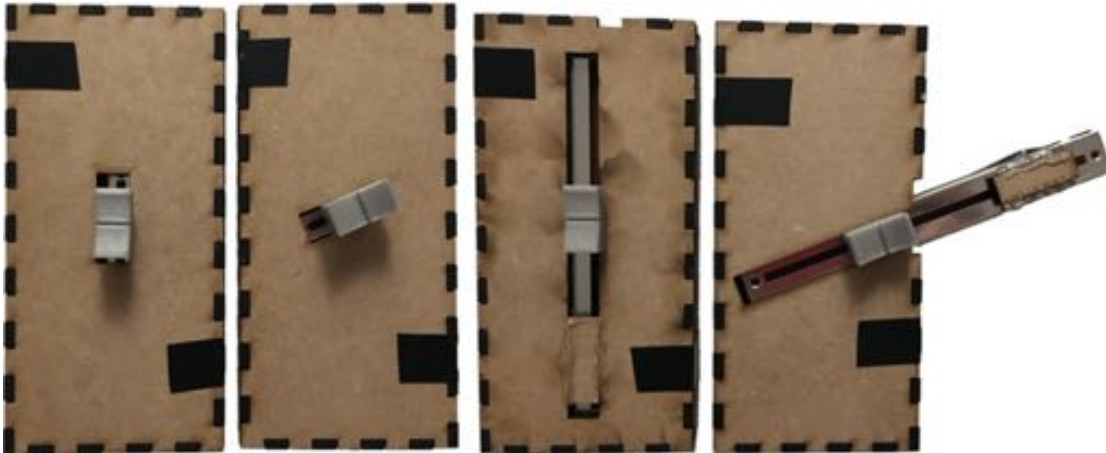


Figure 7.1: Prototypes : small vertical slider, small tilted slider, large vertical slider and large tilted slider. All prototypes have a concave shaped knob to allow interaction with the thumb.

- NUMBER OF HANDS: one-handed interaction, i.e. interaction with the thumb of the hand holding the device, or two-handed interaction, e.g., one hand holding the device and the other manipulating the cursor.

As dependent variables, we recorded the movement time (MT) for the target acquisition tasks, and the response to SUS questionnaires. The details of the apparatus, participants, procedure and analysis can be found in the corresponding publication [Ros+16].

Results

For two-handed interaction, the large vertical slider is the most efficient (MT=1.33s for the large vertical slider vs. MT=1.35s for the large tilted slider). For one-handed interaction, the difference between the large tilted cursor and the large vertical cursor is marginal. As in all cases, the large vertical slider is among the best performing ones, we conclude that the deformation of the moving device aiming at better performance thanks to a flexible arrangement of the cursor is therefore not necessary.

We now focus on one-handed interaction. We will present our results in light of the low, medium and high difficulty levels of the functional area of the thumb. In Karlson et al. [KBC08], areas of difficulty (easy, medium and difficult) have been proposed according to the perceived difficulty of the users. However, no boundary is described between these 3 areas. In this work, we define the high level of difficulty by the area in which the change of grip is necessary and considerably affects performance. The medium level of difficulty is the area in which a change of grip is necessary but only slightly affects performance. The low difficulty level is the area in which users do not need to change the grip of the mobile device to complete the task. In the rest of this paragraph we will see that our results highlight the low and medium difficulty levels. The high level of difficulty is not observed in our study.

In terms of perceived usability, Table 7.1 shows that the large vertical slider was perceived to be the most usable by participants, followed by the small vertical slider. This is explained by participants' familiarity with this orientation: some participants indicated that they preferred the vertical orientation because it resembled the swiping gestures used daily with their mobile device. However, several

	Vertical slider	Tilted slider
Small slider	73.75	68.75
Large slider	76.875	68.75

Table 7.1: SUS scores for each combination of LENGTH \times ORIENTATION for one-handed interaction.

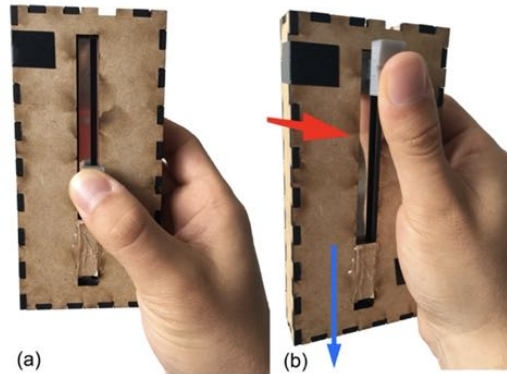


Figure 7.2: (a) Initial grip. (b) Rotation (red arrow) and translation (blue arrow) of the device to reach the target with the large vertical slider. A continuous change in the grip on the cursor is also observed.

participants noted that the large tilted slider was more comfortable to use, e.g., “*I prefer the large tilted slider because it was easier to use with one hand*”.

In terms of grip change, for the two small sliders, the thumb remains by design in the area with low difficulty level. No change of grip is necessary. The orientation of the large tilted slider also avoids any change of grip, and therefore also remains in the low difficulty level. Only the large vertical slider requires a change of grip to perform target acquisition tasks during the experiment. On average 9/10 participants changed their grip. These 9 participants changed their grip an average of 16 times (between 15 and 17 times). Only this large vertical cursor forces the thumb to enter area with medium difficulty level.

We observed that all participants changed their grip on the mobile device (rotation and translation) when they tried to reach the target with the large vertical slider (Figure 7.2). In contrast, with the large tilted slider, all participants maintained the same grip. Changing the grip to a medium difficulty area therefore had little impact on movement time. We explain this by the passive haptic feedback that even the large vertical *tangible* slider provides.

We noticed that when changing the grip on the mobile device, a continuous change of the grip on the cursor also happened. Although this change had no effect on performance during our experiment, we believe that for larger sliders (i.e. >70 mm), changing the grip on the cursor could have an impact on performance. In particular, the effect could be greater if users had to completely reposition their thumb on the button during the task, such as when users reposition the mouse to make large movements (clutching). We study this in the next section.

7.2 ClutchSlider: Extendable Tangible Slider

Our previous study proposed to shrink the tangible control to avoid handgrip changes. However, it confirmed previous work [CD11] by showing the negative impact of small motor scale on performance.

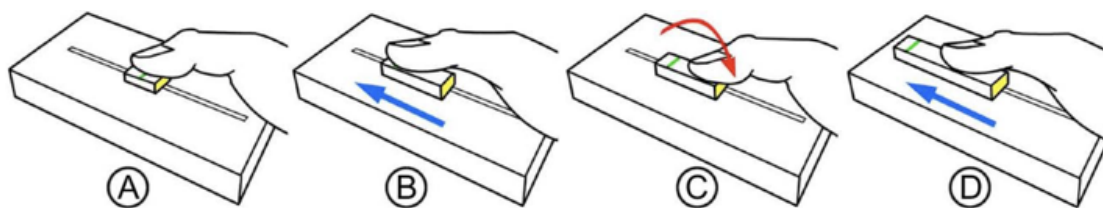


Figure 7.3: Clutching with an extendable tangible slider: (A) the user places her thumb on the slider cursor and (B) begins to push upwards (direction of the blue arrow). (C) When this action is no longer comfortable the user is able to continue to adjust the controlled parameter (as visualized with the green landmark line) by carrying out a clutching action, drawing the thumb down to the comfortable starting position. (D) This is possible because the slider cursor expands (yellow side) in the opposite direction.

Current technologies fail to cover the users' demands, e.g., on eyes-free and mobile tasks as seen in chapter 4. Graphical sliders do not support the eyes-free interaction required by end-users (chapter 4). Standard remote controls offer discrete physical buttons, which can be tedious and/or difficult to operate. Repeatedly pressing a button for specifying a particular value is tiring [Sys11]. Maintaining a button pressed and releasing it when the target is reached requires high sensorimotor coordination [Bjø91]. A solution in favor of eyes-free interaction and against the unreachability of some areas by the thumb, would be to use rate control, i.e. a tangible isometric device to control the direction and speed of movement within the comfortable area, rather than the position of the cursor. However, rate control was found to offer a low degree of perceived usability as compared to position control [WFZ14]. As a consequence, in this section we adopt another solution by considering an extendable slider capable of extending its cursor length (Figure 7.3). The slider's cursor increases its length in order to support thumb-clutching movements. When the cursor is moved upwards, the cursor deforms downwards while letting the slider's landmark move upwards (see 7.3 A-B and C-D), and vice versa. Furthermore, clutching allows us to provide a large motor scale [CD11] while maintaining the movements of the user's thumb within its comfortable area. Users can then always manipulate the cursor precisely, eyes-free, and comfortably –i.e., from the functional area of the thumb.

When targets are near the functional area, two small movements have been identified: (1) fingers placed on the back of the device change position, and (2) the mobile device is tilted within the user's hand. We will refer to these movements as a *handgrip change*. When handgrip changes are not sufficient to reach a target, a shifting of the device within the hand is observable [Hoo13]. We will refer to the shift of the device as a *hand relocation*.

Handgrip changes and hand relocations can be uncomfortable, unstable, and cause the falling of the device. The distinction between handgrip changes and hand relocations is important as they represent two distinct areas outside the functional area of the thumb [Hoo13]. However, the limits between these areas are not defined.

Graphical interaction techniques have been proposed to access targets outside the functional area of the thumb. E.g., double-tapping the home button on iOS will bring the top half of the screen down to the thumb. Others leverage the thumb, e.g., ThumbSpace [KB07] proposes a proxy view of the distant part of the screen within the functional area of the thumb. MagStick [RHL08] and its telescopic stick allows the access to out-of-reach targets. Yu et al. [Yu+13] make use of a graphical circular widget composed of four buttons that appears inside the functional area of the thumb. Each button allow the user to access “magnetized” elements near the corners of the screen. Others expand the interaction space of the thumb by using the back of the device (e.g., [Hak+15; LHG13]).

Tangible interaction can also support interaction with the thumb of the hand holding the mobile

device. To allow reaching targets outside of the functional area of the thumb, one could propose scrolling wheels or dials. Scrolling wheels lack a landmark to provide observability of the parameter. Dials can have a landmark, but the left/right adjustment is not easily mapped to min-max of a parameter, as different cultures can differ on the spatial representation of numbers [SFP09]. The landmark is important when the user needs to acquire the current value (through vision or touch) after the task was interrupted. In this work, we focus on linear controls, such as vertical sliders, since they are commonly used to control a variety of functionalities –e.g., sound, heat, light, TV channels, and data filtering. This allows us to ensure better adoption by providing retro-compatibility (as required in chapter 4).

For these reasons, we explore future emergeable tangible slider for eyes-free interaction. We study an extendable tangible slider that allows thumb clutching in order to support a large motor scale while maintaining the thumb's movements within its comfortable area.

Experiment: Balancing handgrip change, hand relocation, and clutching

We first explore the impact that thumb-clutching movements have on performance. For this, we compared thumb-clutching, performed on a large cursor, with handgrip changes and hand relocations, caused by standard tangible sliders on mobile phones. A within-subjects design was used with three independent variables: *CURSOR*, *DISTANCE*, and *WIDTH*.

The *CURSOR* is used on a mobile device to control a graphical cursor displayed on a distant screen. The *CURSOR* variable is composed of two conditions (see Figure 7.4):

- Small (20mm×10mm×23mm): To reach a target near (resp. outside) the functional area, users have to change their handgrip (resp. relocate their hand, see Figure 7.4(A-B)). It resembles a standard tangible slider;
- Large (150mm×10mm×23mm): To reach a target outside the functional area, users perform thumb-clutching within the area (see Figure 7.4(C)). This is meant as a low-fidelity prototype of an extendable slider.

The *DISTANCE* variable refers to the distance between targets displayed on a distant screen. To explore targets that force handgrip changes and hand relocations, we chose the following values: First, 116mm between consecutive on-screen targets (i.e., 90mm in the control space on the mobile device) proved to force handgrip changes in previous section. Second, 217mm between consecutive on-screen targets (i.e., 150mm in the control space on the mobile device) experimentally proved to force the relocation of the hand. Both distances fit within modern large-sized mobile phones.

The *WIDTH* variable represents the width of the target. In order to analyze performance from coarse to fine adjustment, two different widths were chosen: 7mm and 1.6mm.

The *DISTANCE*×*WIDTH* variables were fully crossed, defining the following task IDs = 4.2, 5, 6.3, 7, as computed in [SM04]. This confirmed our choice by giving medium and hard difficulty levels and avoiding the task being too difficult [SM04].

We then hypothesize that:

- H1** When pointing at closest targets, thumb-clutching (large cursor) and handgrip changing (small cursor) perform equally well.
- H2** When pointing at farthest targets, thumb-clutching (large cursor) outperforms hand relocations (small cursor).
- H3** When pointing at smallest targets, thumb-clutching (large cursor) outperforms both handgrip changes and hand relocations (small cursor).

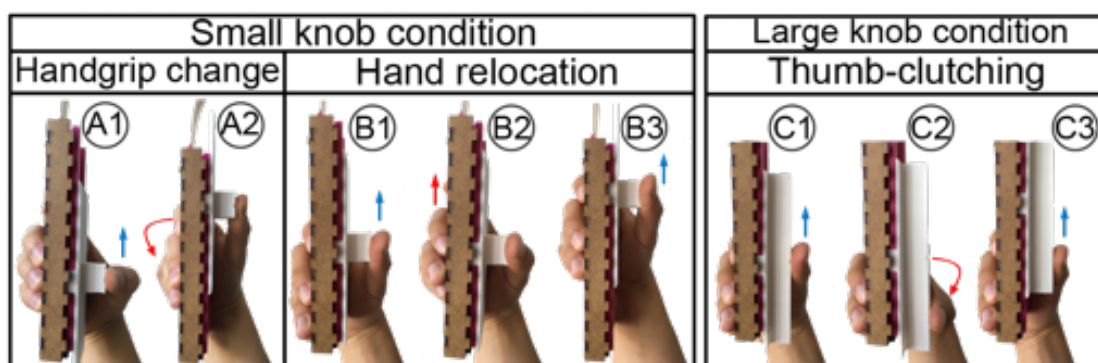


Figure 7.4: The CURSOR conditions and the hand movements related to their operation: (A1) the small cursor is pushed (direction of the blue arrow) with an initial handgrip. (A2) The fingers on the back of the device move (direction of the red arrow), thus changing the handgrip. (B1) the small cursor is pushed (direction of the blue arrow) with an initial hand location. (B2) The hand is relocated (direction of the red arrow) when the thumb's limit is reached. (B3) The cursor is pushed with the new hand location. (C1) The large cursor is pushed (direction of the blue arrow) with an initial handgrip. (C2) Relocation of the thumb. (C3) The cursor is pushed with the same handgrip.

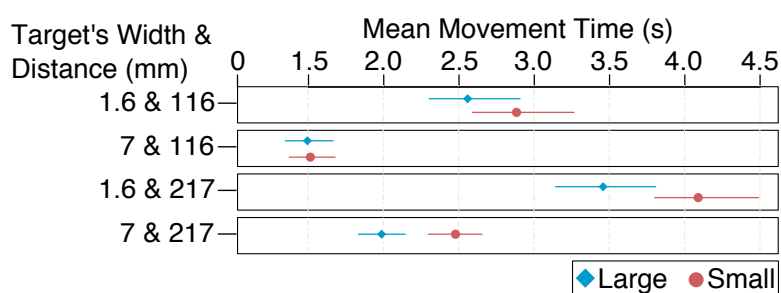


Figure 7.5: Mean movement time for the 2 CURSOR conditions and for the 4 possible DISTANCE×WIDTH conditions (y-axis). Error bars show 95% confidence intervals.

The details of the experimental procedure, apparatus, participants and results can be found in the corresponding paper [Ros+18].

CURSOR, DISTANCE and WIDTH had a significant impact on movement time (Figure 7.5). An interaction between CURSOR and DISTANCE also proved to be significant.

For the 217mm DISTANCE condition, the large CURSOR performed faster for both 1.6mm and 7mm target's WIDTH (+0.6s and +0.4s respectively) than the small CURSOR. The difference between the large and small CURSOR conditions was found significant.

For the 116mm DISTANCE condition, the large CURSOR performed better (+0.4s) than the small CURSOR for a target's WIDTH of 1.6mm. For the 7mm target's WIDTH, the large and small CURSORS performed equally.

To explain the equal performance of the CURSOR conditions for the single 7mm×116mm condition, we used the video footage. We compared the amount of thumb-clutching and handgrip changes performed during the task. On average, 1 clutching movement on the large CURSOR was required (SD=0.4). Only 1 handgrip change was required on the small CURSOR. The hand was therefore

little moved when reaching large targets with a short distance.

Short Distances: Thumb-clutching vs. Handgrip Changes. For small targets (1.6mm) and large targets (7mm) near the functional area of the thumb (116mm), thumb-clutching movements done with the large cursor outperform handgrip changes done with the small cursor (+0.4s). Moreover, participants were also more precise with thumb-clutching. Participants overshoot 9 times more on average with the small cursor than with the large one. H1 is consequently discarded.

Long Distances: Thumb-clutching vs. Hand Relocations. Similarly to short distances, for small targets (1.6mm) outside the functional area of the thumb (217mm), thumb-clutching movements done with the large cursor outperform hand relocations done with the small cursor (+0.6s). Participants overshoot 9 times more on average with the small cursor than with the large cursor. This result suggests again greater precision with the large cursor than with the small cursor.

Regarding large targets (7mm), thumb-clutching outperformed hand relocations (+0.5s). This suggests that hand relocations are more time consuming than a thumb-clutching. We hypothesize that this is due to the special care needed to relocate the hand without dropping the device: video footage shows that participants used all the fingers to displace the device.

Overall, hand relocations were slower and less precise than thumb-clutching when pointing outside the functional area of the thumb; supporting H2.

The aforementioned results on thumb-clutching movements support the results about clutching on relative pointing devices [NVL15].

Small targets. Thumb-clutching movements outperformed handgrip changes and hand relocations when reaching small targets (1.6mm) for both short (116mm) and long (217mm) distances. As explained before, thumb-clutching enabled participants to perform faster and more precisely, thus to reduce overshoot; supporting H3.

Qualitative results. Participants found the small cursor slightly more usable, presumably due to the similar operability between the small cursor and graphical sliders, and the familiarity with the latter. However, they also reported fatigue after using the small cursor. This is confirmed by the video footage: participants were shaking their hands to relax their muscles during breaks. Finally, participants indicated that the large cursor was more comfortable to use since they only needed to move their thumbs.

Experiment with an actuated slider

In previous section, thumb-clutching proved to perform well for targets at the border and far from the functional area of the thumb while offering a stable handgrip. However, in this solution the cursor is long. Even on a future miniature prototype, the cursor has to be long in order to allow clutching. Unfortunately, a large cursor hinders portability of the solution. Therefore, we explore a solution with a smaller cursor. For this, we introduce actuation: we build a prototype that actuates the location of a small cursor so that it moves back in the functional area of the thumb after clutching (Figure 7.6). We experimentally evaluate this prototype. We were particularly interested in observing if the motion of the actuated cursor disrupts the users from being eyes-free. In addition, we wanted to study the impact that the motion of the actuated cursor has on the performance of thumb-clutching movements to reach a target. Finally, we analyzed the perceived usability of such a device.

We performed the same task as in the first experiment but with the actuated knob instead of the large knob. We considered two conditions for the actuated knob in order to study eyes-free

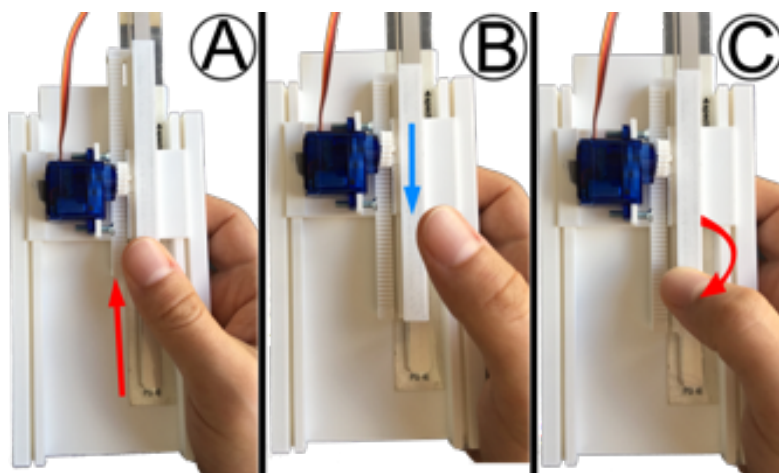


Figure 7.6: (A) The thumb pushes the cursor (direction of the red arrow) until it reaches its maximum elongation. (B) The cursor starts to move back (direction of the blue arrow) while the thumb clutches to a comfortable position. (C) The thumb is relocated within its comfortable area and ready to continue operating.

interaction with it: one condition for which the participant could look at the mobile device to receive visual feedback and one condition with no possible visual feedback by covering the input device with an opaque plastic bag. We also compared these two conditions with an extendable graphical slider. The goal was to compare the performance of clutching when manipulating: 1) an actuated knob that requires no visual attention and, 2) a graphical extendable one that requires switching the visual attention from the mobile device to a distant display.

We thus considered a *TECHNIQUE* variable composed of three conditions. The following three conditions allow participants to perform thumb-clutching movements within the functional area of the thumb with a stable handgrip:

- **Tangible slider with visual feedback (Tangible-Visual)**: Participants are free to look at the input device and obtain visual feedback from the physical landmark.
- **Tangible slider with no visual feedback (Tangible-Blinded)**: Same as Tangible-Visual but the tangible prototype is hidden, thus preventing visual feedback as in [Lis+17]. Participants were asked to operate the prototype inside an opaque plastic bag.
- **Graphical slider with visual feedback (Graphical-Visual)**: An extendable graphical slider that enables users to operate it in the same way as its tangible counterpart.

We discarded the condition with a graphical slider and no visual feedback after we ran a pilot study that showed that it was not possible to properly manipulate the graphical extendable slider without looking at the mobile device.

We consider the same *DISTANCE* and *WIDTH* conditions as in the first study for this experiment. Given these conditions, we hypothesize the following:

H1 Eyes-free interaction with an actuated knob: manipulating an actuated knob will not result in a decrease of performance when users are not looking at the device, compared to when users can look at the device. The automatic motion of the knob does not mean one has to look at the mobile input device.

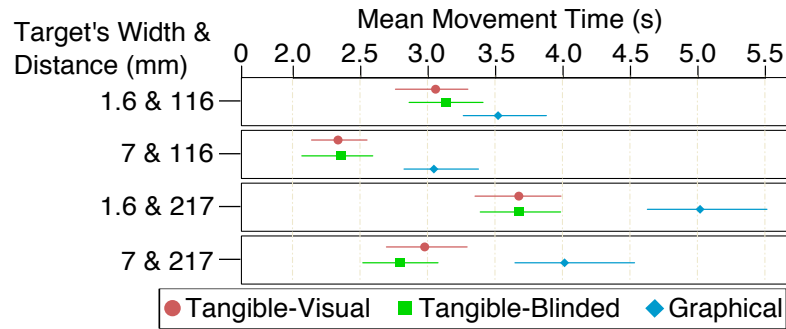


Figure 7.7: Mean movement time for the 3 *TECHNIQUE* conditions and for the 4 possible *DISTANCE* × *WIDTH* conditions (y-axis). Error bars show 95% confidence intervals.

H2 Manipulating an actuated knob versus switching visual attention: manipulating an actuated knob will not result in a decrease of performance compared to the equivalent graphical input method that requires switching visual attention between the mobile device and the screen.

The details of the experimental procedure, apparatus, participants and results can be found in the corresponding paper [Ros+18].

We found a significant effect of *TECHNIQUE*, *DISTANCE* and *WIDTH* on movement time. The interaction between *TECHNIQUE* and *DISTANCE* proved to be significant.

For the 116mm *DISTANCE* condition, the Graphical-Visual condition presents the highest movement time on both 1.6mm and 7mm target's width (3.5s and 3s respectively). We found significant difference between the Tangible-Visual and Tangible-Blinded conditions for both widths.

Similarly, for the 217mm *DISTANCE* condition, the Graphical-Visual condition presented the slowest performance (1.1s more than the tangible conditions) for both widths of target. We found no significant difference on performance between the Tangible-Visual and Tangible-Blinded conditions for both widths of target. These differences are observable in Figure 7.7 where the Tangible-Visual and Tangible-Blinded conditions have similar performance times.

Eyes-free Interaction With an Actuated Tangible Knob. The Tangible-Visual condition performed equally well as the Tangible-Blinded condition for both short and long distances. Based on the number of overshoots, the Tangible-Visual was slightly more precise than the Tangible-Blinded for small targets and short distances (-4 overshoots), and large targets and long distances (-3 overshoots). These results suggest that the motion of the actuated knob did not prevent participants from operating in an eyes-free manner, thus supporting H1.

On the contrary, the Graphical-Visual presented the worst performance. We explain the bad performance of the graphical solution by the number of time that participants looked down to reacquire the cursor of the slider. This effect has already been observed when operating graphical widgets (e.g., in [JDF12; Lis+17] and in chapter 2). We used video footage from the experiment to annotate each time participants gazed at the graphical slider on the input device. The result shows that participants looked down at the input device, on average, two times per repetition of the task; giving a total of 128 gaze deviations. The lack of tangible feedback from the Graphical-Visual condition made difficult for users to land their thumb back into the slider graphical area when clutching. On the contrary, the tangible prototype under both visual conditions did not require visual attention to be operated.

Impact of the Motion of the Actuated Tangible Knob on Performance. The motion of the actuated knob had an unexpected effect on interaction: participants stopped manipulating the slider

while the knob was in motion. Video footage shows that, when performing thumb-clutching movements, 15 out of 17 participants waited for the knob to stop moving before landing their thumb. Since participants stopped manipulating the slider, we argue that the motion of the knob had an impact on performance. To confirm this, we compared the mean number of times the operating hand was idle when using the actuated slider with the large knob from the first experiment. We found that the mean number of idle time increased 35% for the 1.6mm WIDTH condition and 64% for the 7mm WIDTH condition in comparison with the same conditions from the first experiment. Although both conditions were not tested in the same experiment, we expected that the thinner body of the designed actuated knob (- 20mm) would have implied an easier operation, thus better performance. However, this was not the case. We can then only speculate that the motion of the actuated slider had an impact on the performance of thumb-clutching movements. Despite the observed stops in movement provoked by the actuated knob and its resulting drop in performance (+0.6s) in comparison with the large knob from the first experiment, the tangible slider proved to outperform the graphical slider. This suggests that the switching of visual attention required by the graphical extendable slider had a bigger impact on performance than the motion of the actuated knob; supporting H2.

Perceived usability. Both graphical and tangible sliders were found equally usable. We argue that despite the visual attention required by the graphical slider, its high score is due to the familiarity of the participants with tactile interfaces [TPH14].

Regarding our tangible prototype, we argue that a higher fidelity version could have been perceived as more useful. Nevertheless, we consider our tangible prototype as being of medium fidelity since it supported good performance.

Conclusion

Tangible deformable mobile sliders define a new perspective on the problem of reaching targets outside the comfortable area of the thumb when a single hand is interacting *and* holding the mobile device.

The experimental results we present in this chapter show that:

1. The size of the motor space significantly influences the performance (significant difference in performance between large and small cursors);
2. The change in grip required beyond the functional area of the thumb (from easy to medium difficulty) has a marginal impact on performance.
3. In contrast to performance, participants' preferences emphasize the importance of maintaining actions in the functional area of the thumb at the low level of difficulty.

In a second experiment, to define the upper size limit at which performance with a tangible cursor degrades, we experimentally measured the three levels of difficulty (easy, medium and difficult) [KBC08]. We also compared these results with graphical cursors to measure differences in performance and change in grip.

Our first low-fidelity prototype –a tangible slider with a very large knob– gave us insight into the manipulation and performance of an extendable slider and how it compares to a standard tangible slider.

Experimental results show that clutching on this prototype improves performance when reaching for proximal and distant targets. Our second medium-fidelity prototype –a tangible slider with an actuated knob– was compared to an extendable graphical slider. The results show that:

1. The motion of the actuated knob did not disrupt participants from eyes-free interaction;

2. The switching of the visual attention required to operate the graphical extendable slider has a bigger impact on performance than the stops in manipulation during the automatic motion of the actuated knob.

Our results show the benefits of thumb-clutching on tangible extendable sliders for eyes-free and one-handed interaction in the context of remote displays.

To address the limitations of the designed prototype future work could test different directions for deforming the knob instead of moving it. For instance, the knob could extend by morphing out of the surface below the thumb; this would prevent the user from feeling the motion of the knob and therefore stopping the manipulation of the slider. Furthermore, future work could investigate the challenge of combining the use of multiple extendable tangible sliders for the adjustment of different continuous parameters –e.g., for controlling the RGB levels of a projector.

Our results shows the high importance in studying in future work the impact of dynamic shape-change *during* interaction, as this could prevent an efficient interaction. Learning and long-term studies could also show how users get used to novel, dynamic shape-change in the long term, as our observations might be impacted by the novelty effect.

Summary and discussion

In this chapter concluding the second part, we summarize our contributions and assess them through their abilities to improve problem solving capacity of the HCI field [OH16]. We first identify the categories of problems we addressed: empirical and constructive problems, as shown in Figure 7.8. We then assess our contributions through the five complementary criteria, from the problem-solving framework [OH16]: significance, effectiveness, efficiency, transfer, and confidence. By doing so we highlight the strengths and limitations of our contributions. Some of the listed limitations are well identified described in the chapters of this second part and the corresponding publications as future work. We found that it is relevant to gather all the strengths and limitations of our conducted work to take a step back on the conducted research path.

Contributions

In this second part, we presented **constructive contributions**. These explain how to construct a particular interactive system.

First, constructive contributions can present a *first prototype*. For example, the KnobSlider prototype shows a first step in the construction of device changing shape between a dial and a slider, in order to bring such flexibility to physical dials. The zoomable slider prototype is also a first step in the construction of slider changing its length, in order to bring such flexibility to physical sliders. In the same way, the low-fidelity ClutchSlider prototype is also a first prototype.

Second, constructive contributions can *extend, make effective or efficient* a previously existing constructive contribution. For instance the medium fidelity ClutchSlider prototype makes the first prototype (low-fidelity Clutchslider) more effective by making it smaller. Moreover ExpanDial is a prototype of a diameter- and height-changing dial. As a diameter-changing dial was proposed before [OBJ18], ExpanDial therefore extends a previous work in order to bring even more flexibility to physical dials. Finally the SplitSlider prototype is a tangible version of previous, graphical prototypes [Gre+17]. Therefore our prototype extends a previous constructive contribution.

In addition to constructive contributions, this second part presented **empirical contributions**. The empirical contributions are mainly derived from experimental evaluations conducted with our prototypes that are constructive contributions. One exception is the formative study described in Chapter 4. This **formative study** (chapter 4) reveals **unknown phenomena**, i.e. the requirements and current strategies for end-users to balance between their need for physicality and their need for flexibility.

The **KnobSlider's qualitative study** (chapter 5, section 5.2.2) provides empirical knowledge about the ambiguous perception of fast shape-change (**unknown phenomenon**).

The **evaluation of ExpanDial** (chapter 5, section 5.1) explores potential **unknown factors** impacting the qualitative user experience, such as the users' control and perceptive abilities of width and height, or the trade-off between reconfiguration gestures that are general and easy to be applied

		Empirical problems	Conceptual problems	Constructive problems	
Progress of knowledge ↓	1st subtype	Unknown phenomena	Implausibility	No known solutions	
		<ul style="list-style-type: none"> ▷ Formative study 4 ▷ KnobSlider qualitative study (speed) 5.2.2 		<ul style="list-style-type: none"> ▷ KnobSlider 5.2.1 ▷ Zoomable slider 6.1.1 ▷ ClutchSlider (low fidelity) 7.2 	
		Unknown factors	Inconsistency	Partial, ineffective or inefficient solutions	
	2nd subtype	<ul style="list-style-type: none"> ▷ ExpanDial study 5.1.2 ▷ KnobSlider quantitative study 5.2.3 ▷ SplitSlider focus group (design) study 6.2.1 ▷ Mobile slider size and orientation 7.1 ▷ ClutchSlider low fidelity experiment 7.2 ▷ ClutchSlider medium fidelity experiment 7.2 		<ul style="list-style-type: none"> ▷ ExpanDial prototype 5.1.1 ▷ SplitSlider 6.2.1 ▷ ClutchSlider (medium fidelity) 7.2 	
		Unknown effects	Incompatibility	Inability to deploy or implement	
		3rd subtype	<ul style="list-style-type: none"> ▷ Zoomable slider experiments 6.1.2 ▷ SplitSlider experiment 6.2.2 ▷ Mobile slider size and orientation 7.1 ▷ ClutchSlider low fidelity experiment 7.2 ▷ ClutchSlider medium fidelity experiment 7.2 		

Figure 7.8: Problems addressed in this second part of the manuscript and their corresponding contributions. For each contribution, we quote the chapter and section of its presentation.

to all kinds of interfaces and reconfiguration gestures that leverage the input capabilities for each particular interface.

The **KnobSlider’s quantitative study** on speed preference (chapter 5, section 5.2.3) identifies an **unknown factor** impacting the preference on reconfiguration speed, namely the physicality of the display (video vs. physical prototype).

To design **SplitSlider**, we first conducted a focus group study in order to identify the **unknown factors** that lead users to prefer a low-fidelity prototype over another. This study is not reported in this manuscript but in the corresponding publication [Gre+19].

We performed two experiments with the **zoomable slider** prototype: one to evaluate its performance for target acquisition tasks [CM15] –that we do not present in this manuscript– and one to evaluate its limits of usability –presented in chapter 6 (section 6.1.2). The first experiment was a partial replication of previous work done for the mouse [CD11]. Our goal with this partial replication was, in addition to the strengthening of the HCI field, to measure the performance of the zoomable slider on a target acquisition task so that we can examine the results of the second experiment in light of the first one. These experiments aimed at measuring the **unknown effects** (1) of the prototype on small target acquisition, and (2) of resizing on pursuit performance.

We conducted an experiment to assess the discoverability and the perceived ease of use of **SplitSlider** (section 6.2). In other words, we measure the **unknown effect** of users’ knowledge on their use and perception of the prototype.

Some of our contributions addressed simultaneously two subtypes of empirical problems: **unknown factors and effects**, although this reduces the reliability of our results as explained in page 110: the same data should not be used to both generate *and* test a hypothesis, because such an approach can bias the research. Nevertheless, this is often done so in HCI. In section 7.1, we aimed at identifying if the length and orientation of tangible mobile sliders were factors impacting their usability and their performance for target acquisition tasks. We also measure the effect of these factors on their usability and their performance for target acquisition tasks. The same comment applies to the low-fidelity prototype (section 7.2) and the medium-fidelity prototype of ClutchSlider (section 7.2). In

Empirical contributions

	Significance	Effectiveness	Efficiency	Transfer	Confidence			
					Internal validity	Reliability	Reproducibility	Replicability
Formative study	High	High	High	High	High	High	High	High
ExpanDial evaluation	High	High	High	High	High	High	High	High
KnobSlider qual. evaluation	High	High	High	High	High	High	High	High
KnobSlider speed study	High	High	High	High	High	High	High	High
Zoomable slider experiments	High	High	High	High	High	High	High	High
SplitSlider experiment	High	High	High	High	High	High	High	High
Mobile slider size/orientation	High	High	High	High	High	High	High	High
Low-fi ClutchSlider	High	High	High	High	High	High	High	High
Medium-fi ClutchSlider	High	High	High	High	High	High	High	High

Constructive contributions

	Significance	Effectiveness	Efficiency	Transfer	Confidence	
					Robustness	Replicability
KnobSlider	High	High	High	High	High	High
ExpanDial	High	High	High	High	High	High
Zoomable slider	High	High	High	High	High	High
SplitSlider	High	High	High	High	High	High
ClutchSlider	High	High	High	High	High	High

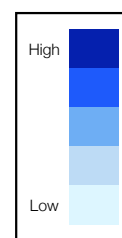


Figure 7.9: Synthetic assessment of the contributions presented in this second part of the manuscript. Light colors show low [significance, effectiveness, efficiency, transfer or confidence], while dark colors show a high [significance, effectiveness, efficiency, transfer or confidence].

the first case, we identify if thumb clutching is a factor impacting on performance, and measure the effect of thumb clutching on performance. In the second case, we identify if the interaction technique, namely actuated, tangible, or graphical slider, impacts visual attention, and measure the effect of each interaction technique on performance.

We now further assess our contributions through the five associated criteria [OH16]: significance, effectiveness, efficiency, transfer, and confidence. Figure 7.9 shows a synthetic summary of this assessment.

Significance

Significance assesses the importance and relevance of the problems addressed. To analyze the significance of our work, we verified if the problems we addressed are in line with the grand challenges of shape-changing HCI research [Ale+18]. When possible, we also verified how many users are impacted by the solution, and the cost of an absence of a solution.

Most of the **empirical work** presented in part II contributes to the understanding of the user experience of shape-change, which is a grand challenge of the field [Ale+18]. For this reason, we rate these empirical contributions with at least medium significance. However, some of these empirical contributions exhibit higher significance.

First, as a way to assess the short-term significance of our **formative study** (chapter 4) for the HCI community, we performed a systematic analysis of the subsequent papers citing the formative study. At the time of the writing of this manuscript, we found a single paper that was not authored by

one of the authors of the formative study. This paper [Rey+18] explicitly builds on top of the *design approach*, rather than on top of our requirements. However, we recruited participants representing a large population of users (e.g., graphic designers were 261,600 in 2014 only in the U.S.), and/or users whose performance is critical to others (e.g., pilots). This increases the significance of the formative study.

Second, we rate the significance of our **evaluation of ExpanDial** as rather high. As reconfigurable dials are deeply studied (e.g., [Mic+04; OBJ18; Oos+19; Rob+16], etc.), we think that it was very important to identify which of their design parameters qualitatively impact the user experience (section 5.1).

Third, we rate the significance of the **medium-fidelity clutchSlider experiment** as rather high, as it allows to identify the impact of actuation on the interaction. Many reconfigurable physical interfaces use technologies like motors that have drawbacks, including the noise and the slow movement for the medium-fidelity ClutchSlider. This result is important for the HCI community as it reminds that the choice of technologies has an impact on the experimental results. This impact is difficult to evaluate.

Fourth, we rate the significance of the **quantitative study of KnobSlider** as rather high. Users preference for speed is important to understand in order to design future reconfigurable devices. In addition, understanding how the prototype (video vs. physical) impacts the user experience of shape-change is highly important, as reconfigurable prototypes are difficult to build and researchers already used videos as a way to quickly build a prototype, instead of building and using physical prototypes (e.g., [PSH14; Str+16]).

Our **constructive contributions**, namely **KnobSlider**, **ExpanDial**, **zoomable slider**, **SplitSlider**, and **ClutchSlider** address the grand design challenge of *when to apply shape-change* and *what shape-change to apply* [Ale+18]. We carefully ground the design of our prototypes, in particular the **KnobSlider**, on contextual interviews with end users, in order to identify when to apply shape-change and what shape-change to apply. The amount of users that could benefit from more flexible dials or sliders is very large, as dials and sliders are present in the every life of the general public, e.g., in the car or at home. In addition, the amount of professionals that could benefit from KnobSlider is estimated to be around 90,000 and 100,000¹ in France. However, there is no scientific study reporting a count of these professions. The lack of flexibility or tangibility causes users to suffer from errors (R4, section 4.2.3), most notably when they need to switch their visual attention to the device (R5, section 4.2.4), time-consuming tasks (R2, section 4.2.2), from the impossibility to work in an environment with limited room when the device is too large (R5, section 4.2.5), from the impossibility to express uncertainty with standard tangible sliders (R4, section 4.2.3), or from unstable handgrips on their mobile phones (R5, section 4.2.5).

Although we do not know yet if anyone built their own KnobSlider, the DIY tutorial for KnobSlider has attracted a lot of attention². Among the 6 papers citing the CHI 2018 KnobSlider paper at the time of the writing of this manuscript, and that are not co-authored by one of the authors of KnobSlider, only one [Mah+19] describes as future work the design of their envisioned solution built on top of KnobSlider.

Effectiveness

Effectiveness assesses the match between the solution and the essential aspects of the problem addressed. To analyze this, we first verified that our evaluation criteria match the priorities of the target users. When relevant, we consider the end-users requirements presented in chapter 4 as the main

¹This figure comes from a subsequent market research aiming at the transfer of KnobSlider to the industry.

²The [instructables tutorial to build KnobSlider](#) counts 10,698 views and 65 “likes” at the time of the writing of this manuscript.

criteria to consider. We also verified that we evaluated our solution with multiple, diverse criteria and in multiple contexts, and that we addressed the difficulties that emerge from real world scenarios.

Empirical contributions

Effectiveness is difficult to assess in empirical contributions [OH16] as it often deals with hardly known phenomena. It is therefore difficult to demonstrate that the essential aspects of the phenomenon have been identified or addressed. However, it is possible to find areas to improve effectiveness when we find relevant factors that could be evaluated in the future.

We think our **formative study** has a rather high effectiveness, as we used a qualitative method (contextual inquiry) that allows for our findings to be strongly grounded in the real-world experience of end users.

Overall, we think the **qualitative evaluation of the KnobSlider** prototype is effective. On the one hand, the study allows to identify potential factors impacting the user experience with the device. The study was conducted with target end-users, enabling the design of future devices as closely as possible to the end-users' requirements. On the other hand, the study lasted around 1 hour with each participant. A more in-depth qualitative study, spending more time with each participant and having them to perform a more realistic task would have probably lead to more effective results.

The **quantitative experimental evaluation of KnobSlider** presents aspects reducing the overall effectiveness that are related to the studied variables, but overall, and based on the selected participants, this evaluation presents a high effectiveness. For instance, a limitation is that we did not consider virtual reality, although this might be a way in the future to quickly evaluate reconfigurable device concepts. Another example limitation is that participants did not manipulate the physical KnobSlider prototype, in order not to introduce a bias in our study comparing with a video presentation of the prototype. However, we expect the manipulation to impact the users' preference on the speed of shape-change. Our choice of participants allowed to improve the effectiveness. We chose to recruit non-professional users. For the qualitative study, we asked professional users because we wanted to understand the current interaction, usages, and applications. This is a common practice used in the user-centered design process, a typical *modus operandi* from designers and HCI researchers. However for the controlled pairwise comparison study, our goal was to investigate perception of the movement and this could be studied with non-professional users, as both professional and non-professional users have not experienced reconfigurable controls before, and perception of the shape-changes should be the same for them. Having non-professional users also allowed us to have a broader range of participants and to increase the sample size for statistical tests. Therefore, we think this experiment shows rather high effectiveness.

The qualitative study conducted for the **evaluation of ExpanDial**, on the one hand, allowed to identify the essential aspects impacting the user experience with the device. On the other hand, our study was conducted in the form of a focus group. While focus groups have clear benefits to explore users' agreement, focus groups suffer from the biases of the moderators' directions and the participants themselves [Mor96]. Our study clearly suffers from a bias in recruiting, as all participants were PhD students or post-docs in computer science. A study with more diverse participants, would further benefit the results, and maybe allow the identification of other factors. We also think that the results would benefit from a comparison with a baseline, as it is not clear if the factors identified in the experiments were specific to the ExpanDial prototype or can apply to other reconfigurable dials. Therefore, we think this study shows medium effectiveness.

The **experiments with the zoomable slider**, with the **SplitSlider**, with **sliders with varying length and orientation**, and with **ClutchSliders** target the evaluation of the users' requirements for fast interaction (R2, section 4.2.2) and accuracy (R3, section 4.2.3). The interaction required users to interact eyes-free (R4, section 4.2.4) as they had to watch the screen in front of them.

As these metrics (speed, accuracy and visual attention) were identified in our formative study as end users' requirements, we believe these experiments capture the essential aspects of the problems. The evaluation however only took place in the lab, and not *in situ*, in a mobile environment (R5, section 4.2.5), and with non-professional users. During these experiments, participants also only interacted with a single parameter, and did not have to interact with multiple parameters as they do in the real world (R1, section 4.2.1). Therefore, we think these experiments show medium effectiveness.

Constructive contributions

The **zoomable slider prototype** and **SplitSlider prototype** need users' manipulation in order to resize. This might hinder fast interaction (R2, section 4.2.2) and simultaneous interaction with several zoomable sliders (R1, section 4.2.1). On the contrary, the **ClutchSlider prototype** is actuated. The current footprint (R5, section 4.2.5) of the **zoomable slider prototype** is rather high, as the location of its cursor is tracked through cameras. The mobility of the current **SplitSlider** and **ClutchSlider prototypes** is hindered by their tethered connection to an Arduino board (R5, section 4.2.5). The prototypes however ensure eyes-free interaction (R4, section 4.2.4). For these reasons, we evaluate their effectiveness as rather low to medium.

We think our **ExpanDial prototype** offers a solution to cover many of the shapes we observed in our formative study (see chapter4). As a consequence, we think our **ExpanDial prototype** supports many way of using dials in a single dial. However, the prototype is rather large compared to existing dials (R5, section 4.2.5). In addition, the prototype presented in the manuscript does not address the issues raised in its evaluation. Such improvements are future work. For these reasons, we evaluate their effectiveness as medium.

We ensured effectiveness of our **KnobSlider prototype** through the design process, based on the end users requirements. To verify the effectiveness, we conducted a qualitative study of the KnobSlider prototype with end-users. This evaluation included the different users and tasks that KnobSlider was designed for. This study allowed us to identify the areas for improvement. In particular, although the KnobSlider prototype is smaller than the ExpanDial one, participants found it still too large. In addition, the prototype presented in the manuscript does not address the issues raised in its evaluation. Such improvements are future work. As a consequence, we believe the effectiveness is high, but not very high.

Efficiency

Efficiency assesses the cost in applying the solutions proposed, relatively to the gain achieved. To analyze this, we verified how much effort and/or resources are needed to produce the solution, the scalability of the solution, if we provide a tool for designers to leverage the solution and if we share datasets and code.

Empirical contributions

We rate all our experimental contributions at least as efficient. For these experimental contributions, we fabricated prototypes with the fidelity necessary to address our research questions. Higher fidelity prototypes would have often been a waste of resources *for the same study*, although higher fidelity prototypes would enable more effective studies.

We rate higher the efficiency of our experiment focusing on the impact of size and orientation of sliders on the performance in a mobile context as its experimental material³ is shared on the Web.

³<http://iihm.imag.fr/coutrix/studies-files/SizeOrientation/>

Constructive contributions

Most of our constructive contributions are easy to produce as they only require access to a FabLab equipped with consumer-grade machines, like 3D printers and laser-cutters. The materials needed to build them are cheap, e.g., consumer grade PLA or wood. They also require simple electronics components such as arduinos.

Compared to a standard dial, the proposed **ExpanDial prototype** requires 6 motors in addition to the dial. Compared to previous implementations of reconfigurable dials, for instance the Ripple Thermostat [OBJ18], ExpanDial requires 5 more motors, in order to enable the independent actuation of the diameter and the height of the dial. Ripple thermostat had also an additional motor as they investigated haptic feedback, which was not our focus with ExpanDial. To fabricate an ExpanDial, we share our design in the paper and proposed an [ExpanDial tutorial on the Web](#).

Compared to having both a slider and a dial, the **KnobSlider prototype** requires 5 more motors to enable the change of shape. To enable only two shapes, namely a slider and a dial, a single motor should be possible. However, we chose to have 5 motors, one for each joint, in order to enable future interaction techniques supported by shapes in-between a slider and a dial, as shown on Figure 5.5 on page 61. Building KnobSlider requires access to a precise 3D printer that is seldom found in FabLabs in order to ensure that the pieces easily fit together. To fabricate a KnobSlider, we share our design and provide a [tutorial on instructables](#).

We made the [source to make a zoomable slider](#) available on the Web. However, for end-users to leverage the solution, the Optitrack tracking system is rather expensive. On the contrary, for research purposes, such tracking systems are often present in research labs. This tracking system was chosen for its simplicity to implement a reliable tracking of the zoomable slider. As a consequence, we evaluate the solution as rather highly efficient.

The **SplitSlider** and **ClutchSlider prototypes** are rather easy to produce. However, the code and models of the ClutchSlider are not available on the Web, while [the model of the SplitSlider is available on the Web](#).

Transfer

Transfer assesses how well does the solution transfers to other problems. To analyze this, we evaluated how many users, tasks and contexts can or could benefit from the solution.

Empirical contributions

The transfer of empirical contributions is also called external validity. Transfer is difficult to assess for empirical contributions [OH16] without performing additional experiments. For this reason, our assessment will most often be speculative. In general, we cannot be sure that our experimental contributions could be applied to further users, contexts, such as new tasks and new widgets, in the field or in the long term.

Our **formative study** aims at generalizing through the recruitment of participants from diverse professions. It would be interesting, however, to observe and interview more professions, like color graders, photographers, etc. to verify this. We believe our results would transfer in the long term, as most of our participants were already experienced professionals. For these reasons, we rate the transfer of these two empirical contributions higher than the others.

As opposed to the formative study, the results of the **qualitative study of KnobSlider** should apply to others professionals provided that they share the same requirements for their control interfaces, such as color graders, control panels users in production plants, etc. Transfer could however be improved by extending the panel of participants and their tasks, and by interfacing KnobSlider with

their own apparatus and having participants use it in the long term. In our study, despite our effort, only 2 participants were female (graphic designers). We regret that this might mirror the unbalanced gender in these users groups.

We think the results of our **quantitative study of KnobSlider** should transfer to reconfigurable devices that exhibit the same amplitude of movement and sharp edges like KnobSlider, and that are used at around the same distance to the users' body.

The **experiment with the zoomable slider** on target acquisition is a partial replication that shows that previous results with a mouse [CD11] transfer to this new slider. However, we did not try to transfer the results of the second experiment to other devices such as SplitSlider or KnobSlider.

Our experiments on the **impact of length and orientation** for mobile tangible sliders, and on the **ClutchSlider** apply to sliders but not to other types of tangible widgets such as the dials of chapter 5. However the number of potential future users and tasks supported by these interaction techniques is rather high.

Our **evaluation of ExpanDial** did not consider other prototypes of reconfigurable dials. We also only recruited academic staff in computer science. For this reason, we rate the transfer of this contribution lower.

We did not try to transfer the results of the **evaluation of SplitSlider** to other devices such as the ones proposed in the focus group (section 6.2). In addition, the tasks supported by SplitSlider are limited to the ones for which users can be uncertain about the value to enter. As a consequence we evaluate the transfer to low.

Constructive contributions

Transfer, or general nature, is often shown for constructive contributions through application examples [OH16]. For instance, our evaluation of the **ExpanDial prototype** assesses its transfer through the 41 application ideas suggested by participants. We can reach better transfer in the future by implementing these applications to evaluate the success of this transfer.

Our **KnobSlider prototype** already applies to the 5 different professions from our formative study (chapter 4). We assess the transfer of our prototype through the introduction of a new profession, namely photograph, and new participants in our pool of participants for the qualitative study. The interviews with professionals also attempted to identify applications for the KnobSlider prototype to further increase its transfer in the future. To better assess the transfer of the KnobSlider prototype, we could study its application to training in simulators, color grading consoles, etc. that are expected to share the same requirements as our pool of end-users.

Although the design of the **zoomable slider prototype** is grounded on our formative study (chapter 4) and its resulting end-users requirements from diverse professions, we did not assess how the zoomable slider transfers to these possible applications. As a consequence, we evaluate the transfer of the zoomable slider prototype to rather low.

The transfer of **SplitSlider** was assessed during the focus group where we asked participants when they experience the need to input uncertain data in public. The case study of the experiment, i.e. surveys in public spaces, comes from the results of this focus group. While we take the example of trains in our experiment, we think SplitSlider can apply to other domains that require surveying their users. However, the prototype has to be improved first to make inputting uncertain data discoverable by users.

Possible applications of **ClutchSlider** range to all the professions of our formative study (chapter 4), as well as others with similar needs (e.g., Color graders). However, we did not verify this transfer. As a consequence, we rate its transfer to medium.

Confidence

Confidence assesses how well will the solution hold as time passes. To evaluate this, we verified empirical validity, reliability, replicability, reproducibility, robustness, if we allow re-analysis, and how many metrics were used to assess validity and reliability.

Empirical contributions

Confidence is more particularly assessed for empirical contributions through the following four criteria: internal validity⁴, reliability, reproducibility and replicability [OH16].

Internal validity of empirical contributions

Internal validity is the adequacy of the experimental procedure, the method for the recruitment of participants, and the methods for analysis, in particular the statistical methods when applicable.

Overall, our qualitative studies followed standard procedures. The two following studies happened *in situ*. For these, we chose thematic analysis [BC06] to analyze the data collected. We think that the thematic analysis allowed us to strongly ground our findings in the participants' experience. The advantage of this method is that it helps summarizing key features of a large body of data, highlighting similarities and differences across the data set, and generating unanticipated insights.

We estimate that the recruitment of participants for these studies was adequate: For instance, for our **formative study**, we tried to have as diverse professions as possible, while having as experienced participants as possible (ages 25–63). We had 8 participants, a number presented as being sufficient for the contextual inquiry method [HWW05]. We believe the contextual inquiry method is efficient to reveal issues in the interaction between end users and a system, as shown by its extensive use [HWW05]. For our **qualitative study of KnobSlider**, we tried to reach high confidence through the recruitment of 10 participants, with a rather broad age range (32 – 63). However for both studies, we could recruit only two female participants, mirroring the minority of females in these professions.

One qualitative study, the **evaluation of ExpanDial**, happened in the lab. We struggled to recruit for this study, and conducted it with 10 participants (2 females) from our university (Ph.D. students or post-docs in computer science). Although their field of study was rather large (researching on HCI, machine learning, geomatics, compilers, etc.), we think this limits the internal validity of the study. However, participants had a rather large range of ages (between 25 and 43 years old) which strengthen its internal validity.

Our quantitative studies also mostly followed standard procedures. For these studies, we recruited participants on the campus. We do not consider that this harms the validity of these studies, as these was motor-visual or perception studies and we did not think this can heavily be impacted by the profession.

In particular, we carefully assessed the internal validity of our **quantitative study of KnobSlider**. The procedure we followed supports a paired comparison experiment [Dav63]. Paired comparison experiment is a typical method used to gather Quality of Experience (QoE) feedback in HCI [Che+09; AR17; SRI17]. Estimating preferences of objects based on subjective judgments is a critical step in psychological experiments with applications in many research fields such as marketing, environmental sciences, and health economics. Quality of Experience feedback is used for, e.g., surveys on product design preference, and also in many research fields where measure subjective judgment such as preferences and importance, including policy design, voting systems, and marketing [Jen86; Jen86; Win80]. We analyzed our results based on the three-step analysis for pair-comparison studies [Che+09].

⁴ *External validity*, on the other hand, is assessed through the *transfer* criteria, i.e. how well does the experiment apply to other situations, tasks, users, etc. or in the field or in the long term.

For our **experiments with the zoomable slider** and our evaluation of the **impact of length and orientation** and of **ClutchSlider**, the procedures and analysis we followed has been extensively used in HCI (for the target acquisition and pursuit experiments).

The **evaluation of SplitSlider** was conducted on participants that were used to take public transportation, and hence already went through this type of surveys. Our experiment could not follow common procedures such as, e.g., target acquisition experiments, as inputting an uncertain value is –unfortunately– a seldom task in HCI. We chose to have participants to use the system with no information first, as this is what would happen in the field. As we wanted to also evaluate SplitSlider’s ability to input uncertain values, we introduced the second phase after explanation. We think the procedure is valid.

Reliability of empirical contributions

Reliability assesses how consistent were the results across, e.g. participants, types of measure, or repetitions.

We think our **formative study** shows high reliability as we only reported as requirements the findings that were consistent across participants.

The results of the **qualitative study of KnobSlider** were rather consistent across users. E.g., most of them commented that the slider was not smooth enough, and the prototype was too big and not stable enough for their own tasks.

We thoroughly assessed the reliability of the **quantitative study of KnobSlider**. To do so, we checked *individual consistency* for this experiment, i.e. each participant’s consistency, by using Transitivity Satisfaction Rate (TSR). TSR quantifies how much the participants’ preferences were transferred when comparing their preferences with different pairs. For example, a participant responded that speed condition A is more preferable than condition B and condition B is more preferable than condition C. If the participant responds that s-he prefers A over C, we can say that the responses to the condition A, B, C are consistent.

In the physical device condition, five participants showed a TSR of 1, which is the perfect consistency. Three participants had a TSR between 0.71 and 0.75, meaning some disagreement. One participant showed a TSR of 0.33.

In the video condition, five participants had a TSR above 0.8 (range from 0.82 to 1.0, avg. 0.92). The four remaining participants’ TSR ranged from 0.33 to 0.67. Our hypothesis about the inconsistency is that participants get used to faster speed of shape-changes more easily in the video condition, and they changed their preferences. This however has to be checked in future work in order to make our results more reliable.

We then evaluated the *overall consistency* of responses among the participants in each device condition. We used Kendall’s τ coefficient to calculate the overall consistency. We computed the ranking of preferred speed conditions for each participant, and then calculated Kendall’s τ coefficient, which shows how similar the rankings are. The participants in the device condition had Kendall’s τ of 62%, and the participants in the video condition had Kendall’s τ of 75.3%. This shows that there is a positive correlation between the participants’ preferences, rather than a negative correlation, i.e., that the participants liked the speed properties in a similar order, and not in an opposite order.

We therefore evaluate the reliability of the this experiment to medium.

The **evaluation of ExpanDial** was qualitative and therefore was aiming at varied feedback. However, consistent answers or gestures suggestions were also showing a consensus among participants. We report in chapter 5.1 the number of participants that suggested each gesture (Figure 5.2). There was little agreement between the participants, therefore we evaluate the reliability of this qualitative study to rather low.

For the other five remaining empirical contributions, we used widespread controlled tasks in the

lab (target acquisition or pursuit) and did not explicitly evaluate their reliability. The consistence between participants and repetitions together is implicitly evaluated through, e.g., the confidence intervals.

Reproducibility of empirical contributions

Reproducibility is the ability for others to recreate the same results by running the same analysis again from the collected data.

We did not make the raw data of our **formative study**, our **evaluation of ExpanDial** and our **qualitative study of KnobSlider** freely available, as it is difficult to make qualitative data anonymous. It is not possible to make public the audio or video data, or even the transcripts of the data, as the data contains references that would compromise the anonymity of the participants. A partial publication of the data would have been possible, but we thought this was misleading as not all the data would be made public. It is knowingly difficult to ensure reproducibility for qualitative research without breaking anonymity.

Some of our experiments provide the collected data and the analysis code. This is the case for the **study on the impact of length and orientation**, for which we provide the [analysis code](#) and the [data set](#). However, for other experiments, we did not plan for this at the time of the writing of the consent form.

Replicability of empirical contributions

Replicability assesses the ability of our empirical contributions to be repeated by running the whole experiment again and obtain a consistent result.

To replicate the **qualitative evaluations of ExpanDial and KnobSlider**, one needs to build the prototypes. For this, we tried to explain how we built the prototypes in a manner as detailed as possible in the papers [Kim+19; KCR18a]. We also provide a [tutorial and ExpanDial's models](#), and [KnobSlider's model](#) and [fabrication tutorial](#) on the Web. Then, both studies, like the **formative study** that do not need any specific material, easily allow replication. For this, one would need to recruit relevant participants and follow the procedure explained in the corresponding paper.

To replicate the **quantitative study of KnobSlider**, we do not provide the material to run the experiment (videos, questionnaire), but only the [KnobSlider's model](#) and [fabrication tutorial](#). The procedure is explained in the paper. We, however, did not share the analysis code. This enables a medium replicability of the experiment.

The experimental codes and fabrication materials of the **experiments with the zoomable slider**, the **SplitSlider experiment**, the experiment to evaluate the **impact of length and orientation**, and the experiments with **ClutchSliders** are not distributed. As a consequence, a replication would need to build the prototype and code the tasks again. In this case, it is difficult to evaluate the impact on the results of a difference between two different implementations of a prototype and of an experimental software.

Constructive contributions

We assess in particular our confidence in these contributions through their robustness and replicability.

Robustness of constructive contributions

Robustness assesses how our contribution addresses any elements that could work against it.

The **ExpanDial**, **KnobSlider**, **zoomable slider**, **SplitSlider** and **ClutchSlider** are early and fragile prototypes. After a few days of extensive use, typically for a study or an exhibition, we

experienced damages, e.g., the KnobSlider broke. The zoomable slider prototype has to rest on a horizontal support surface and be manipulated carefully. The markers necessary for its tracking are also hindering free movements from the users and are mounted on fragile sticks. As we take a user-centered approach, we thought that rapid prototyping, through cheap material such as PLA, wood, etc. and easy fabrication, was most important in order to gather *early* users feedback. We are currently building of a more robust and smaller KnobSlider prototype for a long-term field study.

Replicability of constructive contributions

Replicability assesses the ability of our contributions to be exactly copied or reproduced.

We do not provide the source files and instructions to make the **ClutchSlider** prototype. As a consequence, the replicability of this prototype is rather low.

As stated above, except the tracking system, the **zoomable slider prototype** is easy to build, from the shared [models of the zoomable slider](#). The tracking system lowers its replicability. We therefore evaluate the replicability of the zoomable slider prototype to medium.

We explained in the **ExpanDial** paper how we built the prototype in detail. We provide the [ExpanDial's model and mounting instructions](#) on the Web in order for others to be able to print the custom-made parts and copy the ExpanDial prototype. We provide the [KnobSlider's model](#) and [fabrication tutorial](#). We therefore evaluate the replicability of these prototypes to be high.

We also provide the [models to make the SplitSlider](#) prototype, however without instructions.

Part III

Discussion and Research project

Chapter 8

Summary and Discussion

In this chapter, we briefly summarize our contributions and present how the assessment of their abilities to improve problem solving capacity of the HCI field [OH16] can help improve our future work.

Figure 8.1 classifies the contributions presented in this manuscript to the HCI field into three categories of problems they can address: empirical, conceptual and constructive problems. The Figure shows that our contributions address these three subtypes of problems. We can also see in Figure 8.1 that most of our contributions are empirical and constructive, which is in line with the HCI field [OH16]. First, 2 of our **empirical contributions** reveal unknown phenomena. For instance, the formative study (chapter 4) reveals the unknown requirements and current strategies for end-users to balance between their need for physicality and their need for flexibility. Second, 7 of our empirical contributions presented in this manuscript reveal unknown factors. For instance, the evaluation of ExpanDial (chapter 5, section 5.1) explores potential unknown factors impacting the qualitative user experience, such as the users' control and perceptive abilities of width and height. Third, 6 of our empirical contributions presented in this manuscript measure unknown effects. For instance, the Emergeables experiment (chapter 2, section 2.2) measures the effect of the resolution of the widgets on performance.

While none of our **conceptual contributions** address the plausibility subtype of problems, our 2 conceptual contributions address inconsistency and incompatibility subtypes of problems.

Our **constructive contributions** address the problem of absence of a solution (e.g., the zoomable slider prototype) and the problem of partial, ineffective or inefficient solutions (e.g., the ExpanDial prototype). None of our contributions address the implementation and deployment aspects of a prototype.

In the next sections, we will further reflect on our assessment of our contributions through the five following criteria [OH16]: significance, effectiveness, efficiency, transfer, and confidence. Figure 8.2 summarizes this assessment.

Significance

Significance assesses the importance and relevance of the problems addressed. To analyze the significance of our work, we verified if the problems we addressed are in line with the grand challenges of shape-changing HCI research [Ale+18]. When possible, we also verified how many users are impacted by the solution, and the cost of an absence of a solution.

Empirical problems		Conceptual problems		Constructive problems	
1st subtype	Unknown phenomena	4 5.2.2	Implausibility	No known solutions	5.2.1 6.1.1 7.2
	Formative study KnobSlider qualitative study (speed)			KnobSlider Zoomable slider ClutchSlider (low fidelity)	
2nd subtype	Unknown factors	2.2 5.1.2 5.2.3 6.2.1 7.1 7.2 7.2	Inconsistency	Partial, ineffective or inefficient solutions	
	Emergeables experiment Expandial study KnobSlider quantitative study SplitSlider focus group (design) study Mobile slider size and orientation ClutchSlider low fidelity experiment ClutchSlider medium fidelity experiment		Emergeables concept : 2.1 Morphees+ : 3	Collection of everyday objects Expandial prototype SplitSlider ClutchSlider (medium fidelity)	3.1 5.1.1 6.2.1 7.2
3rd subtype	Unknown effects	2.2 6.1.2 6.2.2 7.1 7.2 7.2	Incompatibility	Inability to deploy or implement	
	Emergeables experiment Zoomable slider experiments SplitSlider experiment Mobile slider size and orientation ClutchSlider low fidelity experiment ClutchSlider medium fidelity experiment		Morphees+ : 3		

Figure 8.1: The problems addressed in the manuscript, the corresponding contributions and the chapter and section of the manuscript where the contribution is presented.

Empirical contributions

	Significance	Effectiveness	Efficiency	Transfer	Confidence		
					Internal validity	Reliability	Reproducibility
Formative study	High	High	High	High	High	High	High
Expandial evaluation	High	High	High	High	High	High	High
Emergeables experiment	High	High	High	High	High	High	High
KnobSlider qual. evaluation	High	High	High	High	High	High	High
KnobSlider speed study	High	High	High	High	High	High	High
Zoomable slider experiments	High	High	High	High	High	High	High
SplitSlider experiment	High	High	High	High	High	High	High
Mobile slider size/orientation	High	High	High	High	High	High	High
Low-fi ClutchSlider	High	High	High	High	High	High	High
Medium-fi ClutchSlider	High	High	High	High	High	High	High

Conceptual contributions

	Significance	Effectiveness	Efficiency	Transfer	Confidence
Morphees+	High	High	High	High	High

Constructive contributions

	Significance	Effectiveness	Efficiency	Transfer	Confidence	
					Robustness	Replicability
KnobSlider	High	High	High	High	High	High
Collection of objects	High	High	High	High	High	High
Expandial	High	High	High	High	High	High
Zoomable slider	High	High	High	High	High	High
SplitSlider	High	High	High	High	High	High
ClutchSlider	High	High	High	High	High	High

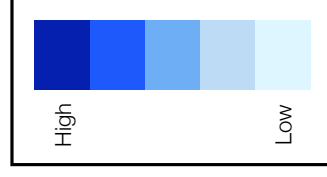


Figure 8.2: Our synthetic assessment of the contributions presented in this manuscript. Light colors show low significance, effectiveness, efficiency, transfer or confidence, while dark colors show a high significance, effectiveness, efficiency, transfer or confidence.

We found that our work was well aligned with the grand challenges of the field [Ale+18], and that many users are impacted by our contributions, directly or indirectly. We found the use of our work by the HCI community rather limited during the short time between the publications and the writing of this manuscript. To make sure that this is not a problem in significance, we would like in future work to provide the HCI community with tools to easily leverage our contributions. If our contributions are significant and the cost of using them is lowered through a tool, then they should be used by the HCI community, designers or target users. To specifically address the problem of significance, we would like in future work to ground our work in formative users studies.

Effectiveness

Effectiveness assesses the match between the solution and the essential aspects of the problem addressed. To analyze this, we first verified that our evaluation metrics matched the priorities of the target users. When relevant, we consider the end-users requirements presented in chapter 4 as the priorities of the target users. We also verified that we evaluated our solution with multiple, diverse criteria and in multiple contexts, and that we addressed the difficulties that emerge from real world scenarios.

Aligned with prior work [OH16], we found that effectiveness is difficult to assess in empirical contributions: it is difficult to demonstrate that the essential aspects of the phenomenon have been identified or addressed.

To improve the effectiveness of our work in the future, we would like to do the following. First, we would like to perform more empirical work comparing TUIs with high fidelity technologies like haptic interfaces or virtual reality. Such interfaces could provide advantages comparable to reconfigurable TUIs. Second, there is also a need to improve effectiveness through users studies with more tasks, and more complex tasks, closer to the end-users' tasks. We would also like to improve the effectiveness in the future by recruiting our participants outside of the lab, and rather among our target users. There is a need for *in situ* and longer studies in order to improve the effectiveness of our work. Third, we also note the need to run again the same experiments with the newest technologies, in order to verify that the results still hold.

The effectiveness of our constructive contributions was hindered by the lack of actuation, wireless connection and the rather large size of the prototypes. The engineering effort that is necessary to improve their effectiveness is important and time-consuming. The pace of HCI publications does not encourage this type of engineering work that is time-consuming. We find that there is a trade-off between effective prototypes required for effective, long-term and *in situ* studies, and low-fidelity prototypes that allow short lab studies focusing on one particular factor, but with limited effectiveness.

Finally, we found very difficult to track the use of conceptual contributions, although this is necessary for their improvement. We believe that teaching might be a way to observe this and to more rapidly enhance HCI conceptual contributions. The HCI community would need to change their practice to exchange, share and more easily publish conceptual work.

Efficiency

Efficiency assesses the cost in applying the solutions proposed, relatively to the gain achieved. To analyze this, we verified how much effort and/or resources are needed to produce the solution, the scalability of the solution, if we provide a tool for designers to leverage the solution and if we share datasets and code.

For our experimental contributions, we fabricated prototypes with the fidelity necessary to address our research questions. Higher fidelity prototypes would have often been a waste of resources *for the*

same study, although higher fidelity prototypes would enable more effective studies.

Sharing datasets and code contributes to the efficiency of an experimental contribution as it makes it easier to run the experiment. Note that sharing datasets and code also contributes to its confidence too as it allows for replication and reproduction. We could further improve the efficiency of our experimental contributions in the future by systematically sharing the experimental code as well as the experimental data and its analysis code. In general, we identify a strong need for sharing the material needed for the HCI community to build on our contributions to improve future efficiency.

Transfer

Transfer assesses how well does the solution transfers to other problems. To analyze this, we evaluated how many users, tasks and contexts can or could benefit from the solution.

Aligned with prior work [OH16], we found that transfer is difficult to assess it for empirical contributions without performing additional experiments. For this reason, our assessment was most often speculative. In general, we cannot be sure that our experimental contributions could be applied to further users, contexts, such as new tasks and new widgets, in the field or in the long term.

We found that improving the transfer of our constructive contributions is very time-consuming often through subsequent user studies for further users groups, contexts of interaction, or tasks. This is a point to keep in mind when undertaking this type of work which may not be valued by publications. Other forms of valorization of this type of research are therefore to be created. A solution to improve transfer in the future would be to perform these further experiments for the first, original publication, or in a later journal extended version as we did for KnobSlider [KCR19].

We found that tracking the use of conceptual contributions in the long term might allow to assess the transfer, however, long after the original publication.

Confidence

Confidence assesses how well will the solution hold as time passes. To evaluate this, we verified empirical validity, reliability, replicability, reproducibility, robustness, if we allow re-analysis, and how many metrics were used to assess validity and reliability.

Internal validity of empirical contributions

Internal validity is the adequacy of the experimental procedure, the method for the recruitment of participants, and the methods for analysis, in particular the statistical methods when applicable.

Reviewers of our publications including controlled quantitative experiments, most often on a target acquisition or pursuit tasks, mostly found our methods for analysis relevant. However, we personally felt the pressure to use dichotomous presentation of our results¹ through hypothesis testing. Even though we use this in addition to other statistics that are recognized such as confidence intervals, we do not agree, like many others (e.g., [DCH14; BD19]), that adding a dichotomous presentation of the results is the right approach. However, we find it hard when one of the co-authors is a student to take the risk that the paper is not accepted by not taking into account the reviewers' comments. The time for a student to show that they are an able researcher is very short, e.g. 3-4 years for a PhD student, and their abilities are very often assessed through their publications. However we are conscious that this is potentially harming the HCI community in the long-term.

¹We get in reviews comment like "Do not report exact p-values, but only if the p-value is lower or greater than a significance threshold", etc.

Reliability of empirical contributions

Reliability assesses how consistent were the results across, e.g. participants, types of measure, or repetitions.

For all our controlled experiments using widespread controlled tasks in the lab (target acquisition or pursuit), we did not explicitly evaluate their reliability. The consistence between participants and repetitions together is implicitly evaluated through, e.g., the confidence intervals. As a consequence, it is taken into account in the reporting of the results. We systematically explored the data after its collection, for instance by drawing graphs of raw data, overall boxplots and boxplots per participants, checking the learning or fatigue, etc. However, often these results are not reported in papers, but should be present in the supplementary material or through novel writing and publications approaches like [Dra+19]. Reporting the reliability of the results is a key point that we can improve in the future.

Another way to improve the reliability of our experiments is to register our experimental plan in advance, i.e. submitting it to a registry. Preregistration separates exploratory studies to generate hypotheses, from confirmatory studies to test hypotheses. While both types of studies are important, the same data should not be used to both generate *and* test a hypothesis, because such an approach can bias the research. Nevertheless, this is often done so in HCI, even though it reduces the reliability of the results. Aiming to improve this in our practice, we started recently to register our experiments. E.g. [we registered our last study](#) published at the ACM conference ISS 2020 [FC20].

Reproducibility of empirical contributions

Reproducibility is the ability for others to recreate the same results by running the same analysis again from the collected data.

We found that it is difficult to make qualitative data anonymous. It is not possible to make public the audio or video data, or even the transcripts of the data, as the data contains references that would compromise the anonymity of the participants. A partial publication of the data would have been possible, but we thought this was misleading as not all the data would be made public. It is knowingly difficult to ensure reproducibility for qualitative research without breaking anonymity.

Some of our experiments provide the collected data and the analysis code. This is the case for the study on the impact of length and orientation (section 7.1), for which we provide the [analysis code](#) and the [data set](#). However, for other experiments, we did not plan for this at the time of the writing of the consent form. This makes it difficult to have the participants' consent to share the anonymous data afterwards. To improve this in the future, we made and share with the research team a template for consent forms that include this need to share experimental data, so that our research team does not forget to include it in the future.

Replicability of empirical and constructive contributions

In the case of empirical contributions, replicability assesses the ability of the work to be repeated by running the whole experiment again and obtaining a consistent result. In the case of constructive contributions, replicability assesses the ability of the work to be exactly copied or reproduced.

In both cases, a way to improve the replicability of our work is to systematically share the models of the prototypes, write tutorials on how to make them. In particular for empirical work, we need to share the experimental code, the collected data set, and the analysis code. We need in the future to be more consistent, and insist when we work in teams, to share our source models for fabrication, and also write instructions. We saw with the KnobSlider building instructions on [instructables.com](#) that this was time-consuming, but also very rewarding as we could see the interest of the audience. A way to foster the sharing of these sources and instructions would be to increase the reward, i.e.

exchange feedback when someone tries to copy a prototype. This is something we already started to improve, and further work on in the future.

Another way to improve the replicability of our experimental contributions in general, is to recruit more, and more diverse, participants. While we try as much as possible to reach gender balance, we do not know how some of our results would transfer to younger or older users, or from background that we cannot find on our campus. This is a common transfer problem that can be solved through better replicability of HCI experiments, as participants, and their situation when interacting, are necessarily different in a replication.

Robustness of constructive contributions

Robustness assesses how our contribution addresses any elements that could work against it. Most of the prototypes we presented in this manuscript are fragile. As we take a user-centered approach, we thought that rapid prototyping is most important in order to gather *early* users feedback. To improve this in our future work, we plan to get funding to build more robust prototypes, to support for instance long-term field studies. This is what we are currently doing for KnobSlider.

Conceptual contributions

For conceptual contributions, confidence is assessed by checking that we did not forget to consider any important elements [OH16]. We found that this is redundant with our assessment of effectiveness.

Conceptual contributions can be easily cited by others as they can easily find elements in conceptual contribution to position their own work. Despite this, conceptual contributions are not common in the HCI community [Ras+16a], and we find that such contributions evolve very slowly. For example, we find that it is currently early to assess our confidence for the **Emergeables concept** and the **Morpheus+ taxonomy**, as it was little applied (as seen on p.37) in the papers citing it.

Towards strengthening future research

To conclude, we are happy to see that our research is not exclusively driven to problems that are novel (i.e. of subtype 1 in Figure 8.1), although this is a bias of the HCI field [OH16]. Our future work should continue to address the grand challenges of the field, and strive for many users to be impacted, whether directly or indirectly, i.e. through addressing the designers' problems. We would like in future work to provide the HCI community with tools to more easily leverage our contributions.

Our future work should also challenge the effectiveness of shape-changing interfaces by comparing them to high-fidelity technologies also allowing both physicality and flexibility, such as haptic interfaces or augmented reality. These might in turn also provide a reliable way to simulate shape-changing interfaces that are still difficult to prototype. We also would like to perform users studies with more tasks, and more complex tasks, closer to the end users' tasks. There is also a need for *in situ* and longer studies in order to improve the effectiveness of our work. To do so, our future work should also provide the engineering effort that is necessary to improve the effectiveness and robustness of our prototypes, even though the pace of HCI publications does not encourage this approach.

We used a large range of study methodologies in the manuscript. We performed studies before designing a device (*exploratory studies*) or after designing the devices (*evaluative studies*). We performed studies *in the lab*, i.e. we fully controlled the physical environment and the recruitment of the participants. We also performed studies *in the field*, i.e. we did not fully controlled the physical environment and the recruitment of the participants. For instance, our contextual interviews (chapter 4) took place where the participants worked, and some participants (and we) did not know they (and we) would perform the interview a few minutes before we started, e.g. working at (and

passing by) an outdoor musical venue. We performed *quantitative studies*, i.e. we measured the value of a variable of our interest, as this is often the case in controlled experiments. We also performed *qualitative studies*, where we aimed at observing as many different values as possible for a variable, without paying attention (yet) to the importance of each value. While we used a large range of quantitative and qualitative research methods, both in the field and in the lab, current approach lacks an evaluative, possibly quantitative, study in the field, e.g., a longitudinal user study with one of the designed artefacts. This is planned for future work with the KnobSlider (see section 5.2), currently in an industrial transfer project to reach a technological maturity allowing such studies.

Most importantly, we identify a strong need for sharing practices and materials in the HCI community to improve or simply assess effectiveness, efficiency, transfer, or confidence. This would help to improve our conceptual contributions, but also the replicability of our experimental and constructive contributions. Making the sharing systematic requires the whole research team to prepare for it from the very beginning of the work, e.g., using sharing platform like GitLab or Open Science Framework as part of the research process.

Chapter 9

Challenges

Imagine living in a world where programmable matter has become reality. We can control the computer by manipulating physical objects that reconfigure themselves as we need (Figure 9.1). Wouldn't it be convenient to have a single device that can serve any purpose, instead of multiplying devices, from the smart watch to the desktop? How convenient would it be to have a single tool that can adapt to the situation, like a swiss army knife able to continuously adapt its shape? When running, we would control the music by manipulating a small device attached to our body (Figure 9.1a, left). When back in the metro, we would hold it with two hands to control and cancel the noise around us and tune the music, interacting with its larger set of control widgets (Figure 9.1a, right). When reaching home, we would lay the device on the table to control the music from there. The device would spread on the available surface, avoiding other objects and providing the most efficient control for tabletop interaction. When our old, motor-impaired parent would join us at the coffee table, the device would enlarge the control widgets to suit the motor ability of our parent (Figure 9.1b). When comes the time to prepare dinner, we would duplicate a tangible music controller from the table by dividing it into two parts (Figure 9.1c) and take one along in the kitchen while the other stays at the table for our parent.

Such an interface rearranges itself — and/or at the initiative of the user — to provide with the best control depending on users, tasks, and environments. The work presented in this manuscript only started to scratch the surface of this vision. To get there, **my project aims at further pushing the limits of physical flexibility in the control of Tangible User Interaction. The ambition is**

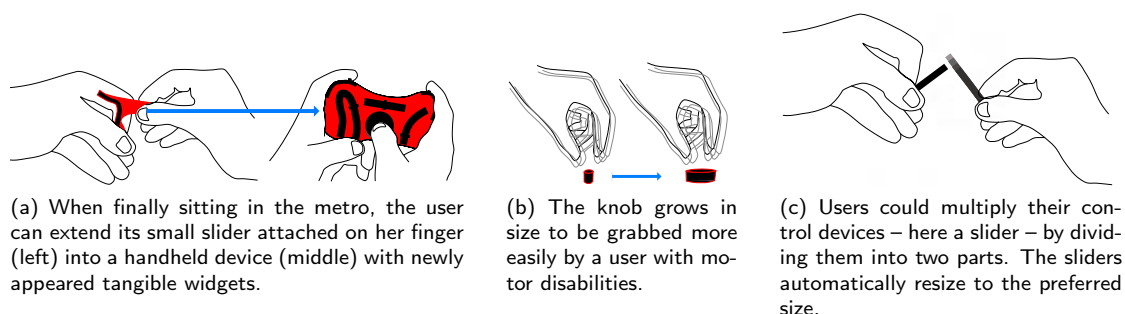


Figure 9.1: My project envisions shape-changing input devices, adapting to environments, users, and tasks.

to meet the important challenge of bringing both flexibility and tangibility to HCI.

Bringing physical flexibility to TUI challenges early works (see, e.g., [KKK01; BT02]), which explored the shapes designers should give to physical input controls. Early TUI work took for granted that the physical shape was a never-changing parameter and their goal was to find the best compromise, at all times, between shape and performance. Such a compromise is meaningless now that the shape is dynamic.

Most of the HCI work on shape-change studies how it supports the output of information to users. An example beyond resizable displays is the change of the shape of a device to provide in-pocket notifications [DA14]. Others address shape-change as a way to provide input to the system. For instance, manual deforming an elastic, deformable display can trigger commands [TPH14]. Others study the change of shape to support a change of the hand grip, i.e. only a limited aspect of input. For instance, the shape of a mobile phone can mimic the one of a gamepad when playing video games [Rou+13].

The very few works that address the flexibility of tangible input lack the necessary systematic approach to advance the field. Current approaches fail in different ways. First, they are centered on technology [Váz+15]. Second, they address local interaction issues [Bai+13]. Third, they do not ground their research on existing interaction [RSL14], even though it is known that if an interaction technique is difficult to learn, it won't be adopted (as seen in chapter 4 and in [Ols07; Sca+11]). Fourth, they address subjective perception of reconfigurable control [SKB17; OBJ18], because objectively measuring the user experience is a difficult task with reconfigurable prototypes [Ale+18].

Compared to prior work, the **originality** of my project lies in its scope and its scientific approach. First, I plan to address the **continuous adaptation** of input through shape-change, instead of considering discrete adaptation of input, or limited the research to manual deformation as an input to the system (as in, e.g., [BT19]). Second, I plan to address the **fundamentals** of interaction instead of taking a technologically-driven approach, as it is usually the case with new interaction paradigms. I also plan to address the **challenges of computer science**, and aim at making a profound turn in the theories for input and in the way we currently program the interaction.

Another originality is that I plan to ensure a **smooth transition from current interaction to future flexible TUI**. It is otherwise difficult for users to give up on already satisfactory UIs [Ols07; Sca+11] (chapter 4). As HCI is a research field that suffers from a lack of transfer to the general public [Ols07], my project will start from physical controls iteratively optimized during decades, and study what opportunities shape-change brings to them.

This chapter presents the research agenda for reconfigurable user interfaces which aims at advancing flexible physical control through shape-change. The intended breakthrough of this research project is to bring the flexibility of control to TUI through physical shape-change. My project will bring user interfaces like the one of Figure 9.1 into reality. For this, I aim at designing fundamental knowledge, tools and techniques for flexible tangible control. Flexible control of TUI will bring together the best of GUI and TUI, going much beyond current respective benefits of GUI or TUI.

In this promising perspective where the shape of physical interfaces can dynamically change, how can each possible shape that we can cover dynamically support all the possible variations of users, task and environment? To tackle this difficult problem, we need to address scientific challenges in the HCI areas of **design, engineering and theory** (Figure 9.2). First, we need fundamental knowledge about the interaction with reconfigurable input devices (section 9.1.1); we need to design interaction techniques with reconfigurable control devices (section 9.1.2); we need to build prototypes to assess new interaction techniques (section 9.2.1); we need tools for producing this next generation interaction (section 9.2.2); and we need to refound HCI theories (section 9.3). These are the five scientific challenges that I plan to address.

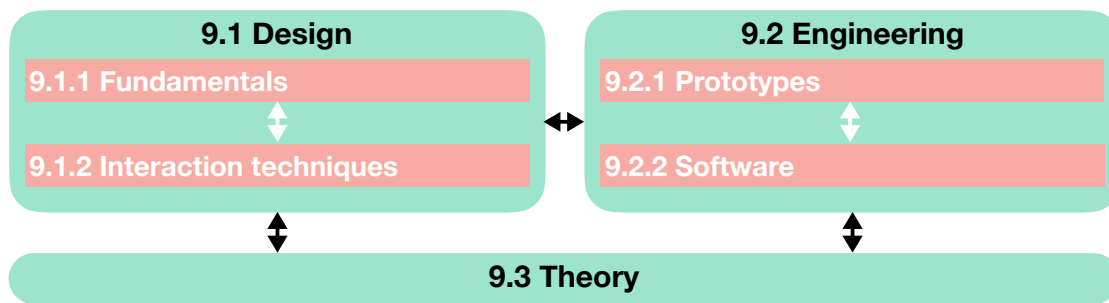


Figure 9.2: The challenges addressed in the research project.

9.1 Design

9.1.1 Fundamentals

The first scientific challenge is **the lack of knowledge on the fundamentals of interaction with physically flexible controls**. We need to gain knowledge on the factors and the effects of physical shape in the interaction with the computer. This empirical problem is fundamental as it can strongly motivate and orient the research on this topic.

HCI lacks combined knowledge on haptic, tangible and reconfigurable interaction. This lack of knowledge applies in particular to the sensory-motor level of the interaction. Our objective is to build empirical knowledge about the fundamentals of interaction with physically flexible controls. As shown in Figure 9.3, to achieve this aim, we plan to perform user studies in the lab and in the field: while most study will take place in the lab, we will also go *in the wild*, to study how the knowledge found in the lab transfers to the field. Simultaneously, we plan to first explore the impact of static shapes on interaction, and then the impact of dynamic shape-change on interaction.

Impact of static shape on interaction

First, bringing physical flexibility to TUI challenges fundamental knowledge on interaction. For instance, handbooks in ergonomics [KKK01; BT02] give recommendations on the shape of physical input controls. These current recommendations are based on studies that date back from after the second world war, e.g., [Bra69; Cha51; HW52; Hun53]. These studies took for granted that the physical shape was a never-changing parameter and their goal was to find the best compromise, *at all times*, between shape and performance. While this work is useful, such compromise is now meaningless. The novel research question is to quantify the benefits and drawbacks along the shape parameters, such as diameter and height for a dial. This will allow to dynamically provide users with the best possible shape, *at any instant*. As the shape becomes dynamic, the compromise users make becomes dynamic, depending on their abilities, task and environment. For instance, a dial could now become very large for a very short time if the user needs temporarily very high accuracy, even if such large devices were discarded by the designers when they considered the fixed shapes of a dial. As a first step, we plan to systematically explore the impact of static physical shapes on interaction, to develop new knowledge on the usability of static shapes. Research issues to be addressed include:

Identification of relevant shape parameters. What could be a minimal set of parameters to describe the shape of an interactive device? One approach would be to explore the shape parameters that are the basis of Morphees+ [KCR18a] (chapter 3). Another approach could be to describe

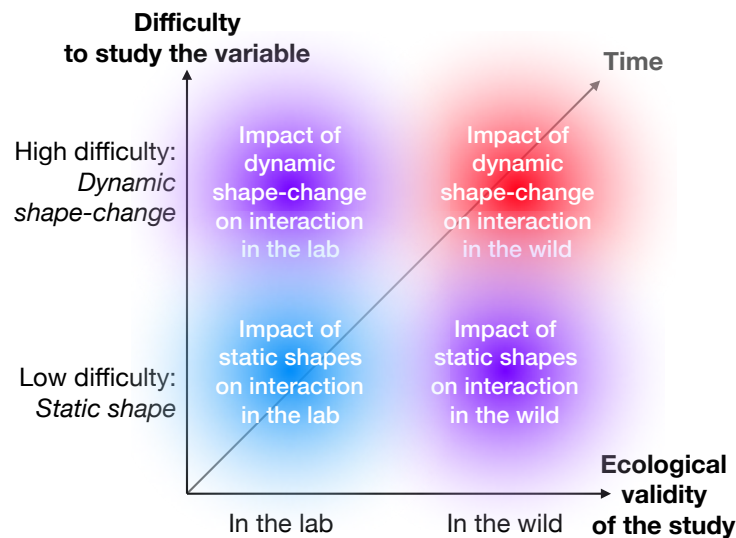


Figure 9.3: To build fundamental knowledge on interaction with physically flexible controls, we plan to explore the impact of static shapes on interaction, before exploring the impact of dynamic shape-change on interaction. We also plan to start from controlled, lab studies, and explore how this knowledge transfers to the field.

shapes like a constructive solid geometry, and explore all the primitive shapes and the operation that can be applied to them. The problem is that the space of possible shapes is huge. We need to identify studies with precise scopes within this vast design space, while ensuring the validity and transfer/generalizability of the results. Another approach would then be to propose a geometric modeling of the deformation of a physical widget. Such a model could apply to all existing physical widgets such as push buttons, dials or sliders. This would allow to propose a model of manipulation of physical widgets, whether these are current ones or in-between, hybrid shapes.

Appropriate mapping between tasks and physical objects. Which physical object (or manipulation) is more efficient for which task? Even a few milliseconds gain in performance can greatly impact users' life, as many users might repeatedly perform the same task. Physical objects can be pushed/pulled vertically (buttons), slid horizontally in different directions and in 1D (sliders) or 2D (pens), as well as rotated in different directions and from 1D (knobs) to 3D (trackballs). These physical objects can be mapped to different visual representations: vertical/horizontal on-screen slider, angular on-screen dial, checkboxes, 3D positioning, color picking, etc. This question also implies the exploration of the affordance or grasps used by users for a given shape and a given tasks, as we studied for ExpanDial [Kim+19].

Shape changes resolution. How many shapes are necessary to provide users with optimal flexibility for control? i.e. how far should technological research go in order to provide a shape-change that is smooth enough?

Shape limits quantification. What are the extreme limits of a physical shape? For example, a very large rotary dial may improve precision, but the fatigue caused by its manipulation would defeat this benefit. Knowing such limits will allow the design of proper transitions to alternative techniques.

Comparison of physical shapes against existing concurrent techniques. How does the performance of different shapes compare to existing concurrent techniques, like graphical interaction techniques with cutaneous and/or kinesthetic feedback? This will help to appropriately design the transition/combination to/of multiple techniques addressed in section 9.1.2.

Transfer of sensory-motor learning between different shapes. To which extent does the sensory-motor skills learned with one shape transfer to another one? The transfer of skills between interfaces has been studied for widespread interfaces, for instance touch interaction [BR15]. It is currently unknown to which extent users' skills acquired with a shape transfers to another shape. This is however a very important question as we need to address the transition between shapes.

Resolution. While psychology explored the spatial resolution of the human finger (e.g., [VJ94]), results are dependent on the device used [BWC11; BR12]. It is therefore essential that we address this important challenge for reconfigurable input devices, in order to identify the resolution needed for reconfigurable devices in the future. However, no such study has been conducted for reconfigurable control.

Impact of dynamic shape-change on interaction

Second, it is currently unknown how the shape, manipulation, and shape-change parameters, such as the ones of Morphees+ (chapter 3), of an input device should relate to the shape and dynamics of the corresponding display. Previous research on this topic is fragmented. For instance, MacKenzie et al. [MSB92] compare a mouse, a trackball and a stylus with tablet, but for the same unique visual display of a pointing task. Most of the performance studies of TUI tackle the comparison with other paradigms, like with a mouse [FB97; JDF13; TKI10; Bes+17] and/or a touch surface [JDF12; TK13; TKI10; Wei+09; Bes+17]. They seldom address the mapping between the input device and the corresponding display. A study shows that tangible sliders combined with linear displays and knobs combined with circular displays lead to similar task completion time [Mül+14]. However, it is not clear how this applies when the physical device can dynamically change shape. Designing an appropriate reconfigurable input device for a task requires a careful study of the relationship between mental representation of the task and action on the device that can change shape, as this was done for 3D tasks [Jac+94]. We will build such fundamental knowledge at the sensory-motor level of TUI, in order to identify the opportunities for flexible input devices. In particular, we will address the following research questions:

- What is the impact of the dynamic change of physical shape on user experience?
- How does the manipulation of a device evolve when the latter is changing its shape? What shape and shape-change support a particular hand position, movement, and force? To answer these questions, existing experimental methods in ergonomics would not scale to the many possible shapes and dynamics. We plan to capture a large amount of 4D scans showing how users manipulate different shapes, and how this manipulation evolves during shape-change. From this data, statistical modeling will allow us to predict expected grips and manipulations from the shapes' dynamics.
- Is physical flexibility less efficient, equivalent or more efficient than software flexibility for the control of UIs? For instance, how does interaction with a control-display gain obtained through a change of shape of the control device compare with the interaction using the same control-display gain obtained through software?

- Is the interaction more efficient or comfortable when the system actuates changes of the physical shape, or when the user takes the initiative of shape-changes despite the additional articulatory task? In the later case, what are the most efficient manipulations to manually reshape a Tangible User Interface? In case the two approaches are found to be complementary, the studies will provide knowledge on how to design their combination/transition.

9.1.2 Interaction techniques

The second scientific challenge is that **efficient interaction techniques with physically flexible controls define an unknown area of HCI**.

Reconfigurable interfaces is an emerging field of studies in HCI [Ras+12; Ale+18]. Most of the emerging work study how to support the output of information to users (e.g., [Rou+13; DA14; Bai+13; Yao+15; Tah+15]). Others study shape-change as a way to provide input to the system [Kha+11b; Tak+12; TPH14; Tah+15] but do not propose any flexibility for this input. Others study the change of shape to support a change of the grip [Rou+13; Yao+13], i.e. only a limited aspect of input.

The very few work that address the flexibility of tangible input lack the necessary systematic approach to advance the field. Current approaches fail in different ways. First, they are centered on technology. For instance, a few work propose a first exploration of the opportunities brought by pneumatic actuation to HCI [Yao+13; Váz+15].

Second, they address local interaction issues. For instance, by raising some keys of the keyboard, Bailly et al. [Bai+13] allow pushing the keys sidewise. Although useful, this work does not study continuous shape-change and aims at improving a local interaction issue.

Third, they do not ground their research on existing interaction. For instance, Rubik's engineering solution inspired a few interchangeable shapes of a mobile phone [RSL14]. This is problematic, as we know that if an interaction technique is difficult to learn, it won't be adopted [Ols07; Sca+11]. We know that it is difficult for experts to give up on already satisfactory UIs as seen in chapter 4 [KCR18a], even though a performance benefit is proven [Ols07; Sca+11].

Fourth, they address subjective perception of reconfigurable control [SKB17; OBJ18], because objectively measuring the user experience is a difficult task with reconfigurable prototypes [Ale+18].

Our resizable slider [CM15] or SplitSlider [Gre+19] provided proof-of-concepts that the flexibility of GUI techniques can translate to tangible input devices through shape-change. This is however only the tip of the iceberg, and the design space of reconfigurable input devices must be systematically explored to provide interaction techniques that easily bring objective benefits to users.

Our aim is to design novel interaction techniques leveraging physically flexible controls.

First, interaction techniques have used software flexibility for decades, altering for instance the motor/visual space to ease the interaction. It is not clear how their design can be mapped to the change of shape, or if new techniques, specific to physical shape-change, will be more efficient.

We will start exploring devices that change in resolution, definition, number of dimensions and range. Raising, extending and swelling up are the first possibly suitable shape-changes to be designed and explored.

We will also explore the design space defined by all the possible transitional shapes between existing input devices. Such transitional shapes can provide opportunities to provide an improved user experience. For instance, the shape in-between two "standard", existing shapes can allow for a mixed control of a parameter, as a rounded slider could support the control of a cyclical, but bounded, parameter; An angled slider can provide the opportunity to mark a value of interest through the shape; Etc.

Second, software flexibility assumed that the input device was of fixed-shape, and one cannot assume that the same performance will hold through a reconfigurable tangible control.

Further interesting leads lie at the intersection between possible benefits of shape-change and existing GUI techniques that have already proven to improve interaction. For instance, dynamic control-display gain based on pointer acceleration, commonly used with commercial rotary knobs¹, has been shown to improve performance [Cas+08]. However, it prevents users from benefiting from interaction where the physical angle matches an on-screen digital angle, known as absolute. By dynamically changing the diameter of the rotary knob, one can imagine interacting with dynamic curvilinear control-display gain, while still preserving the absolute angular interaction.

We believe these ideas are only a few examples showing the tip of the iceberg, and further work during the project will be inspired by the advance knowledge on flexibility from GUIs. Doing so, we will open this new area for research in TUIs.

Third, if flexibility can be brought to control through both software and physical shape-change, interaction techniques need to be carefully designed, in particular (1) their novel change of shape and (2) the synergistic combination of physical and software transitions, as both can apply.

We will ground our research in current widespread TUI. Our vision is to start from existing physical controls, iteratively optimized during decades, and study what opportunities shape-change brings to users' interaction. Doing so, our aim is to ensure retro-compatibility with current users' practices and minimize later adoption problems [Sca+11; Ols07].

Interaction techniques can be suggested by formative user studies (section 9.1.1), derived from the current version of the theory (section 9.3). Interaction techniques will allow to confront the theory with practice and to implement the results of the preliminary experiments showing opportunities for shape-change. Conversely, the design of interaction techniques can also induce new fundamental user studies (section 9.1.1) and will be evaluated through prototypes (section 9.2.1), after inducing new leads for the new or extended theory of input devices (section 9.3).

9.2 Engineering

9.2.1 Prototypes

The third scientific challenge is that **building prototypes is difficult as the material and hardware technologies are not mature yet**. However, it is important that interaction techniques are experimentally evaluated, using for instance low-fidelity prototypes.

The prototyping of reconfigurable user interfaces, let alone their development, is currently a hard problem [Ale+18]. Building prototypes is however crucial in order to enable user studies and advance the field. Current approaches for implementing reconfigurable interfaces range in a continuous space between rigid articulated bodies [KCR18a] and soft bodies [Yao+13], and between things (objects) and stuff (made of atoms) [Le +16], and between 1D [CM15] and 3D [Tao+18] change of shape. Some approaches allow holes in the shapes, while others cannot support porous shapes. Some allow a change in stiffness, while others do not. Software challenges, on the other hand, are often little explored or reported, as researchers often struggle with physical prototypes first.

4D printing is in its infancy in HCI [Tao+18]. 4D printing allows for a flat shape to become a 3D shape through folding. It is however unclear what range of 3D shapes can be implemented this way, e.g., what range of sizes for a cylinder. It is also unclear what changes between 3D shapes this can allow. E.g., does it enable a sphere to change to a cube? Collaborations with material scientists is needed to identify the opportunities and limits of this technique for HCI.

¹<https://store.griffintechology.com/powermate>

Mechanically articulated rigid structures (e.g., [KCR18a; NFI15; Rou+16]) allows for deformable user interfaces while its outer surface stays rigid. Rigidity might be desirable, for instance to support touch interaction [Rou+16] – at least as we know it on touchscreens – or to serve as a guide to tangible interaction [KCR18a]. It also partially allows porosity in the interface.

The implementations proposed are often hard to build, bulky and fragile, limiting the advances of the field. The limited range of techniques to build prototypes limit the range of interaction techniques that can be implemented, preventing from a larger exploration of the design space of reconfigurable interfaces. The HCI field however only started to scratch the surface of all the opportunities that material sciences offers to design and implement shape-change [Qam+18].

Pneumatic actuation [Yao+13; Váz+15] allowed so far to implement very limited shapes, based on inflation or folding along a single line of crease. However, research in material sciences showed that it is possible to make more advanced materials to allow for more elaborate changes of shape [Sié+ar]. HCI however did not leverage this work yet.

Rod-based displays (e.g., [Fol+13; Rob+16; Har+15]) allows for 2.5D shape displays. Our work on *Emergeables* (as seen in chapter 2 and in [Rob+16; Pea+17]) started to explore the direct manipulation of the rods, in particular tilting and turning. Stacking of tilting elements was then proposed to allow for flexible surface, partially allowing holes in the shape [Tia+18]. The modularity of the rod-based approach can also be found in the swarm approach, however limited to 2D display made of mobile robots moving on a table [Le +16], and in *Cubimorph* [Rou+16], a chain of reconfigurable cubes that can form a limited range of 3D shapes.

The software challenge of introducing the interaction between the user and programmable modules has been barely addressed so far in the field of robotics [Bou+16] and HCI [Le +16; Rou+16]. As an example, *Cubimorph* [Rou+16] proposed an adaptation of the probabilistic roadmap algorithm for the reconfiguration. This however applies to a chain of modules and not to detachable modules. Previous work in molecular robotics, e.g., [Bou+16], did not study yet the impact of users interaction with programmable matter. Further work is needed to bring the modularity of these approaches to the next level, and allow for fully reconfigurable interactive prototypes in 3D, like programmable play-doh.

The work presented in this manuscript, among others, showed that it is possible to build prototypes. Existing prototypes however allow a very limited range of shape-change and consequent work is needed to explore new ways of prototyping, among others through the many new opportunities brought by foldable and inflatable materials as well as molecular robotics.

Our objective is to build prototypes corresponding to the interaction techniques. We will build prototypes combining physical, hardware and software elements.

Physical elements will be explored, leveraging current knowledge from other fields such as material sciences (Figure 9.4). Our research hypothesis is that part of the complexity of implementing shape-change can be deported to the material itself. Novel materials can physically implement the change of shape at the heart of the matter. Deporting the complexity of current shape-changing mechanism into the structure of the matter rather than in the hardware and software should allow simpler systems, therefore cheaper and more robust. In particular, we plan to explore two different reconfigurable and programmable materials: Inflatable structured materials and folding materials, i.e. origami (folded sheets) and kirigami (folded and cut sheets). We will characterize the range of 3D input devices that can be implemented through the many implementations of the structures of these materials, in order to enrich the shape vocabulary of input devices. The benefits we expect from these materials are safety and robustness – crucial for users studies – thanks to their high compliance (i.e. softness and stretchability). We started to work together towards such a vision.

Hardware elements will be leveraged to sense and/or actuate the change of shape through the computer. Interesting leads include Teflon wire, shape-memory alloys, motors, pneumatic or hydraulic micro-pumps, or optical tracking. Additionally, we will go beyond these elements. Programmable

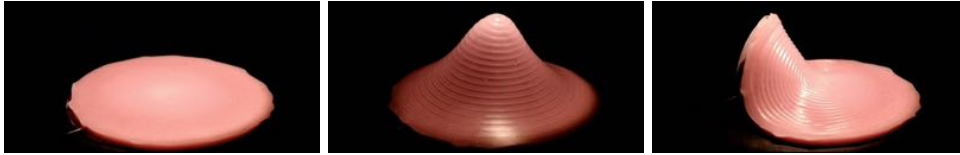


Figure 9.4: A same material, studied by [Benoît Roman](#) and his colleagues, can be deformed in many different ways. “Programming” the materials with so many possibilities for shapes and shape-changes has never been leveraged in HCI. Future joint work will explore, among others, the design space of such materials.



Figure 9.5: Current prototype of one of [Julien Bourgeois](#)'s $\varnothing 11\text{mm}$ micro-robots (left), that can connect and roll around each other, thanks to their wrapped circuit (center) and embedded hardware (right), here shown on the edge of a coin. Future joint work will explore, among others, smaller ($\varnothing 3\text{mm}$) micro-robots, equipped with further sensors for interaction.



Figure 9.6: Envisioned “molecular” dial adapting its handle to the user’s finger size.

matter, implemented as a modular robot composed of a huge number of mm-scale modules (Figure 9.5 and 9.6), could ultimately solve the many drawbacks of current solutions, such as adding matter to a pre-existing set of “molecules”. We will bring the modularity of reconfigurable prototypes to the next level, and allow for fully reconfigurable interactive prototypes, like programmable play-doh. Figure 9.6 illustrates such a envisioned “molecular” reconfigurable device, with a handle adapting to the user’s finger size. We started to work together towards such a vision.

Software elements of our prototypes will ensure interaction with minimal latency and maximum precision and accuracy to allow the exploration of the limit of the interaction rather than the technology. We will address the challenge of programming interaction between the user and programmable matter. This challenge has been barely addressed so far in the field of robotics [Bou+16] and HCI [Le +16; Rou+16]. Configuration of the shape through software will be studied. Our experience in software programming of such prototypes will fuel the development of a tool for future developers (section 9.2.2).

Our approach is to work in close loop with interaction design (section 9.1.2) and users studies (section 9.1.1) through small iterations and rapid prototyping (from low fidelity to high fidelity prototypes). The prototypes will fuel the development of the tool (section 9.2.2) and conversely, the tools developed in section 9.2.2 will help the development of prototypes.

There is a risk that the designed interaction techniques cannot be turned into fully functional prototypes due to current technology limitations. Despite the fact that the technologies enabling this project might emerge decades from now, we know that scientists are working on such technologies. This is why we plan to collaborate with roboticists and material scientists. We, like HCI innovators [Har18], believe the design of interaction techniques must start now. Reconfigurable UIs can follow a development path similar to the one of touchscreens. Indeed the first appearance of a touchscreen prototype in research dates back to 1965 [Joh65], while they reached general consumer market 42 years later with the Apple iPhone. Even though the technology was not ready in the late twentieth century, touch interaction techniques have been researched. We believe the same should happen for reconfigurable UIs.

Meanwhile, to mitigate this risk, we will build mock-ups to allow user studies. For instance, we can build larger-scale prototypes as proof-of-concepts, expecting for the technologies to miniaturize in the future (as it happened for the first prototype of the computer mouse by Douglas Engelbart). We can also build non-functional prototyping (video, paper, etc.). Another way to mitigate this risk is to make a human operator simulate the non-functional parts of the prototype (i.e., wizard-of-oz). Such a human operator can actuate or sense the change of shape at a higher resolution and frequency, and with lower latency, than what is achievable through current technologies. To raise up to the challenge of simulating the actuation of a continuous change of shape, we plan to build mechanical prototypes allowing for human operator(s) to operate the mechanics (e.g., through levers or strings).

9.2.2 Software

The fourth scientific challenge is that **the way interaction is currently implemented in software is not suitable for reconfigurable input**. While technology is steadily progressing towards enabling physical shape-change, Computer Science, and Human-Computer Interaction (HCI) in particular, need to make a profound turn in the way interaction is supported by software. The tools that developers are currently using have been developed for fixed-shape physical user interfaces. Their elements for handling inputs assume fixed, or at best discretely interchangeable, standard devices. Subsequent work is needed to propose a generic way for reconfigurable input devices to impact relevant software elements, as well as a generic way for software elements to redefine the physical shapes of input devices.

Model-View-Controller (MVC) is a widely used software architecture for the development of User

Interfaces [KP88]. In current programming, the *Controller* of MVC handles the user's inputs. Its extension to TUI has been proposed, but as a base for a tangible interaction model (MCRit [UIJ05]), rather than a software architecture model.

Software tools to facilitate the prototyping of Tangible User Interfaces exist, like our OP toolkit among others [CN11]. Their extension to reconfigurable interfaces, as with MVC, is not straightforward as their underlying theories are challenged by this research project.

Our experience with reconfigurable prototypes presented in the first parts of this thesis, lead us to identify the scientific challenge of implementing the software to handle flexible tangible input. It is not clear in current implementations, e.g., of MVC, how to continuously and dynamically redefine the *Controller* as the physical interface continuously changes. It is also not clear how the *Controller* can modify the shape of the tangible input device.

Since 2014, new hardware and software tools emerged to help the prototyping of reconfigurable interfaces. Changibles [Rou+14b] helps the prototyping of shape-changing assemblies through a software tool that helps designing shape-changing units to be assembled in a larger reconfigurable object. Shape-clip [Har+15] allows transforming any computer screen into an actuated shape display. Shape-display shader language [WAH15] is a software tool to ease the programming of 2.5D shape-changing displays in a hardware independent manner. These tools do not address the way we program interaction with flexible physical control. They are dependent on platforms that offer only a limited range of shapes.

Subsequent work is needed to propose a generic way for reconfigurable input devices to impact relevant software elements, as well as a generic way for software elements to redefine the physical shapes of input devices.

The objective of this research axis is the development of a software tool to program such physically flexible control of user interfaces. We will study the impact of physically flexible control on the way we currently program interaction. We will propose a re-foundation of the existing model of architecture and enable the continuous, dynamic redefinition of the software as the physical interface changes, and vice-versa.

We plan to consider the widespread *Model-View-Controller* (MVC) model of architecture [KP88]. MVC is now widely spread and for this reason, we hope for better transfer of our new tool.

In current programming, the *Controller* of MVC handles the user's inputs. We will explore how to continuously and dynamically redefine the *Controller* as the physical interface continuously changes its shape and control properties. Beyond proposing a generic way for reconfigurable input devices to impact relevant software elements, we will also propose a generic way for software elements to redefine the physical shapes of input devices. As first elements of this exploration, we will study an approach inspired from computer graphics based on physical shapes primitives to program the matter of input devices.

Our tool will be based on the state-of-the-art (e.g., [KP88; CN11; Har+15; Rou+13; WAH15]), the theory (section 9.3) and, more importantly, on the experience of building prototypes (section 9.2.1). The theory (section 9.3) will help to identify the relevant, flexible dimensions of control that will transform, and that can be transformed by, the *Controller*. In the long term, we plan for our experience in programming physically flexible controls to be capitalized through a tool for developers.

This long-term research axis requires consequent experience in building and programming prototypes. Early version of the tools will be used in building prototypes, in order to experience its use and improve it.

9.3 HCI theory

The fifth scientific challenge is that this vision implies to **revisit the foundations of current HCI theories**. Models on static input devices have been used as a reference by the HCI community since the eighties. Many models and theories are challenged by the idea of physically flexible control. They were proposed at times where physical interfaces were of fixed shapes. A first example is the model of static input devices [CMR91] that has been used as a reference by the HCI community since the eighties. This model represents an input device as a six-tuple (M, In, S, R, Out, W) , where:

M is a manipulation operator (e.g., Linear vs. Rotary, Position vs. Force or Absolute vs. Relative);

In is the input domain (e.g., $[0, 100]$);

S is the current state of the device;

R is a resolution function that maps from the input domain set to the output domain set;

Out is the output domain set (e.g. $[0, 270]$);

W is a general-purpose set of device properties that describe additional aspects of how a device works.

Input devices that can change their shape and consequently alter the properties of interaction, challenge such foundational theories. This foundational six-tuple is challenged and will be generalized with a new theoretical framework. As a first element of a theory, a reconfigurable device becomes a whole range of fixed devices. The transition between fixed devices will be described. All elements of the six-tuple become dynamic and can virtually reach any values already covered by existing fixed-shape devices. Similarly the TAC (Token and Constraints) paradigm for specifying TUI [Sha+04] does not consider shape-change and does not capture the flexibility of TUI.

Another example of a model that is challenged by physically flexible controls is our Mixed Interaction Model [CN06]. The most important contribution of this model is to offer a description of mixed physical-digital objects (Figure 9.7). In this model, a physical object is composed of a set of physical properties and in the same way a digital object is composed of a set of digital properties. A mixed object is then composed of two sets: a set of physical properties linked with a set of digital properties. To describe the link between the two sets of properties, it considers the two levels of a modality (d, l). The modalities that define the link between physical and digital properties of an object are called linking modalities. An input linking modality is responsible for acquiring a subset of physical properties, using an input linking device, and interpreting these acquired physical data in terms of digital properties, using an input linking language. An output linking modality is in charge of generating data based on the set of digital properties, using an output linking language, and translating these generated physical data into perceivable physical properties thanks to an output linking device. The originality of this model is that it inherited from the large body of knowledge and theory of multimodal interaction. However, the model is challenged by the new idea of physically flexible control, as it took for granted that the linking modalities are static. Also, physical properties that change their shape to alter the interaction are not characterized by the model.

Frameworks dedicated to reconfigurable interfaces have emerged since 2012. An early analysis of reconfigurable interfaces [Ras+12] identified in the literature eight types of shape change and how to characterize the transformation. They characterize whether the user or the system actuates the change of shape, but did not relate this to the flexibility of control. Even more recent work proposes a model of the interaction between the user and the underlying digital (computational) model through dynamic physical materials that are computationally transformable [Ish+12]. The theory will not address the whole interaction with reconfigurable materials, but rather targets how the change of shape affects the control of the user on the digital system. Another available design space [Kwa+14] has the originality to take the viewpoint of the users, but does not address the flexibility of control. The introduction of shape resolution [Rou+13] and its metric in 13 features in Morphees+ (chapter 3 and [KCR18b]) describe different types of possible changes in shapes and how designers can maximize

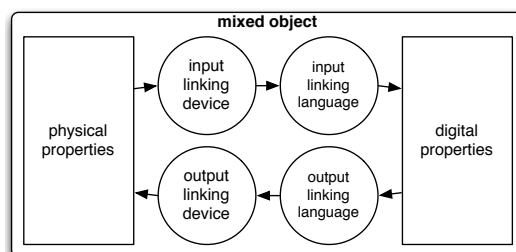


Figure 9.7: The mixed interaction model describes a mixed, i.e. physical and digital, object [CN06].

the different ranges of shapes. These features have not been studied yet regarding their impact on the control of the interface. Our recent work helped to identify the scientific challenge of establishing a theory, that can describe, compare and generate novel input interaction. All these works bring elements for a future theory, and need to be re-founded to provide a new theory of physically flexible control.

Our objective is to devise a new theory to support new, physically flexible control in Human-Computer Interaction. Toward this aim, we will provide a thorough state-of-the-art of existing, related theories and identify their strength and weaknesses for their extension. As a starting point and as sketched out above, we will consider the model of reference for static input devices [CMR91], our Mixed Interaction Model [CN06], and more recent models and design spaces that cover change of shape [Ish+12; KCR18b]. Further analysis of the state of the art will provide a comprehensive and exhaustive review of the models that are challenged by the idea of physically flexible control.

Conclusion

The goal of my research project is to bridge the gaps in design, engineering and theory. We would like to propose a theoretical framework, interaction techniques, working prototypes, user studies demonstrating the benefits and limits of the physical flexibility of control, and a software framework to integrate physical shape-change when programming such new user interfaces. Doing so, this project aims at breaking down the barriers to further advance flexible physical control through shape-change in order to make the interfaces of Figure 9.1 widely and routinely used in various contexts.

Putting this research program in the perspective of HCI history and innovation, its scientific challenges structured around design, engineering and theory fit Brian Gaines' BRETAM model of technological development and diffusion [Gai91] (Figure 9.8). This shows the usefulness and relevance of the scientific challenges that we plan to address. The BRETAM model defines six phases: Breakthrough, Replication, Empiricism, Theory, Automation and lastly Maturity. The idea of reconfigurable interfaces is found as early as in 1965 [Sut65] (Figure 9.9), however rather as a concept than as a technological breakthrough. In this paper, Sutherland presents the ultimate display as "a room within which the computer can control the existence of matter". Although technological breakthrough has happened progressively through the introduction of actuation [PMI02] or malleable materials [PRI02] into the research in TUI, we position the breakthrough in 2007 [PNO07] as this is the first paper taking a step back on the progress of TUIs towards physically reconfigurable UIs. Reconfigurable UIs have now hardly reached the replication stage. Further work corresponding the replication phase is currently needed: proposing prototypes (section 9.2.1), gaining fundamental knowledge (section 9.1.1) and designing interaction techniques (section 9.1.2), so that lessons can be drawn later in the empiricism stage. Software tools (section 9.2.2) will further help to speed the replication phase. The two phases following Empiricism are called Theory and Automation. When the

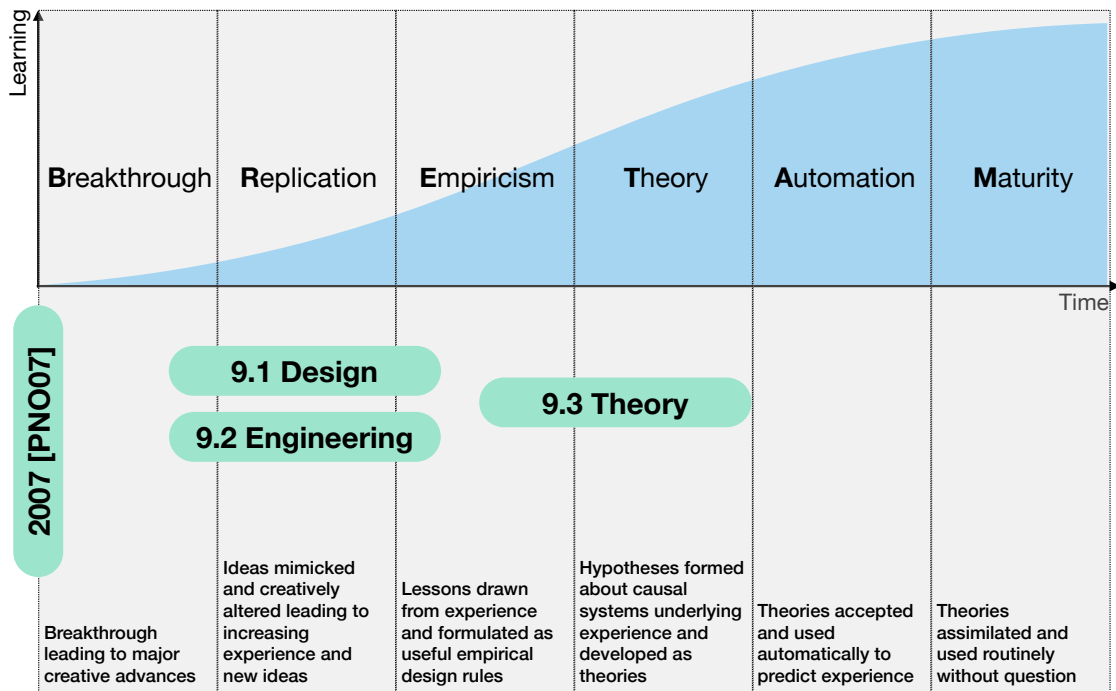


Figure 9.8: Our research project according to the BRETAM model. The figure is based on [Gai91].

technology reaches this phase, hypotheses are formed about the causal systems underlying experience and developed as theories (section 9.3). In the automation phase, theories are accepted and used automatically to predict experiences and to generate design rules. According to Gaines' model, at the Maturity phase theories have been assimilated and are used routinely without questions. This will be the case when reconfigurable UIs start being widely deployed in routinely used interactive applications. The time gap between early academic HCI studies and commercial products is around 20 years [Har18]. The research is now at a stage where the idea of reconfigurable interfaces seems impractical and challenging. We think that our role is to study this idea now [Har18].

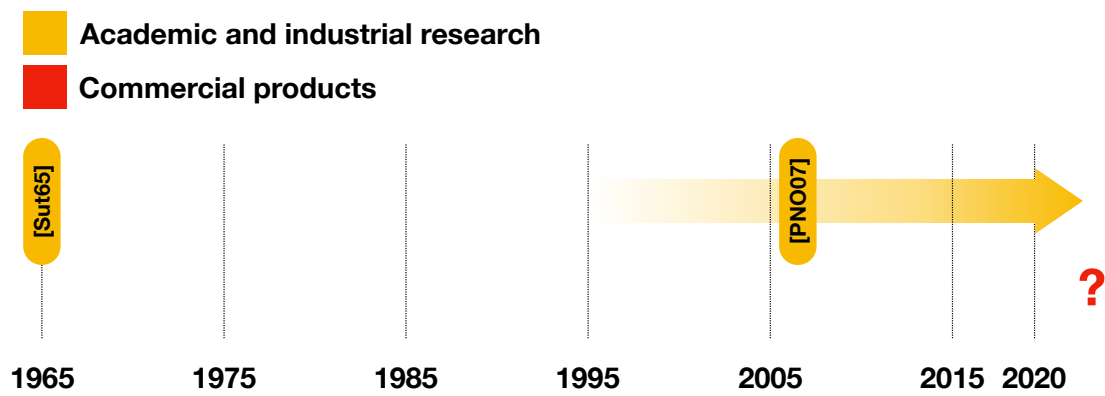


Figure 9.9: Our research project in the perspective of the history of HCI. Figure adapted and extended from [Mye98; Har18].

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